EXPERIMENTAL STUDY AND SIMULATION OF MULTI-HOLE EXTRUSION PROCESS

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

by

Ratnakar Das

(Roll No. 07610302)

Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati–781039
INDIA

January 2012

EXPERIMENTAL STUDY AND SIMULATION OF MULTI-HOLE EXTRUSION PROCESS

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

by

Ratnakar Das

(Roll No. 07610302)

Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati–781039
INDIA
January 2012

Department of Mechanical Engineering,
Indian Institute of Technology Guwahati,
Guwahati-781039,
INDIA

CERTIFICATE

It is certified that the work contained in the thesis entitled "**Experimental Study and Simulation of Multi-hole Extrusion Process**" submitted by **Mr. Ratnakar Das** to the Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy has been carried out under my supervision in the Department of Mechanical Engineering, Indian Institute of Technology Guwahati. This work has not been submitted elsewhere for the award of any other degree or diploma.

(Dr. U. S. Dixit)

18-01-2012

Professor
Department of Mechanical Engineering,
Indian Institute of Technology Guwahati,
Guwahati– 781039,
INDIA

Dedicated to……

My parents

My teachers

&

My family

Acknowledgement

I would like to express my sincere gratitude towards many people who have helped me during the tenure of my PhD work at IIT Guwahati. I take this opportunity to express my deep gratitude to all of them for their support and help during various phases of my research work.

I am highly indebted to my supervisor Prof. U.S. Dixit for his constant guidance and encouragement during the research work. I am grateful to Prof. Dixit as without his support and advice, it would not have been possible for me to continue my research work. He has helped me at various difficult phases of my work with his valuable guidance and moral support. I am also thankful to Dr. Sankha Deb, a former faculty member of IIT Guwahati who helped me in the initial phase of my research work. I would like to thank my doctoral committee members, Prof. S. K. Dwivedy, Dr. R. Ganesh Narayanan and Dr. Arbind K. Singh for their valuable suggestions and encouragement during the period of my research work. I am also grateful to the past and present heads of the mechanical engineering department, Prof. U.S. Dixit, Prof. D. Chakraborty and Prof. P. Mahanta for extending various facilities during the tenure of my doctoral programme. I also gratefully acknowledge the financial assistance provided by the All India Council for Technical Education through project AICTE: 8023/RID/BOIII/NCP (21) 2007-2008, project identification number at IIT Guwahati being ME/P/USD/4 for the research work. I like to acknowledge the technical support of CIPET, Changsari, Guwahati during fabrication of micro dies.

I am thankful to Dr. D. K. Sarma, Workshop Superintendent, Indian Institute of Technology Guwahati for his invaluable help and support during my PhD work. I wish to express my sincere thanks to Mr. Rituraj Saikia, Mr. Sanjib Sarma, Mr. Pranjol Paul, Mr. Jiten Basumatary, Mr. Dhrubajyoti Bordoloi, Mr. Amal Kalita and Mr. Nip Borah for their assistance during the experimental work. I sincerely thank all the workshop staffs for their help in fabrication of experiment set up. I am also thankful to Mr. Arun Borsaikia, Scientific Officer of Civil Engineering Department for helping me to carry out some experiments. I wish to express my sincere thanks to Dr. Manjuri Hazarika, Mr. Sachindra Mahto, Mr. M. Chandrasekaran, Mr. M.K. Sinha, Mr. Dillip Kumar Biswal and Mr. Biswajit Nayak for their help during various phases of my research work. I express my sincere thanks to Mr. Purnendu Mandal for helping me in learning the 3D modeling. I am very much thankful to Dr. S. K. Pal, Department of Mechanical Engineering, IIT Kharagpur for providing me the facility to carry out finite element simulations with DEFORM 3D®. I acknowledge the moral support and advice of Dr. Nishikanta Kundu of Reliance Industries Limited.

I shall always be grateful to my parents (Mr. Upendra Nath Das and Mrs. Sashi Devi) for their great encouragement and wishes. Most deeply, I thank my wife Lakshmi for her constant encouragement, support, patience and motivation for completion of this thesis work. Love and affection of my beloved son, Siddharth is the source of inspiration during my PhD programme.

Finally, I bow my head to the God Almighty in deepest gratitude and seek blessings.

18th January 2012

Ratnakar Das
IIT Guwahati

Abstract

Among all manufacturing processes, the extrusion technology has a special place because it produces parts of superior quality with minimum waste of material. The ever-increasing cost of material, energy and manpower requires that the extrusion process and tooling must be designed and developed with the minimum number of trial and the shortest lead time. Extrusion process can be broadly classified into single-hole and multi-hole extrusion processes. The multi-hole extrusion is carried out with a die having more than one hole. This process is productive for fabricating the parts of smaller length and cross section and is very suitable for microextrusion.

The present thesis explores the multi-hole extrusion process. Experimental study has been carried out to find out the effect of different process parameters on the extrusion load and quality of the extruded products. A series of experiments has been carried out with different dies (having different number of holes) with commercially available aluminum and lead alloy. Extrusion ratio, die land length, die pockets, billet length and lubrication are considered as process parameters. It is observed that the extrusion load depends on all these parameters. The reduction in die land length helps in reducing the extrusion load. The radii of curvature of the extruded products are dependent on location of the holes of the multi-hole dies, lubrication and die land length. In the present experiments, a mix of inward and outward bending of the extruded products is observed. The die pockets also affect the extrusion load and the profile of the extruded products. For a particular multi-hole die design, there exists an optimum pocket depth with which the least extrusion load is obtained. From the experimental study, it is observed that hardness, tensile strength and surface roughness of the extruded products depend on extrusion ratio, die land length and lubrication conditions. The study of multi-hole extrusion process with imposed vibrations reveals that the imposed vibrations reduce the extrusion load and improve the product quality.

Bending and unequal product lengths are common phenomena in multi-hole extrusion process, which are dependent on many process parameters. Studies on this are based on mathematical modeling and finite element simulations, but it is difficult to design a robust die that can produce straight products. In view of it, in the present work, a constrained multi-hole extrusion process has been proposed. The constrained multi-hole extrusion set up is developed to produce equal product lengths without bend. This process is somewhat similar to combined extrusion and closed-die forging process. The mechanical properties of the extruded products obtained from constrained multi-hole extrusion process are better than the extruded products obtained from free multi-hole extrusion process under similar extrusion conditions. The constrained multi-hole extrusion process consumes more power as compared to free extrusion. However, this can be compromised for getting better quality products.

In the present work, a commercial finite element analysis package DEFORM 3D® has been used to obtain the extrusion load for multi-hole extrusion with different multi-hole dies. The extrusion load obtained by finite element analysis is compared with the experimental result and a good agreement is observed. This indicates the possibility of reducing the number of experiments and supplementing them by simulations for the purpose of die design.

Microextrusion process has been proved as a successful method to produce metallic micro pins from the small billet dimensions at low extrusion ratio. In this work, a relatively bigger billet is used and multi-hole extrusion is used to get micro products. The present experimental study on multi-hole microextrusion process investigates the effect of extrusion speed, billet length and die land length on the process. Wax and lead alloy have been extruded through five-hole micro die having average hole diameter of 350 μm. The micro hardness and micro tensile strength of the extruded lead products have been studied. The effect of extrusion speed on extrusion load is significant. The extruded product length from centre hole is larger than that from peripheral holes. These variations are due to the high friction at the container-billet contact region and die land length in contrast to meso extrusion. Peripheral products have higher hardness compared to centre products. Increase in die land length increases the hardness. Higher tensile strength is observed for the products coming out from the peripheral holes as compared to the centre hole products.

Contents

List of Figures

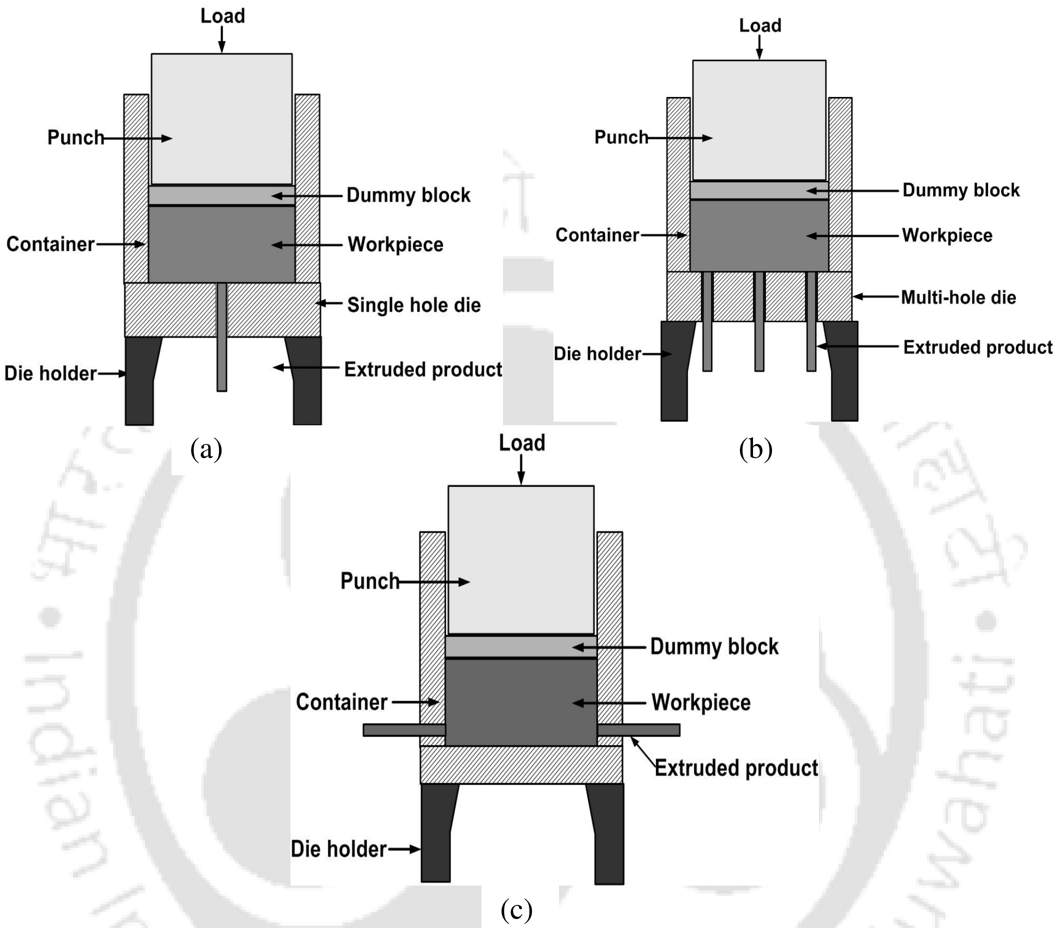
List of Tables

Chapter 1

Introduction

Manufacturing includes the processes like primary shaping, metal forming, metal cutting, heat treatment and metal joining. Among all manufacturing processes, metal foming technology has a special place because it helps to produce parts with excellent mechanical properties with minimum waste of material. Metal forming is a manufacturing method by which a metal of any shape and geometry is transformed into a useful part with well defined shape, size, accuracy, tolerance, properties and appearance. Forming of metals to near-net-shape or net-shape dimensions reduces material removal requirement and thus results in saving of the material and energy. Metal forming process includes large number of processes such as forging, rolling, extrusion, drawing, deep drawing and stretch forming etc. Among these processes, extrusion process has an industrial history spanning for more than 170 years. Extrusion is a compressive deformation process by which a block of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure. Different extrusion processes such as forward extrusion, backward extrusion, lateral extrusion, multi-hole extrusion and extrusion-forging process have their importance in industry for specific applications. The schematics of single-hole extrusion, multi-hole extrusion and lateral extrusion are shown in Figure 1.1 to understand the basics of these processes.

Multi-hole extrusion process is an extrusion process in which the die has more than one opening and is generally used to increase productivity or to reduce the extrusion load. Multi-hole extrusion process has gained importance in recent past. The present thesis studies the multi-hole extrusion process experimentally as well as through simulations. The keywords of this thesis are multi-hole extrusion process, process parameters of multi-hole extrusion process, constrained multi-hole extrusion process and multi-hole microextrusion. These are briefly introduced from Sections 1.1−1.5. Organization of the thesis is presented in the last section of this chapter.



(a) (b) (c)

Figure 1.1. Schematics of (a) single-hole extrusion (b) multi-hole extrusion (c) lateral extrusion

1.1 Micro, Meso and Macro Extrusion Process

Micro products are characterized by small dimensions, either of the products itself or functional features or structures of the products. A product can be said as micro product whose main functional features are in the µm range irrespective of its physical dimensions. Geiger *et al.* (2001) defined micro products as products with at least two dimensions in the sub-millimetre range. Microforming processes such as microextrusion, microembossing, microstamping, and microforging have been used successfully to produce micro products. In this thesis microextrusion is defined as an extrusion process that provides a part or feature whose at least one orthogonal view can be enclosed in a square of 1 mm size. In this thesis, only the parts of circular cross-section are produced. The following terminology will be used through out the thesis. Extrusion process providing a product of less than 1 mm diameter will be called microextrusion and the extrusion process providing the parts having diameter in the range of 1-10 mm will be called meso extrusion. The extrusion process providing the parts having diameter greater than 10 mm will be called macro extrusion. The terminology adopted in this thesis is same as mentioned in the book chapter of Muammer and Tugrul (2011).

1.2 Multi-hole Extrusion Process

Extrusion through a die having more than one hole is known as multi-hole extrusion. Multi-hole extrusion is extensively used for high production rate. Multi-hole extrusion is also used where pressure required for extrusion is in excess of press capacity. It is used for the production of small and precise products such as parts used in automobiles, health-care and aviation industries. Today in the era of globalization, multi-hole extrusion is a good solution to meet the demand of productivity with low cost.

Theoretical and experimental studies on multi-hole extrusion process are not new. Plain strain solutions of the extrusion problem were first given by Hill [1948] and later Green [1955] modified these solutions considering the unsymmetrical dies and also used them to analyse the problems of multi-hole die extrusion. Afterwards, slip line field method and upper bound solutions have been used by many researchers to study the multi-hole extrusion process. In the beginning of research, the focus was on the reduction of extrusion load. In recent past, die designs, types of dies, surface finish of dies and containers have been investigated by many researchers. Some empirical relationships on process parameters and the outputs such as extrusion load and exit velocities of the extruded products are established.

Mathematical modelling and finite element analyses have been carried out on multi-hole extrusion process to study the product quality and optimizing the die design. However, literature survey indicates a number of unexplored areas. Multi-hole extrusion process is found to be an important research area to explore the different aspects of improving product quality and productivity.

1.3 Process Parameters in Multi-hole Extrusion Processes

For obtaining the minimun extrusion pressure and optimum exit velocity, proper die design is necessary. The extrusion pressure and exit velocity depend on the eccentricity of holes, the friction factor, the extrusion ratio and the extrusion rate. The extrusion ratio, *R*, is defined as the ratio of the initial cross-sectional area of the billet to the final cross-sectional area after the extrusion. For single-hole extrusion,

$$R = \frac{A_i}{A_f}, \tag{1.1}$$

where A_i is the initial cross-sectional area of the billet and A_f is the cross-sectional of the extrudate. For multi-hole extrusion producing n extrudates each of cross-sectional area A_f,

$$R = \frac{A_i}{nA_f}. \tag{1.2}$$

Optimum location of hole in the multi-hole dies is one of the major causes to achieve a balanced material flow at the die exit. This can also avoid any curvature or bending of the extruded products. Knowledge of flow stress and strain-rate of the billet material, billet temperature (for hot extrusion) and extrusion ratio is required for economical use of the extrusion press.

The principal variables that influence the extrusion force are extrusion ratio, working temperature (for hot extrusion), speed of deformation and the flow stress of the material. At low extrusion ratio, the amount of plastic strain is low and the work done during the extrusion is less. Hence, any material extruded at low extrusion ratio has structure similar to cast one. Thus, low extrusion ratio may not be guaranteed to meet the mechanical and physical specifications of the material. For high extrusion ratio, the situation is just opposite. The extrusion process can be influenced by the speed of deformation. Increase in ram speed can increase the extrusion pressure due to strain-rate hardening. The stain-rate is a key issue for the extrusion of strain-rate sensitive materials. Extrusion of hard alloys sometimes becomes difficult unless the flow stress is decreased by heating.

The progress towards fulfilling the demand of better quality and high production rate has created wide research area to explore. Apart from the standard and conventional affecting process parameters, some more areas are needed to be studied. Recently, some process parameters have been investigated in detail in single-hole extrusion processes which were earlier less explored. These parameters are die land length, die pockets, eccentricity of pockets, surface finish of the die and container wall, die entry and exit angle, effective lubrication and other externally effecting sources like ultrasonic vibration and localized heating etc. In the present work, some of these process parameters are studied in multi-hole extrusion process.

During last decade, many researchers carried out investigations on the quality and productivity of the extruded parts from single-hole extrusion. Different process parameters have been investigated individually as well as in combination. Extruded product length, surface quality, mechanical properties and bending aspects have been studied. Die wear, continuous extrusion and minimization of extrusion load have also been the focus of research. In the case of multi-hole extrusion process, limited researches have been carried out till today. Investigations on different issues like deciding the number of orifices on the multi-hole die to obtain optimum extrusion load, use of die pockets to balance the material flow and effective lubrication for better quality products need further study. In view of this, there is a good possibility of investigating the effect of key process parameters on multi-hole extrusion process and some of them are discussed in this thesis. For some cases, the experimental results are also compared with the finite element simulations carried out using commercial finite element package DEFORM-3D®.

In this work, a constrained multi-hole extrusion process has been proposed to obtain the extruded products of equal length. The proposed constrained multi-hole extrusion process also eliminates the bending of the extruded products. The increased mechanical properties of the extruded product are found with the products of constrained multi-hole extrusion process. The comparative study on free and constrained multi-hole extrusion is also carried out. Many advantages favour the constrained multi-hole extrusion process in spite of higher extrusion load requirement.

1.4 Multi-hole Microextrusion Process

The uses of micro products and micro components have increased in recent years. The most important groups to use the micro products and components are information technology companies, medical and bio-medical technologies and space technologies. For the products with dimensions in micrometer and nanometre range, it is no longer insignificant to define how they are produced, handled and measured. Metal forming offers some attractive characteristics that are superior to other processes like chemical etching and photo-lithography processes due to high production rate, better material integrity, less waste and low manufacturing cost. Fundamental issues on micro metal forming have been studied by many researchers. Bringing up a microforming to real mass production application is really a difficult task. When the forming process is scaled downed to micro dimensions, microstructures and surface topology remain unchanged. But the workpiece material can not be considered as continuum. The limitations of micro-forming are largely influenced by the workpiece dimensions (known as size effect). Apart from feasibility, microforming also focuses on the suitability of the manufacturing process to be employed in mass production. The conventional macroscale manufacturing technologies such as sheet metal forming, deep drawing and extrusion process are being modified for microforming.

Extrusion process has been adapted to produce micro parts. It is a fast process with low material waste. Saotome and Iwazaki [2001] used backward extrusion process to produce micro gear of diameter 100 μm. Microextrusion set up was fabricated by Krishnan *et al.* [2007]. They studied the frictional behavior by performing a series of experiments. Conventional drilling and polishing was carried out to produce the microextrusion dies. In single-hole microextrusion, segmented dies are found to be convenient in use as they can be removed from the die block. To improve the productivity, a multi-hole microextrusion has been proposed and some studies on multi-hole microextrusion process have been carried out. The difficulties encountered during fabrication of microextrusion set up and experiments are explained in the thesis. The extrusion load, length and mechanical properties of the extruded products are also investigated.

1.5 Primary Objectives and Organization of the Thesis

The primary objectives of the present thesis are to carry out some studies on multi-hole extrusion process. Experimental work is carried out to study the effect of different process parameters in multi-hole extrusion process. Effects of extrusion ratio, die land length, lubrications, die pockets and vibration have been investigated. In order to produce the extruded product of equal length, a constrained multi-hole micro extrusion process has been proposed. Its performance in terms of extruded length, mechanical properties and extrusion load are studied. Micro multi-hole extrusion has been carried out and the extruded products of approximate diameter of 350 μm have been produced.

The thesis consists of eight chapters, which are organized as follows:

- The first chapter has provided the introduction along with the primary objectives and organization of the thesis.
- Chapter 2 presents a review of literature of the multi-hole extrusion, single-hole extrusion and microextrusion processes. Different challenging issues, scope and detailed objectives of the present thesis have been described.
- Chapter 3 presents the details of the experiments. The experimental set up, fabrication of different multi-hole dies and billet preparation procedures have been explained. Procedures for measurement of hardness,

tensile strength, surface roughness and radius of curvature have also been described.

- In Chapter 4, the results of experimental studies have been discussed. The effect of different process parameters on ram forces, radii of curvature, hardness and tensile strength of the extruded products, surface roughness of the extruded products have been explained.
- Chapter 5 deals with the finite element simulations of multi-hole extrusion. The comparison of simulation results and experimental results are presented.
- In Chapter 6, a constrained multi-hole extrusion process is proposed. The constrained multi-hole extrusion process has been developed for producing equal length of the extruded products. Extrusion load requirement for free and constrained multi-hole extrusion are studied. Mechanical properties of the extruded products of free and constrained multi-hole extrusion are compared and the advantages of the constrained multi-hole extrusion process are highlighted.
- Chapter 7 deals with the study on multi-hole microextrusion process. The fabrication of multi-hole micro die and the extrusion set up are explained. The effect of different process parameters such as extrusion speed, die land length and die pockets on extrusion load and strength of the extruded products are explained. The difficulties encountered during extrusion set up fabrication and experiments are presented.
- Conclusions and scope for future work are presented in Chapter 8 followed by references and appendices.

Chapter 2

Literature Survey

2.1 Introduction

Extrusion is a manufacturing process that is used to produce products of a fixed cross-sectional profile along the length. The material is placed in a closed container and pressed by a ram at high pressure to pass through a die. The design of the die opening determines the cross-section of the extruded product. A patent granted in 1797 by Joseph Bramah described a press in which lead was forced through a die. This was the earliest extrusion machine. With the development of aluminum, which was commercially available in 1886, the extrusion process was established as an important industrial process. Today, extrusion is used in the manufacturing of many different products of different materials. There are many different methods of extrusion but a classification is often done with respect to the direction of the extrusion relative to the ram. In direct or forward extrusion, the flow of material is in the same direction as the motion of the ram. If the flow of material is opposite to the motion of ram, it is called indirect or backward extrusion. Direct extrusion and indirect extrusion are the two basic methods of working. In spite of the advantages of indirect extrusion, the direct process is more widely used because of complexity in the designing of hollow ram and extrusion press in indirect extrusion.

The essential features of the extrusion process are the occurrence of extremely high pressure during the process. The shaped dies can reduce power consumption significantly. Other parameters such as extrusion ratio, die length, ram velocity and friction factor between the die-billet interfaces also affect the power consumption. In extrusion process, most of the work done during the plastic deformation and in overcoming friction at the die billet interface is converted into heat. The research on extrusion process is decades old. Like forward extrusion and backward extrusion, multi-hole extrusion has also attracted the attention of many researchers. Extrusion through a die having more than one hole is known as multi-hole extrusion. Multi-hole extrusion is extensively used for attaining higher production rate. Normally, multi-hole extrusion is used where pressure required for extrusion is in excess of press capacity. Multi-hole extrusion can also be used for the production of small and precise products such as parts used in automobile, healthcare and aviation industries. Today in the era of economic industrialization multi-hole extrusion will be a good and appreciable solution to increase the productivity with the least possible cost. With clear quantitative understanding of the multi-hole extrusion process, it is possible to set different process parameters for producing the desired quality products. The demand of micro-components has encouraged the scaling down of traditional macro-manufacturing to micro scale manufacturing. In recent years, successful attempts have been made to produce micro components by microforming processes. Microextrusion is one of the major microforming processes and an interesting area of research.

In this chapter, a review of available literature in the area of multi-hole extrusion process as well as single-hole extrusion process is presented in different sections. Section 2.2 presents an overview of literature on multi-hole extrusion process. Section 2.3 discusses the literature on experimental studies on single-hole extrusion process. Experimental studies on multi-hole extrusion process are discussed in Section 2.4. Section 2.5 presents the literature on modeling of extrusion process. Methods adapted for enhancing the efficiency of the extrusion process are discussed in Section 2.6. In Section 2.7, literature on the study of mechanical properties and microstructure of the extruded products are discussed. Section 2.8 presents the literature on microextrusion process. The challenging issues of multi-hole extrusion process are discussed in Section 2.9. Detailed objectives of the present work have been presented in Section 2.10.

2.2 An Overview of Literature on Multi-Hole Extrusion

There are a number of theoretical and experimental studies on single-hole extrusion process. The literature on multi-hole extrusion is quite sparse. Although the multi-hole extrusion of metal was popular in industry in the early part of 20th century, there is not enough documentation available in open literature. United States patent number 2720310 (patented on October 11, 1955) describes an innovation for producing a number of extrudates of same lengths from one ingot. The method involves pulling of extrudates by a pulling device comprising a rotating drum secured to a shaft supported by bearings. Dodeja and Johnson [1957] carried out multi-hole extrusion with four different materials: pure lead, tellurium lead, pure tin and super pure aluminum. Dies containing one, two, three and four holes arranged in different fashion were used. The extrusion load was found to be dependent on total reduction and the positions of the holes. The authors observed that the lubrication has significant effect on the flow speed through the holes of multi-hole dies. They also mentioned the availability of only two references on multi-hole extrusion for comparing with their results, which provided only limited information. Johnson *et al.* [1958] presented slip line solutions for single- and multi-hole extrusion to study the dependency of extrusion load on the die profile, friction condition and the extrusion ratio. The potential advantage of lateral extrusion was studied by Johnson *et al.* [1958]. There is more area available on the side where orifices can be placed compared to limited area available at the ends. However, lateral extrusion is not popular in industry, may be due tooling related difficulties.

There has been a period of lull for 3 decades (1960s, 70s and 80s). As an exception, there is a paper by Guanasekera *et al.* [1984] that discusses die design for multi-hole extrusion process. In this period, the research on single-hole extrusion got more attention and many research papers have been published. Starting from the decade of 1990s, the research on multi-hole extrusion has picked up, mainly in the area of modeling. This may be due to simultaneous growth in computer technology. The upper bound method and finite element method have been used to study the multi-hole extrusion process [Keife, 1993; Ulysse and Johnson, 1998; Li *et al.*, 2003a and 2003b; Peng and Sheppard, 2004; Peng and Sheppard, 2005 and Chen *et al.*, 2008]. Most of these research papers explain the effect of different process parameters on extrusion load, exit velocity of the extruded products and quality of the product profiles. However, the experimental studies on the multi-hole extrusion process are very limited. Recently, Sinha *et al.* [2009a] presented a preliminary design of multi-hole extrusion process. The authors designed and fabricated the multi-hole extrusion set up. Experimental results were compared with the results obtained theoretically. Sinha *et al.* [2009b] studied the mechanical properties of the extruded products obtained from multi-hole extrusion with different dies having different number of holes. This study indicates the possibility of using multi-hole extrusion process for producing small metallic components with improved productivity and quality.

2.3 Experimental Studies on Single-hole Extrusion Process

In the year 1810, S. Bramah invented the extrusion process for extrusion of lead and the process was successfully applied for high melting point alloys in the year 1890 [Laue and Stenger, 1981]. The scientific study of the extrusion process started with the development of different mathematical models. Many researchers showed interest in carrying out the experiments for verifying the theoretically obtained results. In the beginning, many experimental works on extrusion process were carried out to validate the results obtained from the slip line field methods. Johnson [1956] carried out experiments with wedge shaped dies having different semi-cone angles. Johnson [1958] carried out extrusion experiments on lead and pure aluminum using the different axisymmetric dies of circular, triangular, square, rectangular and I-section shapes. The different extrusion speed and reduction ratio were considered. The authors studied the effect of die shapes, reduction ratio and extrusion speed on extrusion load. Highest and lowest extrusion load were observed with I-section and square section respectively. Low extrusion load was observed for low extrusion speed. For a constant reduction ratio, the extrusion load was found to be independent of the shape of the sections. Later, different process parameters of the extrusion process were considered during the modeling and experimental studies. The observations made by Johnson [1956 and 1958] are found to be highly informative on the fundamental issues of extrusion process. After that nearly for four decades, research focus was on modeling of the process. Experimental research regained its importance from the beginning this century.

Kim and Ikeda [2000] investigated the effect of some process parameters on the flow behavior of the billet surface layer in the porthole die direct extrusion of aluminum. Flow of the surface layer in extrusion process affects the surface and overall quality of the extruded product. The authors observed that the billet surface has two flow paths i.e., the inward flow along the back face of the billet and the forward flow along the boundary of the dead zone. The extrusion temperature has little effect on the flow behavior of the surface layer. This finding helps to select the ram displacement to avoid the entry of impurities into the extruded part.

Bakhshi-Jooybari [2002] proposed a theoretical model for extrusion force to find out the friction factor at the die-work piece interface. This model works very well for cold extrusion of pure aluminum in dry condition. The friction factor can be obtained by evaluating the equation given by

$$m = \frac{\sqrt{3}}{\pi\sigma_0 d_o}\frac{\Delta F}{\Delta L}, \tag{2.1}$$

where ΔF is the change in the punch load, σ_0 is the flow stress, d_0 is internal diameter of the container and ΔL is difference in billet length. The author carried out extrusion experiments of aluminum and found the average friction factor. It was also observed that this method does not work properly for hot extrusion of lubricated medium carbon steel. Onuh *et al.* [2003] studied the effect of the various extrusion parameters on the extrusion products. The maximum extrusion pressure depends primarily on the die angles, loading rates and reduction in area of cross-section of the complex shaped section. The radius of curvature for both extruded lead and aluminum alloys increase with increase in die reductions in area and loading rate has no significant effect on this. Shiraishi *et al.* [2003] proposed a new extrusion process to extrude the billet through the inclined die by which the extruded product could be easily bent with various curvatures. Moreover, the developed process was a combination of control technique of bending and cross-section shapes.

Donati and Tomesani [2005] studied the influence of die design on extrusion process of AA6082 aluminum alloy. The effects of feeder dimensions and welding chamber height on the strength and deformability of the final product were examined under different processing conditions. The significant improvement in the product deformability was obtained with larger welding chambers. Tiernan *et al.* [2005] carried out the cold extrusion of AA1100 aluminum alloy and studied the influence of die angle, reduction ratio and die land on the extrusion force during the extrusion process. Experiments were conducted using two different lubricants—zinc stearate and an oil based lubricant that contained lead and copper additives. The influence of the different lubrications was studied. Noorani-Azad *et al.* [2005] carried cold aluminum extrusion with conical die and optimum curved die (optimum curved die profile was obtained from incremental slab method). The extrusion load obtained for optimum curved die was significantly less than the optimum conical die.

The effect of relative holes position and length of die land over ram pressure were studied by Ajiboye and Adeyemi [2006a]. It was observed that the contribution of the die land length to the extrusion pressure increases with increasing complexity of the die opening geometry with the rectangular section giving highest extrusion pressure and the square section giving the least extrusion load for a certain die reduction in area at a particular die land length. It was also found that for a percentage reduction in area, the normalized extrusion pressure contribution increases with increasing die land length and for a particular die land length, the normalized extrusion pressure increases with increasing percentage reduction in area. Kumar and Vijay [2007] carried out the designing, fabrication and experiment for shaped extrusion for aluminum alloy and lead alloy. Flat and conical dies of H, T, L, elliptical and two-hole sections were designed on the basis of upper bound technique for cold and hot extrusion. It was observed that the extrusion power increases with increase in the complexity of sections.

Schikorra *et al.* [2007] performed the extrusion of an AA6060 aluminum alloy round profile to investigate the flow pattern of the deforming material, with particular attention to the contact conditions at the container wall. They conducted two types of grid tests. The first way is to divide the billet into two parts, then to mark a grid on one part and to recompose the original billet with a thin layer of a release agent in the middle. The two slices are then extruded together. The second way is to drill equally spaced hole in the billet, then to fill them with rods of a different alloy having a similar flow stress. The analyses of the shape of the deformed rods provide the understanding of the material flow and the friction effect at the billet-container interface. The analysis of the billet test showed sticking condition except at the bearing area, where sliding condition occurs. It was observed that perfect sticking was present at the container wall until the ram did not force the material to move towards the billet axis, in a radial direction path. The effect of the speed was found to be negligible. Shahzad and Wagner [2009] studied the influence of extrusion ratio on the mechanical properties of the extruded magnesium alloy. The extrusion ratio affects the die exit temperature and thereby the grain size. Weaker texture was observed with higher extrusion ratio.

Though the forward extrusion is a widely investigated process, the other extrusion process like backward extrusion, radial extrusion, lateral extrusion, reciprocating extrusion and combined forward-backward extrusion are also studied to understand the usefulness of these processes. These processes are used for producing some specific products at low extrusion load and minimum cost. Plancak *et al.* [1992] carried out radial extrusion and verified the extrusion load obtained from experiment with upper bound analysis. The authors also carried out backward extrusion with a punch of square cross-section for extrusion ratio of 1.67, 1.55, 1.39 and 1.25. Minimum extrusion pressure was observed at extrusion ratio of 1.55 but for this no explanation is given. Choi *et al.* [2001] presented a quantitative analysis of the radial extrusion process combined with backward extrusion. Different variables such as gap size, die corner radius and frictional conditions were adopted as design/process parameters for analysis. The research focused on the analysis of metal flow into the can and flange. The authors carried out the comparison between experimental data and simulation results in terms of forming load and the volume ratio of the flange to can. It was observed that the friction factor has little influence on the volume ratio (flange volume/can volume), the forming load and deformation pattern.

Altinbalik and Can [2006] investigated the lateral extrusion of splines in terms of load requirement and dies filling. The authors observed that the forming load increases with the increase in number of teeth and the tooth profile is not straight due to barreling effect. The degree of barreling increases with number of teeth due to increase in frictional resistance. Yeh *et al.* [1997] developed a reciprocating extrusion process for producing an A1-12% (by weight) Si alloy with fine microstructure and superior properties. The improvement of properties of the alloy was due to the rapid solidification during the reciprocating extrusion process.

Uematsu *et al.* [2006] carried out hot extrusion of magnesium alloy to investigate the working temperature and extrusion ratio on the grain refinement. It was observed that the grain size decreases with decrease in working temperature and increase in extrusion ratio. Fard and Akhlaghi [2007] investigated the effect of extrusion temperature on the microstructure and porosity of Al A356-10% (by volume) SiC composites. The extruded composites exhibited reduced porosity as well as a more uniform particle distribution when compared with the as-cast samples. It was observed that, the increased extrusion temperature provides easier flow of the matrix alloy and non-uniformity in the distribution.

Schikorra *et al.* [2008] worked on the prediction of recrystallized structure in aluminum extrusion. They carried out the whole process in three steps. In the first step, the evolution of microstructure of an AA6060 alloy during deformation was studied by means of small-scale laboratory test, the process parameters being chosen in order to reproduce the typical industrial conditions. In the second step, the analysis of microstructure evolution after the heat treatment was carried out, the obtained information being used in order to fit a re-crystallization model to be implemented in DEFORM, the finite element package. In the third step, the model was used in the simulation of the AA6060 profile extrusion described in (Schikorra *et al.*, 2007) and the result of the simulation were compared with experimental grain size distribution measured on the extruded products. The simulated results were found to be in good agreement with the experimental results. But the occurrence of coarse grain at the peripheral region was not explained.

2.4 Experimenral Studies on Multi-hole Extrusion Process

The increase in production of small sections at high production rate put the challenges in front of the researchers. The concept of multi-hole extrusion then evolved. Initially some theoretical modelings were carried out for find the extrusion pressure. As per the paper of Dodeja and Johnson [1957], preliminary experiment on multi-hole extrusion was carried out by Watkins *et al.* [1954] with one, two and three-hole die at 0.86 reduction. Increase in extrusion pressure for both two hole and three hole die compared to one hole extrusion was observed at same total reduction. In their experiments, the authors used low strain hardening material (lead). Dodeja and Johnson [1957] carried out multi-hole extrusion with four different materials: pure lead, tellurium lead, pure tin and super pure aluminum. Dies containing one, two, three and four holes arranged in different fashion were used. The extrusion load was found to be dependent on total reduction and the positions of the holes. The authors observed the effect of lubrication on the flow speed through the holes of multi-hole dies.

The extrusion die design for manufacturing of complex profile was mainly built upon the experience and experiments. The product profile, quality and low power consumption became the key factors for extrusion industries. The importance of the different process parameters in multi-hole extrusion was realized and studies on these issues were started. The optimal position of die openings and determination of die land lengths were typical problems in multi-hole die extrusion. Keife [1993] conducted experiments with multi-hole die having two die openings and different die land length. He compared the experimental results with the results obtained from 2D upper-bound analysis. Following important observations were made from experiments:

- Die land length affects the shape of the extruded products (curved or straight).
- Velocities of the extruded products are sensitive to die opening positions and die land length.

The flow pattern of metal in extrusion process is complex. The flow is asymmetrical and depends on the distribution of the holes. The mechanical properties of the extruded products, the extrusion pressure and the surface finish of the extruded products are related to the flow pattern. Peng and Sheppard [2004] studied the flow pattern in multi-hole extrusion. They carried out experiments with one-hole, two-hole and three-hole dies. The flow pattern was studied by doing macro-etching of partially extruded billet. The recrystallized grain size was found to be smaller at the surface than that at centre of the extruded products. However, no significant difference in grain sizes at the centre of the extruded products that were extruded from different holes was observed.

Sinha *et al.* [2009a] presented a methodology for preliminary design of the multi-hole extrusion process. The ram force was estimated by using upper bound method considering the process as single-hole extrusion. The overestimated ram force helps in safer design of die and ram. The authors also calculated the die pressure distribution by using slab method. Experiments were carried out with single and multi-hole dies. It was observed that the ram force calculated using the upper bound method is about 25% higher than the experimental results. The ram force obtained for multi-hole extrusion was also found to be less compared to single-hole extrusion process. From the experiments it was observed that the material encounters more resistance to flow through the central hole than through the holes away from the centre, which leads to the difference in length of the extruded products.

Sinha *et al.* [2009b] developed a simplified mathematical model to obtain ram force in a multi-hole extrusion process. Experiments were carried out with nine-hole, thirteen-hole and fifteen-hole dies with lead billets of same diameter and different lengths. The ram force was found to be the least for fifteen-hole die. Ram force increases with increase in billet length. The authors also carried out micro tensile test and micro-hardness test on the extruded products. The strain hardening was found to be the highest for the central hole products and lowest for the holes near to the die wall. A good correlation between the micro-hardness and tensile strength was observed. The authors also carried out multi-hole extrusion of wax and the lengths of the extruded product were found almost equal and this indicates that flow behavior is material dependent. However, the proposed model could not explain the variation in mechanical properties of the products extruded through the same die.

In extrusion process, die pocket is another important process parameter which balances the material flow and thus by produces better quality products. In recent years, pocket dies are in use instead of flat dies. Die pocket shape, design and location decide the flow behavior. In multi-hole extrusion, pockets have been used to control metal flow. Fang *et al.* [2009] produced pockets with different number of steps on the two-hole die to extrude chevron profile aluminum products. It was observed that more number of pocket steps reduces the difference between product lengths. The increase in number of steps in pockets helps in reducing the peak extrusion pressure. The good correlation between experimental and finite element simulation results was obtained.

Effect of pocket shape in multi-hole die hot extrusion of AA6082-O aluminum alloy was studied by Donati *et al.* [2009]. Four different pocket profiles (straight pocket with asymmetric positioning, symmetric 3-stepped pocket, symmetric conical pocket and symmetric pocket with straight walls) were used. The effects of die pockets were found to be different for different profile thickness. At low speed, the thicker profile flows faster than the thinner one and 10% speed reduction with the conical pocket with respect to stepped die pocket was observed. The pockets located symmetrically provided 30% faster material flow than the asymmetric pockets. Greater extruded profile lengths were observed with the dies having three step pockets and conical pockets.

In spite of a number of parametric studies on multi-hole extrusion, the effect of die land length, location of the holes, lubrication and extrusion speed need thorough investigation. In practice, the fabrication of new dies and carrying of number of experiments to get satisfactory results are the time consuming process and involve huge cost. Computer simulations can help in reducing the number of experiments.

2.5 Modeling of Extrusion Process

A number of theoretical models have been developed in past decades by making various assumptions to simplify complex behavior of extrusion process. The developed models and their suitability depend on the use of assumptions. The appropriateness of the assumptions depends on the desired outputs of the model and the simplicity required. This section presents a review of literature starting from the simplified models to the present day computational methods. The methods of analysis are slab method, slip-line field method, upper-bound method, visioplasticity method and finite element method.

2.5.1 Slab Method

The slab method assumes that the metal deforms uniformly in the deformation zone. The workpiece being deformed is hypothetically decomposed into several slabs. For each slab, simplifying assumptions are made mainly with respect to stress distributions. The resulting approximate equilibrium equations are solved with imposition of stress compatibility between slabs and the boundary tractions. The final result is a reasonable load prediction with an approximate stress distribution. This was earliest approach developed in 1920 by von Karman. Here, only a few recent papers are reviewed.

In metal forming, the flow stress is a function of strain, strain rate and temperature. Srinivasan *et al.* [1990] used slab method to develop an expression for local strain rate as a function of the axial location in the deformation zone to generate the controlled strain rate die profile. Wifi *et al.* [1998] used incremental slab method to obtain the extrusion pressure of the hot extrusion for arbitrarily-shaped curved dies. Chitkara and Aleem [2001] used slab method to obtain the peak extrusion load in forward tube extrusion. Of late, the slab method has been replaced by other methods. However, many researchers combined the slab method with upper bound method and finite element method for designing the optimal die profile. To determine the distribution of die pressure, Reddy *et al.* [1995] combined upper bound method and slab method to and calculated the extrusion pressure for different die profiles. The generalized stress and extrusion pressure were calculated from upper bound method and then used to find out the stress tensor along the direction of deformation. Bakhshi-Joobari *et al.* [2007] combined slab method with upper bound method to obtain extrusion load for optimum curved die and optimum conical die. For multi-hole extrusion process, the slab method combined with upper bound method was used by Sinha *et al.* [2009a] to calculate the die pressure distribution. For calculation of average extrusion pressure, the process was considered as single-hole extrusion.

2.5.2 Slip-Line Field Method

A slip-line is a shear line which is tangent, at every point, to the surface of the maximum or minimum shear stress. The material slips (deforms) along the slip lines.

The slip lines also satisfy the yield condition and represent a possible flow field everywhere in the plastic zone of the metal. The boundaries between the forming tool and the metal outside the plastic zone are treated as rigid zones. The slip-line method is based on several assumptions. The slip-line field approach is limited to plane-strain problems. However, the slip-line method has been applied to many practically important problems giving good agreement with the experimental observation. Extrusion has long been the subject matter of slip-line method.

The slip-line method is mathematically well defined method to obtain the stress field in a plane-strain forming problem. However, it becomes very difficult to find a slip-line field which satisfies all the imposed conditions for complicated die geometry and the computation time increases tremendously with increasing geometrical complexity.

Dodeja and Johnson [1957] used slip-line fields to calculate extrusion pressures for the extrusion of sheets through a square die containing one, two and three holes respectively. They also studied the flow pattern and flow velocity. However, no justification was provided on the increase in extrusion load with increase in the number of holes. Johnson *et al.* [1958] developed the methodology for calculating the ram pressure in extrusion through single staggered hole and unequal multi-hole dies using the slip-line field method. The proposed slip-line fields for the analysis of the extrusion process were limited to plane-strain extrusion of non-hardening materials. Due to the limitation of application and difficulties in construction of slip lines, studies on multi-hole extrusion process were carried out with other analytical methods.

In the past, Green [1955] proposed slip-line fields for the calculation of extrusion pressure in unsymmetrical single-hole extrusion process. He investigated the effect of roughness of the container wall on extrusion pressures. The analyses were limited to plane strain extrusion of non-hardening material. Farmer and Oxley [1971] obtained flow field for plane strain extrusion by printed grids and constructed a slip-line field and calculated the direction of maximum shear strain rate from the measured velocity gradient. The stress equilibrium equations of variation in shear flow stress resulting from strain hardening proved successful and applicable to other plane strain process like indentation and blanking.

Fenton and Durai Swamy [1975] developed a numerical calculation based on slip-line field theory to solve the metal flow problems of strain rate sensitive materials by using modified Hencky equations. The inputs for the calculation were die geometry, stress, velocity boundary conditions and material properties, whereas slip-line stress, strains, velocity and average extrusion pressure were the outputs. Authors used computer to solve the problem and plots of the slip-lines, stress, strain rate, velocity fields and extrusion pressure were obtained. They observed that the ram pressure is quite sensitive to the material properties, i.e., ram pressure increases with the increase in strain rate and ram speed.

Chenot *et al.* [1978] proposed slip-line field model to calculate the hydrostatic pressure on the axis of the axisymmertic extrusion through a conical die. The authors derived the velocity field and calculated pressure gradient by trial and error along the die so that the velocity field would satisfy the boundary conditions. The stress field was computed in the deformed region by applying several extrusion ratios and die angles. However, authors did not consider the friction along the die, metal work hardening and different die profiles for the proposed model.

Conning *et al.* [1982a, 1982b] explained the method to construct strain hardening slip-line fields based on experimental flow pattern in the extrusion process. Maximum shear strain rate directions calculated from digitized smoothed flow patterns with Hencky-Prandtl nets were used to outline the complete slip-line fields. Authors also analyzed the computations of velocity field solutions and found out the total strain along streamlines. Wang [1998] presented a new procedure for visioplasticity method in which the finite flow line region was proposed to find out the velocity field and strain rate field. A slip-line model was developed and used to draw the slip-line fields. Author did not consider the friction with boundary conditions.

The slip-line field method is suitable for plane strain conditions and is based on many assumptions. The main drawback of the slip-line method, which can lead to inaccurate estimation of the extrusion parameters, is its inability to incorporate the strain hardening effect easily. Solving the complex problems associated with metal forming is difficult task in slip-line field method and hence other methods have been tried by many researchers. The methods like upper bound analysis and finite element analysis were used to analyse the extrusion process.

2.5.3 Upper Bound Method

The upper bound method is a technique based on the assumed flow field, i.e., on the so called kinematically admissible velocity field, which satisfies the continuity equation and all the velocity boundary conditions. This method does not impose any requirement of stress equilibrium and stress boundary conditions. This method has been widely used for many axisymmetric metal forming problems, the extrusion process has been a proper subject of its application. The upper bound method has been successfully applied even to some complicated three dimensional extrusions problems, such as extrusion of arbitrarily-shaped billets into arbitrarily-sectioned products and helical extrusion etc.

The analysis of multi-hole extrusion process using upper bound method has been used by few researchers. Keife [1993] studied the extrusion process through a die with two openings of different sizes and the influence of the holes positions. He used upper bound method and the velocity fields were optimized numerically. The velocities of the extruded products were found sensitive to the position of die opening and die bearing lengths. Author verified the results obtained from upper bound method with experiments. Ulysse and Johnson [1998] carried out analytical and semi analytical upper bound solution for plane-strain extrusion through single and multi-hole extrusion. The semi analytical solutions obtained for two-hole extrusion die were compared with the results obtained by Keife [1993]. The authors also presented simple expressions to obtain the extrusion pressure, the exit angles and velocities of the emerging products. The expressions are the functions of the dependent process parameters such as eccentricity of the holes, the distance between the holes, the friction factor, ram position and extrusion ratio.

Sinha *et al.* [2009a] estimated ram force in multi-hole extrusion process by using upper bound method. In the calculation, they considered the process as single-hole extrusion. The overestimated ram force helps in safer design of die and ram. Experiments were carried out with single and multi-hole dies. It was observed that the ram force calculated using the upper bound method is about 25% higher than the experimental results. Sinha *et al.* [2009b] developed a simplified mathematical model and used upper bound method to obtain ram force in a multi-hole extrusion process. Theoretical and experimental ram forces were obtained for nine-hole, thirteen-hole and fifteen-hole dies with lead billets of same diameter and different lengths. The ram force was found to be the least for fifteen-hole die. Ram force also increases with increase in billet length.

Limited literature is available on the study of multi-hole extrusion process with upper bound method. However, sufficient number of research on single-hole extrusion has been carried out with upper bound method. Some relevant literatures are discussed here.

Kobayashi and Thomsen [1965] explained the method to find an admissible velocity field and stress field for axisymmetric forming problems. They also obtained an improvement of lower bound by modifying the admissible stress field for the frictionless extrusion of a bar through die with square corner. For the frictionless extrusion of a bar through tapered die, a lower bound solution was obtained for the extrusion pressure with reference to semi cone angle. Authors also suggested that if more definite information like redundant work of an extrusion problem is required, the general method of slip line solution may be used to get lower bound solutions.

For the extrusion of incompressible material, Chen and Ling [1968] presented a method for selecting the admissible velocity fields. The upper bound method was used to find out mean extrusion pressure for the axisymmetric curved dies of cosine, elliptic and hyperbolic type. Osakada and Niimi [1975] suggested a generalized expression for radial flow field for extrusion through a conical die and obtained the extrusion pressure of a rigid-perfectly plastic material by using upper bound method. They also compared the extrusion pressure and hardness distribution obtained from the theoretical calculation with the hydrostatic extrusion of Al, Cu and Al-Cu composites.

Gunasekara *et al.* [1980] observed that manufacturing of shaped die is a difficult task in extrusion industry. They proposed upper bound solution for three dimensional metal flow for extrusion through dies having circular entry and regular polygonal exit profiles. The optimum die profiles were generated with the help of computer to produce drawings of electrodes and then the dies were produced by electric discharge machining process. The reduced extrusion load was obtained from the shaped polished die compared to the flat faced die for same reduction ratio.

For non-axisymmetric extrusion process, Kiuchi [1988] developed a generalized mathematical equation of the kinematically admissible velocity field, which express the three dimensional steady flow of the workpiece. The extrusion pressure, the optimum die dimensions and the dimension of the extruded products were calculated. The developed velocity field was also applied to the analysis of eccentric backward extrusion for predicting the extrusion pressure and the geometry of the extruded products.

Yang *et al.* [1991] applied upper-bound method to determine the extrusion pressure for forward extrusion of composite rods through curved dies considering second order and third order flow functions. The effect of work-hardening was considered in the analysis. The experiments were carried out to verify the results obtained from upper bound method. The second-order flow function was in better agreement with the experimental observation than the third-order flow function both in extrusion load calculation and in deforming regions. The increase in semi-cone angle tends to minimize the extrusion power.

Altan *et al.* [1992] proposed a method of constructing kinematically admissible velocity field appropriate for axisymmetric extrusion and explained two deformation models (flow lines are straight line and flow lines are cubic) for extrusion. Reddy *et al.* [1995] proposed an upper-bound model combined with the slab method to predict the total extrusion power and die pressure distribution in axisymmetric extrusion process. The model proposed by the authors can be used for large class of die profiles in die design for extrusion and wire drawing. However, the authors have not verified their results with experiments with the proposed dies.

Celik and Chitkara [2000] investigated the off-centric extrusion of a square section from a round billet. To validate the results obtained from upper bound method, a number of the streamlined dies were designed by CAD/CAM package and manufactured by means of the EDM process. From the experiments, the authors observed that optimal die design depends significantly on the friction factor, which controls the curvature of the extruded products. Longer die lengths results in smaller curvatures of the extruded products. The theory proposed by the authors gives estimation for the curvature of the exiting product.

Alexandrov *et al.* [2001] proposed a kinematically admissible velocity field based on simple radial flow field combined with asymptotic behavior of the velocity field for the analysis of axisymmetric direct and indirect extrusion. Authors also studied the influence of extrusion ratio on the shape of the dead zone and the extrusion pressure.

In general, the conventional extrusion is carried out by shear faced (flat faced) die. The use of sheared faced dies have many practical problems such as dead metal zone, more redundant work and above all the design of shear faced die is done based on experience and made by trial and error methods. But these methods are approximate and time-consuming methods. The profile of the extrusion dies is always an important parameter to optimize the extrusion pressure. Narayanasamy *et al*. [2006] proposed an upper bound analysis for the extrusion of circular section from circular billets by extruding through cosine die profile. They observed that under no friction condition, the cosine profile die consumes less extrusion pressure compared to straight converging and concave circular profile dies. It was further observed that the cosine profile die needs lower plastic deformation work. Die surface friction and total power consumption by using cosine profile dies was found to be less compared to straight converging die for all the values of relative die length.

The analyses on extrusion pressure by upper bound method have been extended to the extrusion of complex sections. Ajiboye and Adeyemi [2006, 2007] carried out upper bound analysis on the effect of die land length on the extrusion pressure considering the ironing effect at die land region for different cross-sections of the extruded products. The effect of die land length on the extrusion pressure increases with increase in complexity of the cross-section of the extruded products. Bakhshi-Jooybari *et al.* [2007] proposed a combined upper bound and slab method for estimating the deformation load for cold rod extrusion of aluminum and lead with an optimum curved die profile and optimum conical die. It was observed that optimum curved die requires lesser load than the optimum conical die. Experiments and finite element simulations were carried out for verifying the estimated extrusion load. Malapani and Kumar [2007] carried out three dimensional analysis of tube extrusion process using upper bound method. The product profile, shape complexity factor, die and mandrel profile, friction, ram velocity and die length were considered as process parameter. It was observed that for any die profile, the average power varies linearly with friction factor.

Gordon *et al*. [2007] used upper bound modeling to determine adaptable die shapes that produce dies of specified criteria. The description for an extrusion die with a bearing length was developed for the use in the adaptable design method. Optimal die shapes were determined based on the average effective strain criterion and the volumetric effective strain rate deviation criterion. The authors also proposed that an upper bound model can be used to analyze a multi-sectioned dies. Altinbalik and Ayer [2008] proposed a new kinematically admissible velocity field to calculate the load requirements of extrusion of clover sections from cylindrical billets. The derived velocity field was found suitable to three dimensional extrusions of complex shapes. The quality of the extruded product was also investigated and it was observed that the value of deflection was quite small for all billet diameters which is in good agreement with the results obtained by Ajiboye [2007].

Huang *et al.* [2009] designed the streamline function considering the die profile and rigid plastic boundaries. The rigid plastic boundaries were the parametric functions with user defined variables which can be selected to minimize the power by upper bound method. The authors used four different die profiles, the cosine die with zero slope at entry and exit, the elliptic die with zero slope at entry, hyperbolic die with zero slope at exit and conical die with slope at entry and exit. The deformation pattern, extrusion pressure and the effective strain were calculated. The cosine die was found to consume lowest power where as the hyperbolic die consumes highest power.

The upper bound method has also been used to study the backward and radial extrusion processes. Plancak *et al.* [1992] investigated radial extrusion process with upper bound method and predicted the extrusion load. Bae and Yang [1992] applied an upper-bound method to determine the extrusion load and the deformed configuration for backward extrusion of internally elliptic-shaped tubes from round billets. Later, Bae and Yang [1993a, 1993b] presented a kinematically admissible velocity field solution for the backward extrusion of tubes with internal trochoidal gear shape and rounded rectangular shape from the round shaped billets. The authors also presented a kinematically admissible velocity field solution for the backward extrusion of internally circular shaped tube from regular polygonal and circular billets.

Non-axisymmetric combined forward and backward extrusion process was studied by Hwang *et al.* [2003] using the upper bound element technique (UBET). The kinematically admissible velocity fields were proposed to determine the forming load, the extruded product length and the velocity distribution according to the stroke in the combined extrusion process. Ebrahimi *et al.* [2008] used analytical approach to obtain the extrusion pressure and the strain imposed through radial forward extrusion. They derived equations for extrusion pressure by determining the internal power and the power dissipated on all frictional and velocity discontinuity surfaces.

When a material is plastically deformed, a very large part of the work expended appears as heat energy. The temperature generated reduces the flow stress of the material, which consequently lowers the power required for deformation. A numerical method was developed by Ajiboye and Adeyemi [2008] to obtain the non-steady-state temperature distributions during forward extrusion process. The velocity, strain rates, and strain fields within the deformation zones during extrusion were obtained with upper bound method. Heat transfer equations were coupled with upper bound method to obtain internal heat generations.

The upper bound method also has been used to study the extrusion of porous metals. Oh and Phark [1987] developed an analytical model by using upper bound method for forward extrusion of porous metal through an axisymmetric square die. The shape of the boundary of the dead metal zone (linear, bi-quadratic and hyperbolic) and the relative density of the product were optimally determined by minimizing the relative mean extrusion pressure. Experiments were also carried out to verify the results obtained from the developed model. From experiments, it was also observed that the densification does not occur in the deformation zone in the steady state condition. The analytical results of hyperbolic boundaries were in good agreement with the experimental results.

Use of upper bound method to solve many problems of extrusion process led much research activities aiming in finding the new types of velocity fields and optimization of power consumption. The application of upper bound method to solve three dimensional problems also has established a wider horizon for design of different die profiles and production of different complex extruded profiles. The researchers have given more emphasis on reduction of power consumption by using correct die. The upper bound method does not give clear idea about the quality and properties of the extruded products.

2.5.4 Visioplasticity Method

The visioplasticity method combines experiment and analysis. It is originated by Thomsen *et al.* [1954]. A grid is imprinted on the metal or modeling substance before deformation starts. Pictures of deformed grid taken during and after the process enable the investigator to construct the flow pattern. After the velocity vectors have been determined from the actual test, strain rates are calculated and the stress distributions are obtained from the plasticity equations. The method can be used to obtain reliable solutions in detail for the processes in which experimental determination of the velocity vectors is possible. Dodeja and Johnson [1957] introduced the use of visioplasticity method in multi-hole extrusion process and studied the flow pattern of the material through single-hole and multi-hole dies.

Medarno *et al.* [1978] conducted visioplasticity studies of the hot aluminum extrusion. They analyzed the flow pattern and obtained a relationship between the flow pattern and extrusion speed. From these observations, the authors also calculated shear strain and principal strain. The visioplasticity method was used in extrusion forging by Biswas and Rao [1984] to study the nature of metal flow. Biswas and Vidyasagar [1985] studied the effect of die opening and initial height of the specimen on the strain distribution in a plane–strain extrusion forging process by using visioplasticity method. The distortion of the inscribed grid gives the strain distribution.

To obtain fundamentals on the bending of the extruded products through an inclined die, Shiraishi *et al.* [2003] inscribed the grids on half part of the billet and allowed to extrude through the inclined die. The distortion of the grid indicates the asymmetric material flow due to the inclination of the die aperture. Ajiboye and Adeyemi [2006] used visioplasticity method to study the effect of die land length, on the flow pattern and quality of the extruded products. They observed that the dead metal zone was absent in the products obtained from the die with smaller die land length (1 mm) compared to higher die land length (20 mm). As result of this different amount of straining on the extruded products takes place. The variation in straining causes the difference in hardness value. This study provides a good observation the selection of appropriate die land length to obtain the desired properties.

Keife [1993] used visioplasticity method to understand the flow pattern in multi-hole extrusion process. The velocities of the extruded products are found sensitive to the die opening positions and the bearing lengths. Literature on visioplasticity method in multi-hole extrusion is limited. In multi-hole die extrusion, the number of holes determines the extruded product diameter (when the billet diameter is kept constant). For the extrusion of small diameter products, the generation of finer grid and analyzing the deformed grid pattern is a difficult task. This poses difficulty in using visioplasticity method for multi-hole extrusion.

2.5.5 Finite Element Method

Traditional methods used to calculate metal forming parameters *viz.* slab method, visioplasticity method, slip line field method and upper bound method are based on several assumptions and provide limited information about deformation. They are therefore not adequate for the modeling of forming processes with high complexity. Perhaps the most versatile of the computer-based analysis methods is the finite-element method. In this method the material to be processed is mathematically divided into many regions or elements each of which is assumed to deform very simply but collectively deform in a very complex manner. The finite element method (FEM) originated in the field of structural analysis. It has been rapidly expanding to a wider range of non-structural problems for which exact solutions cannot be found with the traditional techniques. As the finite element method together with high-speed computers is capable of predicting the detailed distribution of field variables, it is quite obvious that this method has been widely used for the analysis of metal-forming processes. The models are considered to be two dimensional (plane strain) or three dimensional. Predominantly, finite element analysis of metal-forming problems involves large strain and inclusion of both material and geometric nonlinearities. The finite element method is expected to be used for simulating metal forming processes, because realistic boundary conditions and material properties can be taken into account. Finite element method (FEM) is preferred to other methods, as it is able to relax many of the simplifying assumptions; it can easily incorporate non-homogeneity of deformation, process-dependent material properties and different friction models. The combination of computer aided design packages and the finite element analysis is able to solve more complex problems in metal forming. A number of researchers have employed finite element method for analyzing extrusion problems.

Application of FEM to the modeling of extrusion process started in early 1970s. Iwata *et al.* [1972] carried out elastoplastic analysis of hydrostatic extrusion using FEM. Lee *et al.* [1973] predicted residual stresses in extrusion process with the help of FEM. An elastic-plastic finite element analysis of plane-strain extrusion with friction less curved dies was carried out by Lee *et al.* [1976]. Shah and Kobayashi [1977] analyzed the axisymmetric extrusion through frictionless conical dies by rigid plastic FEM. Zienkiewicz *et al.* [1978] presented the flow formulation approach for extrusion. Tayal and Natrajan [1981]; Gunasekera *et al.* [1982] and Balaji *et al.*[1991] carried out deformation analysis of extrusion process with the help of FEM. Bianchi and Sheppard [1987] carried out finite element analysis of extrusion process and compared the viscoplastic finite element method with slip-line field and upper bound solution. Better results were obtained with finite element method. Work carried out in last one and half decades in the area of multi-hole extrusion and single-hole extrusion is described under separate headings here.

2.5.5.1 FEM in modeling of multi-hole extrusion

Finite element simulations using FORGE3® were carried out by Peng and Sheppard [2004] to study flow pattern, pressure requirement and the temperature developed in multi-hole extrusion. The number and distribution of the holes in multi-hole extrusion are important process parameters. The peak extrusion load was found to increase with increase in number of holes for a given reduction ratio. The optimum value of eccentricity of hole helps in reducing the extrusion load. Later, Peng and Sheppard [2005] carried out finite element simulation to study the influence of the offset of the die pockets on the material flow and structure of the extruded product in multi-hole die extrusion. Significant change in metal flow due to offset of the die pocket was observed.

The control of metal flow is achieved by using variable die land length. But high die land length generates heat during extrusion and this limits the speed of extrusion. Small die land is also not preferred due to its effect on the die deflection. The material flow can also be controlled by using a shaped pocket in front of the die. Li *et al.* [2003a, 2003b] studied the influence of pocket design parameter on metal flow by finite element simulations of two-hole extrusion. They observed that pocket angle plays an important role in influencing the metal flow velocity and the pocket volume was found to be less effective in controlling the velocity of metal flow. The conical pockets were found to be most effective in increasing the flow velocity compared to the stepped pockets. Peng and Sheppard [2005] carried out the three-dimensional FEM simulation FORGE3® on the influences of the die pocket and offset of the pocket on the material flow and the structure. They observed that the balanced material flow and temperature distribution can be achieved by suitably located die pockets.

Fang *et al.* [2009] investigated the effect of steps in the multi-hole die pockets on the metal flow in producing chevron profiles of aluminum using finite element software, DEFORM 3D®. The multi step pockets improve the flow uniformity. The peak extrusion pressure was found to decrease with increase in number of pocket steps when the total pocket depth was unchanged. Experiments were also carried out for validation of simulated results. Chen *et al.* [2008] studied the bending of aluminum alloy tubes in multi-hole extrusion process with finite element analysis. Number of holes and their location on the die are important parameters for bending of the extruded profiles. Extruded tubes bend outward in two-hole extrusion and inward in three-hole extrusion and four-hole extrusion.

The correct die design minimizes the extrusion load and produces better quality product. Trial and error method followed in industries is time consuming and includes high manufacturing cost. The software packages used for die design eliminate such problems and provide better alternate for die design. The optimal die designs are converted to CAD model and dies are produced by both conventional and non-conventional machining. Such kind of die design was carried out by Gunasekera *et al.* [1984] and they developed "STREAM" software to design the shaped multi-holed extrusion dies. The package could be used to design straight, convex, concave, parabolic, streamlined based on radius and streamlined based on area dies. For other die shapes, the subroutines can be appended to the package.

The available literature on finite element analyses of multi-hole extrusion process gives some idea on the effect of different process parameters on the extrusion load and the quality of the extruded products. The other aspects like improvement in properties of extruded products and effect of friction are not well explored. On the other hand, the single-hole extrusion process is well investigated compared to multi-hole extrusion process. Some relevant researches on the finite element analysis of single-hole extrusion process are discussed.

2.5.5.2 FEM in modeling of single-hole extrusion

In the finite element analyses on extrusion process, the die profile, die land length and reduction ratio are considered as major process parameters. The extrusion load, stress and strain distributions, temperature distribution and optimal die selection are some important outputs of the analyses. Yang and Kang [1996] carried out non-steady state analysis for hot square die extrusion of H and L profiles by using the rigid-viscoplastic Arbitrary Lagrangian- Eulerian (ALE) finite element method. They developed a scheme to estimate the variation of die land length, calculated configuration of the die land and compared it with the industrial design. Wifi *et al.* [1998] used an axisymmetric large strain, updated Lagrangian elastic-plastic finite element model using the MARC program to compare the different components of stress developed by the optimum curved die profile and optimum conical die profile in forward hot extrusion.

Wu and Hsu [2002] used the finite element method to analyze the influence of die shapes with different draft angle fillet radii on the extrusion forging deformation. Peng and Sheppard [2005] carried out the three-dimensional FEM simulation FORGE3 on the influences of the offset of the pocket on the material flow and the structure, and compared it with the previously reported experimental work. Noorani-azad *et al.* [2005] studied the effect of die profile on the variation of stress and load in cold forward extrusion of aluminum. The stress and load relations for curved profiles were obtained by using slab method. They obtained optimum die angle for conical die profile considering work hardening of the material, on the basis of the minimization of the stress and load in the die-workpiece interface. The required extrusion load for the optimum curved die is significantly less than the optimum conical die.

Tiernan *et al.* [2005] carried out finite element analysis using ELFEN, FEA software for the cold extrusion of AA1100 aluminum alloy and studied the influence of die angle, reduction ratio and die land on the extrusion force. Ishikawa *et al.* [2006] focused on the deformation of skin layer of billet and the control of microstructure of extrudate in aluminum alloy extrusion. The authors estimated the deformation of skin material of clad billet in finite element analysis DEFORM-2D^{TM}. The results of the FE analysis were verified with the experimental results. The temperature distribution was found to be ineffective to the skin material flow. Skin material was found to flow faster when the friction coefficient was less.

Bakhshi-Joobari *et al.* [2006] studied the reduction of deformation load in backward rod extrusion by means of an optimum die profile. With FEM software ABAQUS, the optimum die angle for conical die was determined. Kumar and Vijay [2007] designed and fabricated dies of different cross sections to analyze hot and cold extrusion. They used HyperXtrude, finite element software to simulate the hot extrusion of aluminum (AA2024) and the extrusion load was found to increase with increase in complexity of the extruded profile. A good agreement between theoretical and experimental power was observed.

Arentoft *et al.* [2000] carried out simulation of the model material with the DEFORM package. The lower extrusion pressure obtained from simulation was lesser to the extrusion pressure obtained from the experiments. The authors observed that the lower extrusion pressure is due to the coefficient of friction that is determined by the ring test which is used in simulation is smaller than that in the experiments. Chanda *et al.* [2000] carried out 3D FEM simulation of the aluminum alloy extrusion process to determine the state of stress, strain and the temperature through square and round dies. Li *et al.* [2004] studied the temperature evolution during the extrusion of 7075 aluminum alloy by means of 3D FEM simulations.

To simulate the bending of the extruded products in extrusion process, Muller [2006] used an Arbitrary Lagrangian Euler (ALE) finite element code, Press Form ver.1.4. Author observed that the friction force inside the bending device do not influence the outflow velocity difference and thus does not influence the desired radius, but it increases the strain within the bending fixture and the required press capacity. Lepadatu *et al.* [2006] used finite element model to predict wear of the die. They presented the investigation on the statistical process variation of the tool wear progression during metal extrusion process. Chen *et al.* [2007] used finite volume method to simulate irregular Al alloy profile extrusion process. As the extrusion ratio is too large (more than 25), the plastic deformation is quite severe. Hence, it is very difficult to get satisfactory results using traditional Lagrangian finite element method to simulate that kind of deformation. Authors built a computer aided optimization (CAO) model based on orthogonal experiments, artificial neural network (ANN) and genetic algorithm (GA) and utilized them to obtain optimal parameters of Al alloy profile extruding process.

The finite element method is widely used for analyzing the extrusion process. This method is capable of predicting quite accurate deformation behavior such as stress distribution and extrusion load. Prediction of the product strength and changes in grain size are difficult to obtain accurately in finite element analysis. Though, some available finite element packages have the facility to observe the microstructure, the reliability depends on how accurately the material properties are given to the database. However, analysis using finite element technique can be computationally expensive and time required for getting converged solution restricts its wider application.

2.6 Methods Adapted for Enhancing the Efficiency of the Extrusion Process

The extrusion process has been studied by many means to reduce load requirement in the process, improvement in product quality and increase in productivity. Some methods used for improving the performances of the extrusion process are discussed here.

2.6.1 Optimization of Die Profile

An extensive literature exists on optimal die profile design based on the power minimization by using slip-line field method, upper bound method and more recently by finite element method.

2.6.1.1 Slip-line field method

Sotrais and Kobayashi [1968] obtained an optimal streamlined die profile for frictionless axisymmetric extrusion by using slip-line field method. They conducted experiments on pure lead. The power required by the designed streamlined die was found to be less compared to the conical die of same axial length.

2.6.1.2 Upper bound method

Chen and Ling [1968] obtained the optimal die length for axisymmetric extrusion of rods through cosine, elliptic and hyperbolic dies, whilst Chen [1970] carried out same study for the plane strain extrusion. Zimerman and Avitzur [1970] obtained the optimal die angles for axisymmetric extrusion of rods through the conical dies by assuming generalized plastic boundaries. Yang *et al.* [1987] and Yang and Han [1987] obtained the optimal die length for the fourth order polynomial dies. Reddy *et al.* [1996] combined the upper bound and finite element method and obtained the optimal die profiles for axisymmetric extrusion process.

Juneja and Prakash [1975] obtained the optimal die angle using spherical velocity field for extrusion of polygonal sections from similar shaped billets through conical dies. Yang and Lange [1984] obtained the optimal length of the streamlined die with upper bound method at various process conditions. Gunasekera and Hoshino [1982, 1985] proposed an upper bound method and obtained the optimal condition to extrude the polygonal sections through conical and streamlined die. The streamlined die was found better.

2.6.1.3 Finite element method

Balaji *et al.* [1991] proposed a model which predicts the deformation field, optimal die geometry and plastic boundary using finite element method. They obtained the optimal die profile which minimizes the redundant work during extrusion. Joun and Hwang [1993] developed an optimization scheme for obtaining optimal die profile which consumes the least power in axisymmetric extrusion process.

In most of the research works, the optimal die design is obtained by minimizing the extrusion power. The reduction of extrusion power is definitely advantageous for extrusion industry but some amount of redundant work during the process is also necessary to improve the strength and quality of the extruded products. Less number of research works has been carried out on the optimal die design based upon the improvement of strength and quality of the products. Jo *et al.* [2001] designed the optimal tool shape in metal forming for the improvement of the mechanical properties of the products by providing uniform microstructure distribution. The proposed method was validated with hot extrusion experiment and finite element analysis. The control of exit velocity of the extruded product is necessary to minimize the distortion of profile. Lin and Ransing [2009] proposed a layout design approach using geometry based die and length design methodology to minimize the variation in exit velocity of the extruded product. This proposed methodology is for single-hole extrusion of any die profile.

2.6.2 Reduction of Friction

The friction encountered at the die-billet interface and billet-container interface effect significantly the extrusion load and quality of the extruded product. The optimized die profile can solve the problem up to some extent but researchers also focused to reduce the friction at the die length and die land region. Bjork *et al.* [1999] coated the extrusion dies by TiC+TiN by chemical vapour deposition technique for hot extrusion. The extrusion load was found to be less in extrusion with coated dies as compared to the extrusion load obtained with uncoated dies. The coating also enhances the die life.

2.6.3 Use of Vibration in Extrusion Process

It has also been observed that vibrating the die can reduce the friction encountered during metal forming. The external and internal friction occurs in the plastic forming of metallic materials. These frictions can be reduced by ultrasound oscillation under suitable conditions. Few studies have been published relating to the behavior of metallic materials during plastic forming with ultrasound. Pohlman and Lehfeldt [1966] studied experimentally the influence of ultrasonic vibration in wire drawing process in reducing the internal friction of the metal and the external friction between tool and work-piece. It was observed that the reduction in drawing force is proportional to the amplitude with which the drawing die oscillates.

Eaves *et al.* [1975] reviewed the application of ultrasonic vibration to deforming metals. It was observed that the change in coefficient of friction often occurs as a result of (i) pumping of lubricant, (ii) increase in chemical reactivity of the surface or lubricant, (iii) softening or melting of asperities and (iv) separation on surface allowing redistribution of lubricant. Work can be done against friction by reversing the friction vector or by reducing the component of friction vector along the direction of deformation. The authors also concluded that the rise in temperature due to dissipation of vibration energy can be efficiently used to change the metallurgical properties of the deforming metal.

Siegert and Ulmer [2001] studied the influence of the ultrasonic vibration on the reduction of friction during wire and tube drawing process. The wire drawing die was oscillated parallel to the drawing direction at ultrasonic frequencies in range of 20-22 kHz. The reduction in drawing force was due to the ultrasonic amplitude. In case of tube drawing, the mandrel was vibrated and results obtained were similar to that of wire drawing. Authors observed that with certain drawing velocity range, smoother wire surface was obtained with higher vibration amplitude. Murakawa and Jin [2001] investigated the effect of radial and axial ultrasonic vibration on the wire drawing die and compared the results with conventional drawing process. Radial vibration was found to be an effective measure against the use of lubricant and also for increasing the critical drawing speed in ultrasonic drawing process. Hayashi *et al.* [2003] carried out finite element analysis of conventional, axial and radial vibration in wire drawing process. The drawing force and stress-strain distributions in the drawn wire were studied. No significant difference in equivalent plastic strain for conventional, axial and radial vibration drawing process was observed. The reduction of drawing speed depends on the amplitude of vibration.

The above discussed research works on wire drawing process and upsetting process shows the effectiveness of ultrasonic vibration in reduction of forming load and better product quality. The effect of ultrasonic vibration on extrusion process was studied by Akbari Mousavi *et al*. [2007]. They carried out the finite element analysis using ABAQUS to find out the effect of extrusion speed, vibration amplitude, vibration frequency and frictional condition on the extrusion force. It was observed that when the extrusion speed is below the critical speed, the extrusion force and the material flow stress were reduced by using the ultrasonic vibrations. The average extrusion force decreases by reducing the extrusion speed or increasing the amplitude of the vibration. The vibration frequency was found to be less effective than the vibration amplitude in reducing the extrusion force. The axial ultrasonic vibration influences the friction force between the die shoulder and the flow material.

Huang *et al.* [2002] studied the influence of ultrasonic vibration on the interfacial boundary condition and thermal effects in soft solid forming operation. Plasticine was used in the upsetting experiments. The upsetting process was also simulated with finite element package, ABAQUS. The authors observed that by applying short longitudinal ultrasonic pulse to the die, reduction in the mean forming force takes place.

The effective use of ultrasonic vibration can be a better alternative in eliminating the lubrication in forming process. However, the experimental research on the effective use of vibration in extrusion process is very limited and needs to be explored.

2.7 Study of Mechanical Properties and Microstructure of Extruded Products

Much attention has been drawn toward the refinement of microstructure of the extruded products because it enhances the mechanical properties. In extrusion of metallic alloys, the mechanical properties of the extrudates are of great interest. The mechanical properties of the extrudates are mostly related to the microstructure evolution of the alloy during the production. In extrusion process, the microstructure evaluation depends on the hot or cold processing. Hardness tests and tensile tests are generally carried out to evaluate the mechanical properties of the extruded products. Microstructure studies are also carried out to monitor the changes in grain sizes. Prediction of recrystallization is also possible with some finite element packages. Literature is available on the study of the effect of different process parameters on mechanical properties and microstructure evolution of the extruded products. Some relevant papers are reviewed here.

Yeh *et al.* [1997] studied the microstructure and tensile properties of the extruded products obtained from reciprocating extrusion process. The strength and ductility of the products were studied with the number of passes. The effect of extrusion ratio on the hardness property of the extruded aluminum products was studied by Onuh *et al.* [2003]. High hardness value was observed at higher extrusion ratio which is due to multiplication of dislocations due to high strains at higher reductions. Increase in extrusion speed also increases the hardness value. Ajiboye and Adeyemi [2006] studied the effect of die land length on the hardness distribution along the length of the extruded products. Lesniak and Libura [2007] observed the effect of die pockets on the micro-hardness of the extruded products. Slightly higher micro-hardness value was observed with the products coming out from the dies with pockets compared to flat die. Thick part exhibits higher micro-hardness than the thinner one. Tiernan and Draganescu [2008] studied the influence of lubricant on the surface hardness of the extruded products. Farhoumand and Ebrahimi [2009] measured the hardness of the extruded products with Vickers scale. The hardness values were compared with the strain obtained from the finite element simulations. Talebanpour *et al.* [2009] studied the strength and hardness of the extruded pure aluminum products obtained from dual equal channel lateral extrusion. The increase in hardness value was observed up to certain number of passes after which the value decreases. Similar observations were made with the compressive strength of the extruded products also.

The improvements in microstructure refinement enhance the yield strength of the product. Uematsu *et al.* [2006] studied the effect of extrusion conditions on the grain refinement in magnesium alloy under the controlled extrusion condition. The decrease in grain size was observed at higher extrusion ratio and increase in working temperature. Shahzad and Wagner [2009] studied the effect of extrusion ratio on microstructure and mechanical properties of magnesium alloy. The authors observed that at higher extrusion ratio, the extrusion velocity increases which results in slightly coarsen grain size. This observation contradicts the observations made by Uematsu *et al.* [2006].

Schikorra *et al.* [2008] carried out experiments and finite element simulations on backward extrusion to predict the grain size distribution on AA6060 extruded profiles. DEFORM-3D was used to find the evolution of strain, strain rate and temperature during different stages of the process. The simulated results are in good agreement with the experimental data. Tumer and Sonmez [2009] proposed a methodology to improve the hardness distribution in backward extruded cup by optimizing the punch shape.

For multi-hole extrusion process, Sinha *et al.* [2009b] carried out experiments with multi-hole dies having different number of holes. The micro-hardness test and micro-tensile tests were carried out on the extruded products of centre as well as periphery holes. The hardness of the extruded lead products from the holes of the outer pitch circle of the radius is lesser than those extruded from the other holes in the die. Similar observations were observed with tensile test. No microstructure study was carried out to observe the effect of different process parameters in grain refinement in multi-hole extrusion process.

2.8 Microextrusion

The demand of micro-components in the field of electronics, aviation and space technology, medical science and the nano technology is increasing day-by-day. The manufacturing sectors are now concentrating on the key issues of micromanufacturing. The fabrication of micro metallic components using the conventional bulk metal forming process is becoming an interesting area of research. The fundamental issues in relation to micro-metal forming have been studied intensively in last ten years. Geiger *et al.* [2001] carried out a critical review on the state of the art of microforming and they observed that scaling effects appear within the process and it must be considered in the areas of forming processes. The microforming can be defined as the process of manufacturing a part or a feature, whose at least one orthogonal view can be enclosed in a square of one milimeter size. Engel and Eckstein [2002] carried out a review on the problems associated with miniaturization. The material behavior, processes, tools and machine tools were found to be the key features in the microforming system. The authors also presented some case studies on microextrusion and micro-deep drawing process to understand microforming phenomena.

Alting *et al.* [2003] presented detailed discussions on the micro products and micro engineering. They also highlighted some technology developments for micro products like mechanical processes (cutting), thermal processes, MEMS processes, LIGA and micro fabrication systems. Milind and Date [2008] presented a brief overview on the problems involved in working with small dimensions in metal forming highlighting the extrusion process.

In microforming, integration of product and process development, consideration of material behavior, tolerance of micro components, standardization and integration of the process are to be evaluated with the industry potentials. Microforming also gets affected with miniature/micro machines. The development of such machines has attracted researchers in recent years. The review on the micromanufacturing research reveals that the conventional bulk and sheet metal forming can be used to fabricate micro components [Qin, 2006; Vollertsen *et al.*, 2009; Qin *et al.*, 2010]. But the material and friction behavior becomes different at micro-scale.

The conventional metal-forming process such as forging, extrusion and deep drawing can be used for forming of micro parts. Among these processes, extrusion process has been used by many researchers to fabricate micro parts. A superplastic backward extrusion machine was developed by Saotome and Iwazaki [2001]. They fabricated the microdies with photochemically machinable glass by photolithography and anisotropic etching techniques. The microgear of 50 μm module of LaAlNi amorphous alloy was fabricated. The microgear with module 20 μm and pitch circle diameter of 200 μm was also produced from the Al–78Zn superplastic alloy. The tool surface finish and lubrication were found as influencing parameter for punch load. In microextrusion, the effect of specimen size, grain size, friction and other process parameters has been investigated by many researchrs. Cao *et al.* [2004] fabricated microextrusion experimental set up and studied the effect of grain size and surface roughness on the microextrusion process. They produced the micropins of 1 mm diameter by microextrusion process. The effect of grain sizes of the workpiece was studied. The extrusion dies with different surface roughness were used to study the effect of surface finish. Krishnan *et al.* [2007] studied the size effects on friction conditions in microextrusion. They used the segmented dies. The pins of 1.33, 1.17, 1.00 and 0.57 mm were extruded. The smallest dimension dies were fabricated by EDM process and others with drilling and lapping process. Finite element analysis was carried out with ABAQUS/Explicit for different values of friction between the die and workpiece. The results were compared with experiments.

It was observed that friction coefficient and friction factor tend to decrease as the size of the pin gets smaller, which contradicts the results obtained by Engel and Eckstein [2002]. The bent pins were obtained from the smallest die, which due to the large ratio of grain size to sample dimension of the pin. The coated dies with less friction give lowest extrusion load and produce longest pins. Mori *et al.* [2007] conducted microextrusion experiments to investigate the friction coefficient at brass-steel interface. No significant effect of the grain size, the contact pressure and specimen sizs on the static and dynamic friction coefficient was observed. They also concluded that the curving tendency of the extruded products is not related to the friction but due to the material response during the extrusion process.

Measurements of micro hardness of the extruded micro pins were carried out by Parasiz *et al.* [2007] to investigate the deformation size effects. They also carried out microstructure analysis to study the inhomogeneous deformation of the pins. The results showed that the pins fabricated with coarse-grained material had higher value of hardness along the centre area as compared to the values obtained for the pins obtained from the fine-grained material. This contradicts the Hall-Patch relationship. The hardness distribution along the length of the pins produced from fine-grained material was found to be more uniform than the pins produced from the coarse-grained material. It is also concluded that when the grain size approaches the specimen size, the location, size and orientation of individual grain affects the deformation of the micropins to a significant degree. Wu *et al.* [2010] carried out micro-back-extrusion of bulk metallic glass (BMG) to produce cup of outer diameter of 2.2 mm and wall thickness of 0.05 mm. The billet of 3 mm diameter of $Zr_{55}Cu_{30}Ni_5Al_{10}$ was prepared by copper mold in vacuum. The better surface quality of the extruded part was observed with higher forming speed as the high forming speed enhances the forming efficiency and avoids the crystallization. Parasiz *et al.* [2011] investigated the effect of specimen size and grain size on deformation during microextrusion. The micro hardness measurement, microstructure and X-ray texture analyses were performed on the extruded products. It was observed that the extra hardening of the material takes place due to miniaturization. The shear deformation in extrusion takes place due to the deformation geometry and friction between die and workpiece. The hardness profile for the coarse grained structure is affected by the surface grains.

Billet preparation for microextrusion is also a difficult task. The smaller dimensions of the billet and the refinement of grain size are the specific issues, which have been considered by many researchers. Cao *et al.* [2004] used the brass billets, which were heat treated to produce new grains of appropriate size. The heat treatment at 610 °C could produce average grain size of 87 µm, whereas at 700 °C the samples having an average grain size of 211 µm. Hirota [2007] fabricated the small billets by extruding a sheet of pure aluminum in the thickness direction The billet of 1 mm diameter was produced by extruding pure aluminum sheet of 2 mm thick. The height of the extruded billet was affected by the material flow. The balance of the inward and outward flow depends on the deformation resistance in that direction. Olejnik *et al.* [2009] produced billets of 1 mm diameter from the ultra-fine grained Al 1070 sheet of 1 mm thickness by micro-blanking. Upsetting of the sheet of Al 1070 of 26 mm thickness was carried out by equal channel angular pressing (ECAP) to get 3.8 mm thickness. Multi pass rolling was then carried out to reduce the thickness to 1 mm. The 1 mm thick sheet was blanked at a speed of 5 mm/min using a 1 mm diameter punch and then the billets were used for backward extrusion of micro-cups.

Some research works have been carried out to understand the material behavior at micro level. Determination of flow stress is important to calculate the deformation load. Chen and Tsai [2006] conducted experiments on two cylindrical specimens with different dimensions. They observed that the hardness increases as the size decreases and the hardness is nearly proportional to flow stress. Thus, micro-indentation can be a viable method of assessing the flow stress of the smaller parts. Barbier *et al.* [2009] carried out compression tests of copper alloy (CuZn10) specimens with diameter ranging from 5 mm to 1 mm to evaluate the size effect on flow stress. The flow stresses were evaluated by inverse method. The flow stress was found to decrease with decrease in specimen size. Chan *et al.* [2011] investigated the size effect on micro-scale plastic deformation and frictional phenomenon by micro-cylindrical compression test, micro ring compression test and finite element simulation. They concluded that the flow stress decreases with the scaling down of specimen size. It was also observed that inhomogeneous material flow and absurd local deformation takes place with decrease in specimen size.

Chan *et al.* [2011] carried out micro forward, backward, combined (forward-rod and backward-can) and double cup extrusion of pure copper. Based on the load-stroke curves, authors observed that grain size effect is more significant in micro-forward extrusion than backward extrusion. In all extrusion cases, inhomogeneous deformation occurs with workpiece of coarse grains size. The authors also carried out finite element simulations of the microextrusion processes with different friction coefficients based on the conventional material model to examine its applicability in prediction of micro-plastic deformation. The flow stress curves obtained from micro-compression tests are used as the material model. For double cup extrusion and combined (micro forward-rod and backward-can) extrusion, the simulation results significantly deviate from the experimental results. This indicates that the conventional material model is not applicable in simulation of the material deformation behavior and evaluation of the interfacial friction in micro-extrusion process.

The friction behavior between the die work interfaces is greatly affected by the miniaturization. Engel and Eckstein (2002) investigated the effect of miniaturization by ring compression test and double cup extrusion. They observed that friction factor increases with decrease in billet size. This effect was also studied in detail by Engel *et al*. [1998]. In extrusion, friction factor increased by 20 times for reduced size when using extrusion oil as lubricant (Gieger *et al*., 2001). While using dry lubricant, the friction does not vary significantly with size. This behavior was explained by the open and closed lubricant pockets model.

A simple mathematical model was developed by Yu *et al.* [2006] for predicting the flow stress as a function of grain size and size of the specimen. The billet shape has a significant influence on flow stress. For the same cross-sectional area, the number of total grains will be same across the cross-section. Number of surface grains increases with the increase of circumference. Therefore the flow stress decreases with the increase in the ratio of circumference to area of the cross section of the billet.

The effect of friction is highly significant in microextrusion. Some researchers have tried to reduce the friction by different methods. Fujimoto *et al.* [2006] applied a novel surface finishing process using high energy ion beam irradiation to finish the surface of the micro die. A hard coating of diamond-like carbon (DLC) was applied to improve the surface quality against wear of the micro-die. Krishnan *et al.* [2007] investigated the feasibility of using low friction coatings in microextrusion. The coating was done on the segmented dies with diamond like carbon with silicon (DLC-Si), chromium nitride (CrN) and titanium nitride (TiN). From the observation on the extrusion lead and extruded pin length, the authors concluded that DLC-Si coating gives best results. With coated dies, longest pin length was obtained. .

The high speed microextrusion machine has been developed by Mahayotsanum *et al.* [2009] to study the strain rate effect and tribological effect. However the authors have not reported any results. Recently, Bunget and Ngaile [2011] investigated the possibility of applying ultrasonic vibration on microextrusion to reduce the friction effect. The imposed vibration reduces the extrusion load. Ultrasonic oscillation results in high instantaneous relative velocities at tool-workpiece interface and this leads to reduction of adhesive bond formation and hence better lubrication conditions. Therefore, ultrasonic microforming is a practical process for difficult-to-lubricate materials.

Microextrusion process has been proved as a successful method to produce metallic micro pins. To improve the productivity multi-hole extrusion can be a suitable alternative. However, no research has been carried out on multi-hole microextrusion process.

2.9 Challenging Issues

In the field of metal forming, single-hole extrusion process is a well researched area. Different extrusion processes like forward extrusion, backward extrusion, radial extrusion and multi-hole extrusion have been studied. The multi-hole extrusion process is found to be a productive method for improving the productivity. Although some researchers have investigated the multi-hole extrusion process, there are only a few publications that try to present in depth information. Some challenging issues are as follows:

- The quality of the extruded products obtained from multi-hole extrusion process is dependent on many process parameters. There are some experimental and finite element simulation results available in the literature; but more study is needed.
- The multi-hole extrusion process produces unequal product lengths due to unbalanced material flow. Many parametric studies have been carried out to minimize the variations in product length. There is a need to develop an efficient multi-hole extrusion set up to produce products of equal length with improved quality.
- Microextrusion has been used to produce micro metallic components. Improvement in productivity with required quality is a challenging task in microextrusion process. Multi-hole extrusion can be a potential process of extruding metallic and non-metallic components. Till date, there is hardly any documented research finding on micro-multi-hole extrusion.

2.10 Scope and Objective of the Present Work

Based on the literature survey and major challenges identified, it is decided to investigate the following aspects of the multi-hole extrusion process in this thesis:

1. **Exploring the effect of process parameters in multi-hole extrusion process:** In multi-hole extrusion process, many process parameters affect the extrusion load, quality and mechanical properties of the extruded products. It is decided to carry out experimental investigations on the multi-hole extrusion process to study the effect of extrusion ratio, die land length, die pocket, lubrication and imposed vibrations on the extrusion load and bending, surface finish and mechanical properties of the extruded products. The extrusion behavior is dependent on material also. In this work, only lead and aluminum material have been used due to ease of experiments with these materials. However, the experimental results of these materials will provide guidelines for other materials. In particular, the experimental study aims to answer the following questions:

   (i) What is the effect of die pocket and die land on the extrusion load and properties of the extrudates?

   (ii) What is the effect of lubrication on the extrusion load and properties of the extrudates?

   (iii) What is the effect of imposed vibration on the extrusion load and properties of the extrudates?

   Answer to these questions (even if partial) will pave the way for further research and development in the area of multi-hole extrusion. Moreover, the experimental results generated in the thesis will be useful for benchmarking of theoretical models.

2. **Development of a technology for producing straight products from multi-hole extrusion:** Multi-hole extrusion process is an effective method to produce many products from same billet at a time. But the unbalanced material flow and influence of different process parameters cause unequal length and bent extruded

products. It is decided to develop a multi-hole extrusion set up to produce products of equal length and to study the effect of process parameters on product quality.

3. **Finite element simulations of multi-hole extrusion process:** Another major objective of the present thesis is to carry out finite element simulations of the multi-hole extrusion process and compare them with experiments. DEFORM 3D® is used for simulation. A comparison of simulation results with experiments will bring out the real assessment of existing simulation capability of rigid-plastic FEM. In the cases, where good matching is obtained between experiments and simulation results, simulation results can be used for augmenting the experimental results and reduce the number of time consuming experiments.

4. **Multi-hole microextrusion:** Efficient use of multi-hole extrusion process for fabricating micro products is the last objective of this thesis. An attempt is made to produce the products of very small sized cross-section by an in-house developed set up.

The research plan is presented in the form of flow chart (Figure 2.1.).

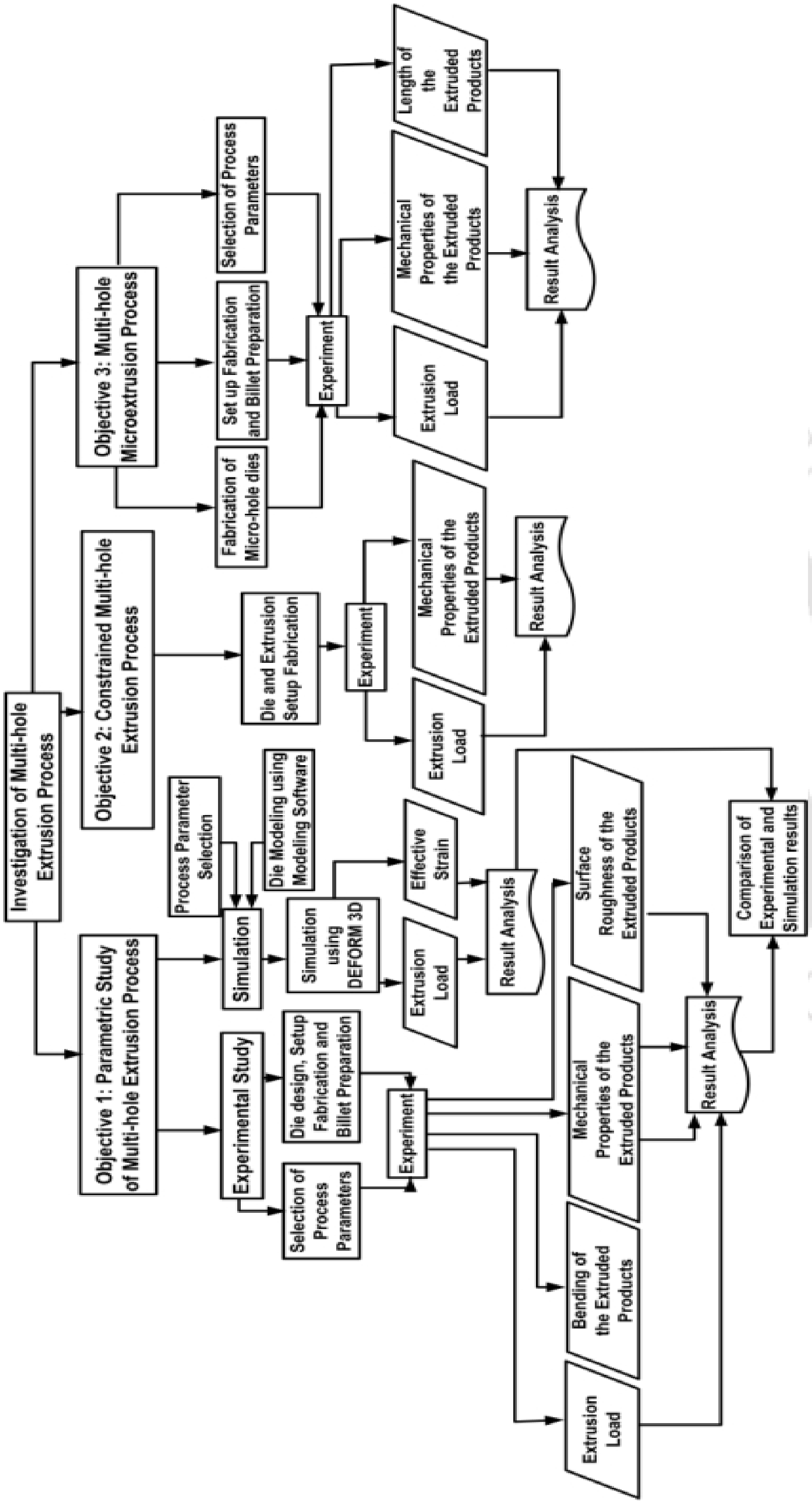


Figure 2.1. Research plan in the form of flow chart

Chapter 3

Details of Experiments

3.1 Introduction

The extrusion is a plastic deformation process in which metal is forced to flow by compression through a die opening of a smaller cross-sectional area than that of the original billet. Extrusion through a die having more than one hole is known as the multi-hole extrusion. The multi-hole extrusion is extensively used for achieving higher production rate and reducing the load requirement. The process is very much suitable for producing micro-sized metallic components. Principal variables which influence the extrusion processes are extrusion ratio, extrusion speed, flow stress and billet temperature. In multi-hole extrusion process, the number of holes and their locations on the die decide the extrusion load and quality of the product. The properties of the extruded product are greatly affected by the way in which the metal flows during extrusion. The metal flow is influenced by many factors such as type of extrusion, frictional effects at the container and die, design and layout of die orifices, billet length, alloy type and temperature.

Selection of proper process parameters in multi-hole extrusion process is very important to obtain desired quality of extruded products. Extrusion ratio in multi-hole extrusion process depends on the number of holes and the diameter of each hole. The amount of plastic strain also depends on the extrusion ratio. In the present work, the strength of the extruded product of multi-hole extrusion process has been investigated for different extrusion ratio.

Die land length is an important process parameter which affects the extrusion load and the quality of the extruded products. One aspect of the quality is the profile (straight or curved) of the extruded product. The material flow, die land length and die angle play major roles in producing different profile. Die land length is found to be one of the most influential process parameters in producing straight or curved products. In multi-hole extrusion process, due to the unbalanced material flow, extruded products get bent. In the present study, it is observed that higher die land length helps in balancing the flow of material at the die exit and produces less curved product.

The mechanical properties such as tensile strength and hardness of the extruded products have also been studied by many researchers. Extrusion ratio and die land length effects are found to be more prominent. Surface finish of the extruded product is also another quality aspect. Though lubrication is the main parameter for surface quality of the product, the combined effects of other parameters along with lubrication are investigated in the present work. Use of ultrasonic vibration in metal forming process to minimize the external and internal friction forces has been an area of research since decades. Till today, the applications of ultrasonic vibration in different metal forming process are less explored. In the present study the effects of vibration on extrusion load and curvature of the extruded products in multi-hole extrusion process are investigated.

In multi-hole extrusion process, it is a challenging task to control the flow of metal at die exit due to complex influencing factors, such as size and shape of product, number and layout of the die orifices and die land lengths. Use of die pocket offers an opportunity to control the metal flow by correct design of the shape of the opening. Very limited work has been done towards investigating the pocket geometry and its effect in multi-hole extrusion process. In the present work finite element simulations have been carried out to study the effect of die pockets on extrusion load and effective strain distribution in multi-hole extrusion process. Experiments have been carried out to verify finite element simulation results.

In this chapter, experimental set up, fabrication of different multi-hole dies and billet preparation have been explained. Procedures for measurement of hardness, tensile strength, surface roughnes and radius of curvature are explained.

3.2 Extrusion Set-up

A 200 kN universal testing machine (Make: Fuel Instruments & Engineers Pvt. Ltd., Model: UTE 20) was used as an extrusion press [Appendix A]. Figure 3.1 shows the photograph of the setup. The container, die, punch and base plate were made of die steel (H13). To study the effect of vibration on the flow process, extrusion load and the radius of curvature, the vibration was induced to the container wall from the external source.

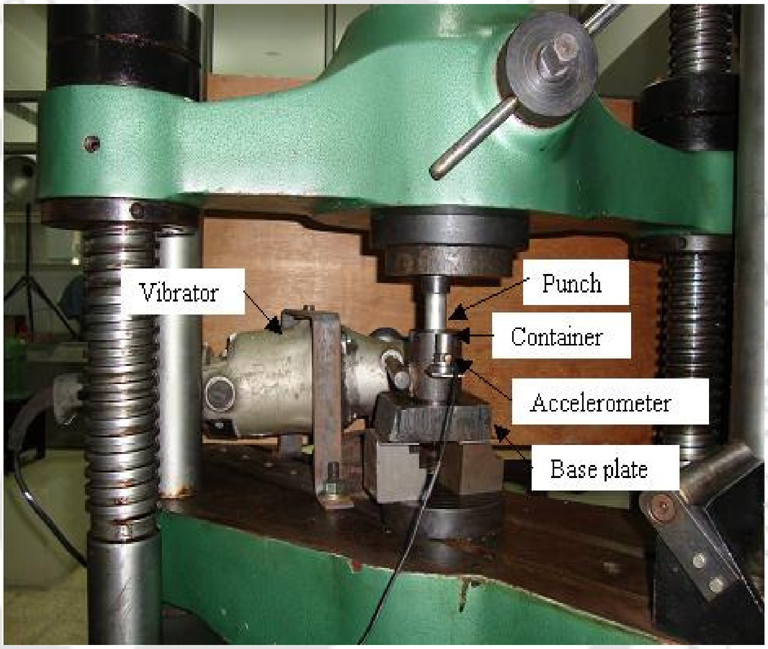


Figure 3.1. Extrusion set up

In the present experimental set up, vibration is imposed to the container of the multi-hole extrusion process. The hand-held grinder is used as vibrator. An eccentric mass is attached to the wheel to increase the vibration. On the outer wall of container, the arrangement was made to place the tri-axial accelerometer for measurement of the frequency and the acceleration of vibration during the multi-hole extrusion process shown in Figure 3.1.

The maximum amplitudes of the acceleration generated by the vibrator are 49, 51 and 70 m/s^2 along x, y and z directions respectively. A schematic of the multi-hole experimental set up is shown in Figure 3.2.

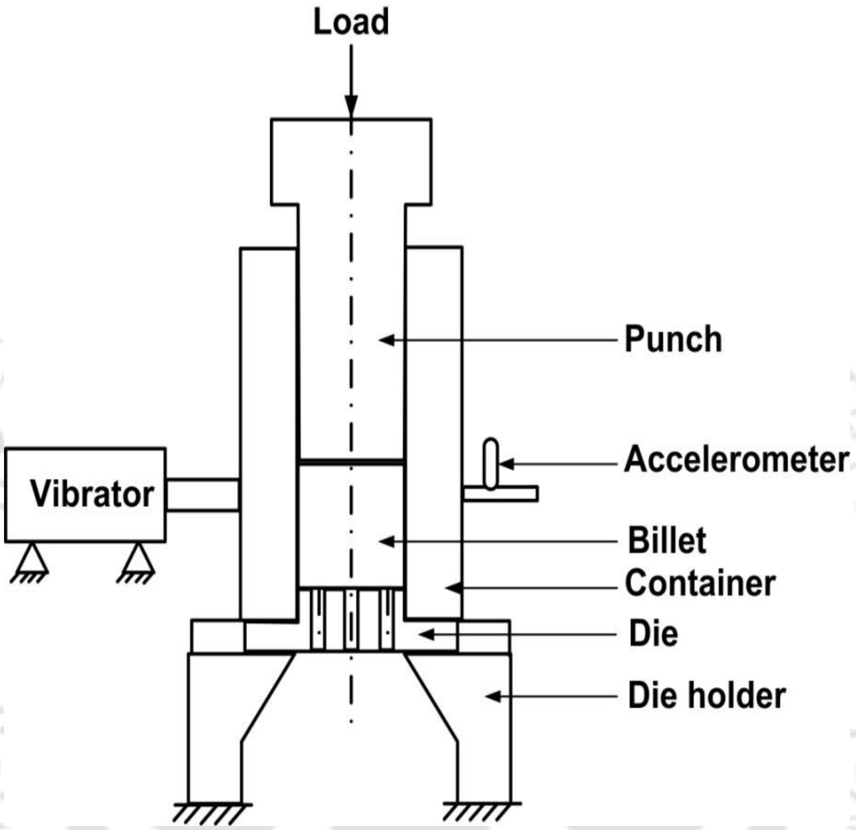
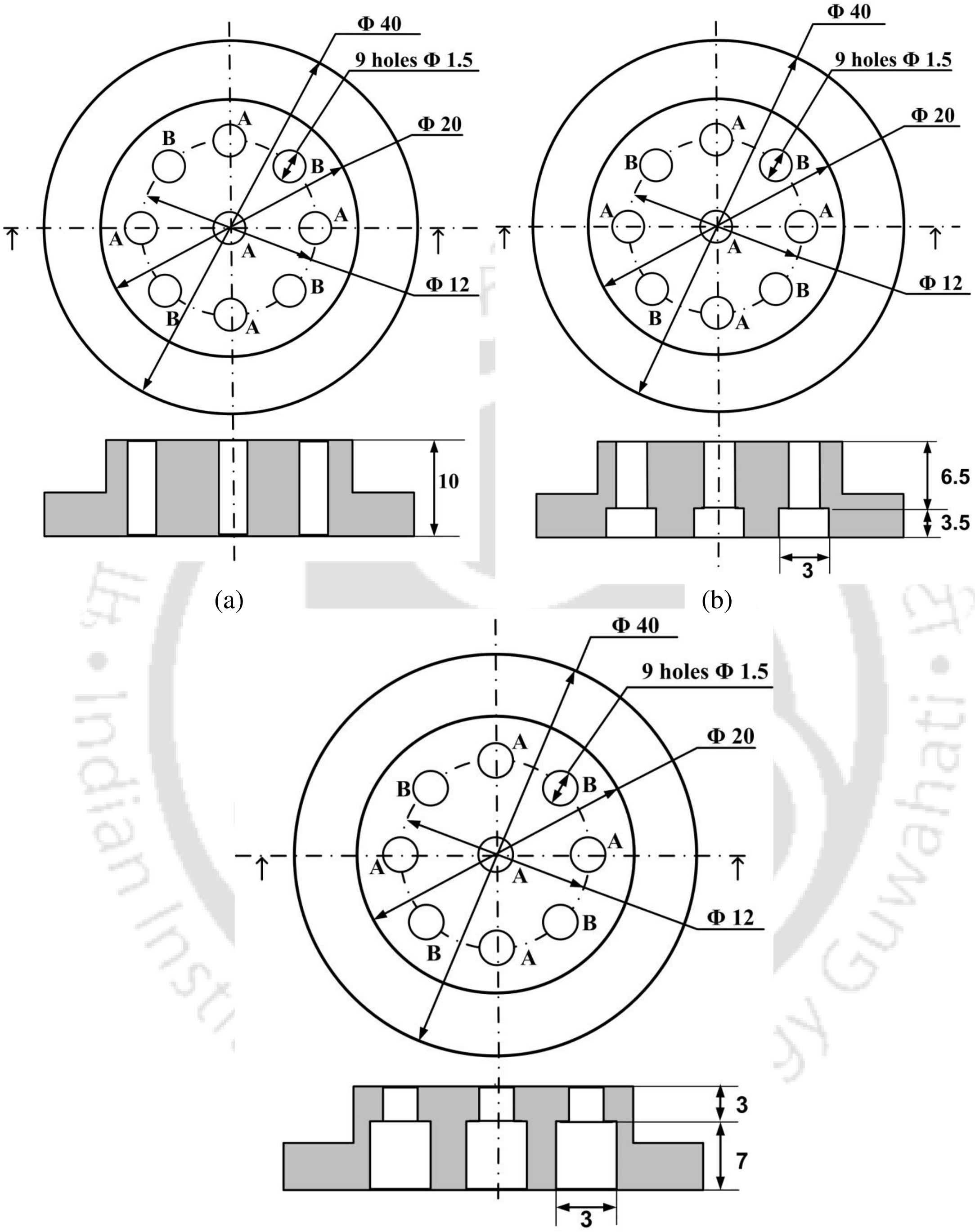


Figure 3.2. Schematic of extrusion set up

Schematic diagrams of 9-hole die with different die land lengths are shown in Figure 3.3. The die land lengths of 6.5 and 3 mm are produced on the holes designated by ‘A’. For the holes designated with ‘B’, the die land length is 10 mm.



(a) (b)

(c)

(All dimensions are in mm; drawing not to scale)

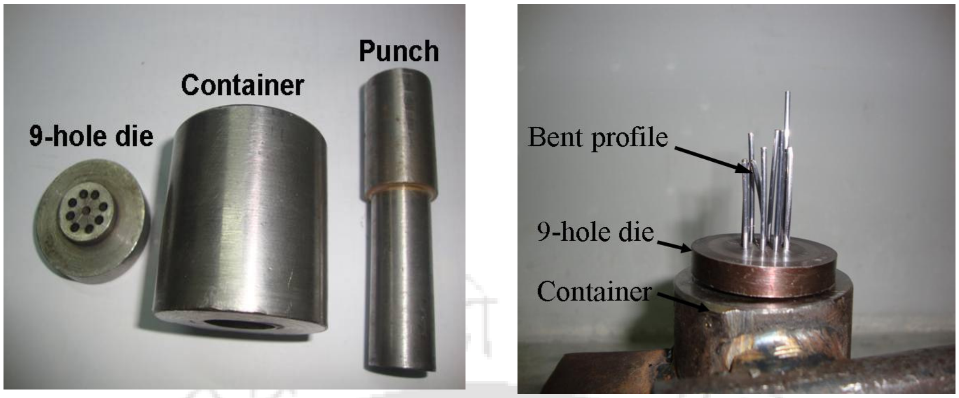
Figure 3.3. Schematic of 9-hole die with different die land lengths (a) 10 mm (b) 6.5 mm and (c) 3 mm

The different die land lengths are produced on the alternate holes of the periphery at a pitch circle diameter of 12 mm. Counter bore of hole diameter of 3 mm are drilled with required depth from the bottom side of the alternate holes of 9-hole die. This reduces the die land lengths. The 9-hole die with die land length of 10 mm is designated as Die I. The die land length of 6.5 mm produced on alternate holes of the peripheral holes as well as on centre hole is designated as Die II. Similarly, die land length of 3 mm produced on alternate holes of the peripheral holes as well as on centre hole is designated as Die III. Table 3.1 shows the different die land lengths used for 9-hole die extrusion.

Table 3.1. Different die land length used for 9-hole die extrusion

Die Type	Die land length (mm)		
	Centre hole	Periphery holes	
	A	A	B
Die I	10	10	10
Die II	6.5	6.5	10
Die III	3	3	10

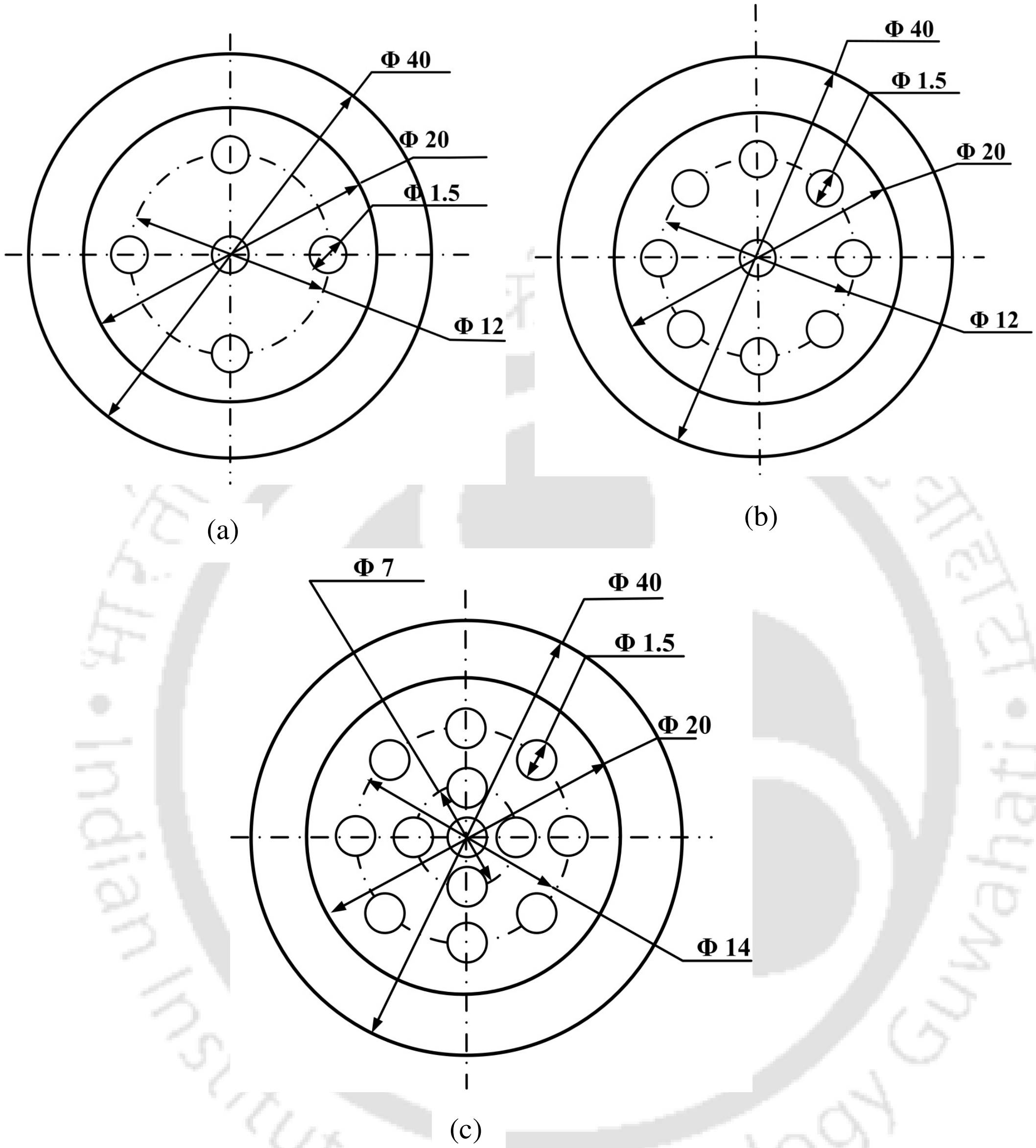
The three types of multi-hole dies (Die I, Die II and Die III) are made separately and allowed to tight fit to the bottom of the container. The production of different die land length will give the information on the effect of die land length on bending of the extruded products along with the combined effect of other parameters. Study of radius of curvature and the effect of lubrication, die land length and vibration was carried out with the dies mentioned in Table 3.1. The 9-hole die, container and punch used for lead extrusion are shown in Figure 3.4 (a). The extruded products form the 9-hole die is shown in Figure 3.4 (b).



(a) (b)

Figure 3.4. (a) 9-hole die, container and punch (b) extruded products from the 9-hole die

To study the effect of die land length and lubrication on the mechanical properties and surface roughness of the extruded products, the multi-hole extrusion was carried out with different set of dies. For the extrusion of lead three different types of dies were used as shown in Figure 3.5. In 5-hole die (extrusion ratio, 35.55), one hole is at centre and other four hole are at the pitch circle diameter of 12 mm (Figure 3.5 (a)). In 9-hole die (extrusion ratio, 19.75), one hole is at centre and other eight holes are at pitch circle diameter of 12 mm in periphery (Figure 3.5 (b)). In 13-hole die (extrusion ratio, 13.67), one hole is at centre, four holes are at pitch circle diameter of 7 mm and other eight holes are at pitch circle diameter of 14 mm (Figure 3.5 (c)). Low extrusion ratio was used for cold extrusion of aluminum in order to get low extrusion load. For this study both lead and aluminum are used as billet material. The details of the dies, die land length and billet dimensions used for extrusion of lead and aluminum are given in Table 3.2.



(a) (b) (c)

(All dimensions are in mm, drawing not to scale)

Figure 3.5. Top view of (a) 5-hole die (b) 9-hole die (c) 13-hole die

Table 3.2. Geometrical parameters for extrusion of lead and aluminum

Parameters	Lead extrusion	Aluminum extrusion
Billet diameter	20 mm	20 mm
Billet length	20 mm	20 mm
Extrusion ratio	35.55 (5-hole die), 19.75 (9-hole die) and 13.67 (13-hole die)	4.94 (9-hole die)
Die land length	10 and 3 mm	15 and 10 mm
Diameter of each hole	1.5 mm	3 mm

For each extrusion test, the container wall, die, punch and the specimens were first cleaned with ethanol to remove any oil or dust content on them. The lubricant was applied manually on the die, punch and container for lubricated tests. Extrusion test were conducted at ram speeds of 1.5, 1.2, 0.9 and 0.45 mm/min for 20 mm billet length. At these speeds the strain-rate effects are insignificant. The strain rates are of the order of 10^{-3} s^{-1}. The ram displacement was kept as 5 mm. After each test, the entire set up was removed from the universal testing machine and the extruded products were cut carefully without disturbing their curved profile for measuring the radius of curvature and length. Three replicates were carried out at different conditions. Replicates are needed to assess the repeatability of the experiments. Three replicates are sufficient, if there is good repeatability in the process. More number of replicates may be required in case of poor repeatability. After the measurement of radius of curvature, the surface roughness of the extruded products was measured. At each replicate, microhardness and surface roughness measurements were carried out at 4-5 places. The combined data of all measurements was used to make inference about average quality attribute along with the standard error in the estimate. The standard deviation was also estimated. The tensile test and micro hardness test are carried out after the measurement of surface roughness.

3.3 Billet Preparation

The commercially available lead and aluminum metals have been used for preparing specimens for multi-hole extrusion. Lead was melted and casting was carried out in a cast iron mould of 200 mm length and 24 mm diameter. Thereafter, cast lead was machined into smaller specimen of 20 and 30 mm height with 20 mm diameter. Annealing of lead alloy billets was carried out by putting them in boiling water with a temperature of 100 ºC for about 45 minutes and gradually cooling to room temperature. Aluminum samples of required dimensions are also prepared from the cast aluminum bar of 24 mm diameter by turning in a lathe machine. Annealing of the aluminum billets was carried out by holding at 345 ºC for 15 minutes and then gradually cooling to room temperature. The compression tests were performed at very low strain rate (10^{-3} s^{-1}) on the lead and aluminum specimens of 20 mm diameter and 30 mm length to obtain stress-strain data for experimental evaluation of yield stress. Concentric grooves of 1 mm depth and 0.5 mm width are made on the faces of the specimen in order to facilitate the retention of lubricant during compression testing. Engineering stress-strain curves for the specimens of lead and aluminum used for extrusion are shown in Figure 3.6. The average hardness values for lead and aluminum specimen samples were found to be 10.2 VHN and 39.5 VHN respectively.

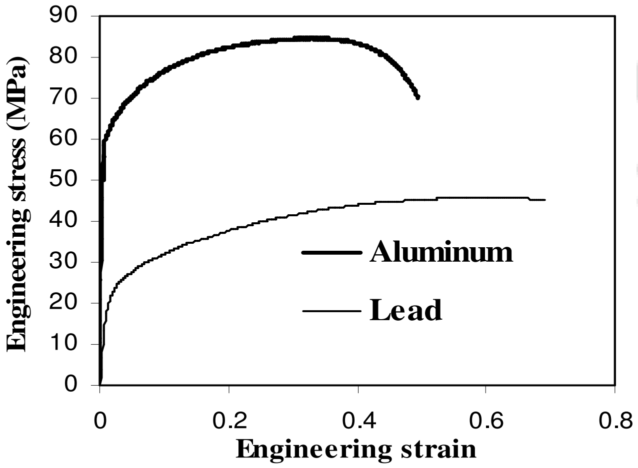


Figure 3.6. Engineering stress–strain curve of aluminum and lead

The composition of aluminum and lead alloy is given in Table 3.3. The Scanning Electron Microscope (SEM) equipped with an Energy Dispersive Spectrometer (EDS) is used to find the material composition The SEM specifications is provided in Appendix A. Figures 3.7 (a) and (b) show the alloying element composition spectrum for aluminum and lead alloy.

Table 3.3. Material composition of aluminum and lead alloy

Aluminum alloy		Lead alloy	
Composition	Weight %	Composition	Weight %
Aluminum	97.55	Lead	92.72
Magnesium	0.88	Tin	1.2
Silicon	0.14	Antimony	6.08
Iron	2.23		

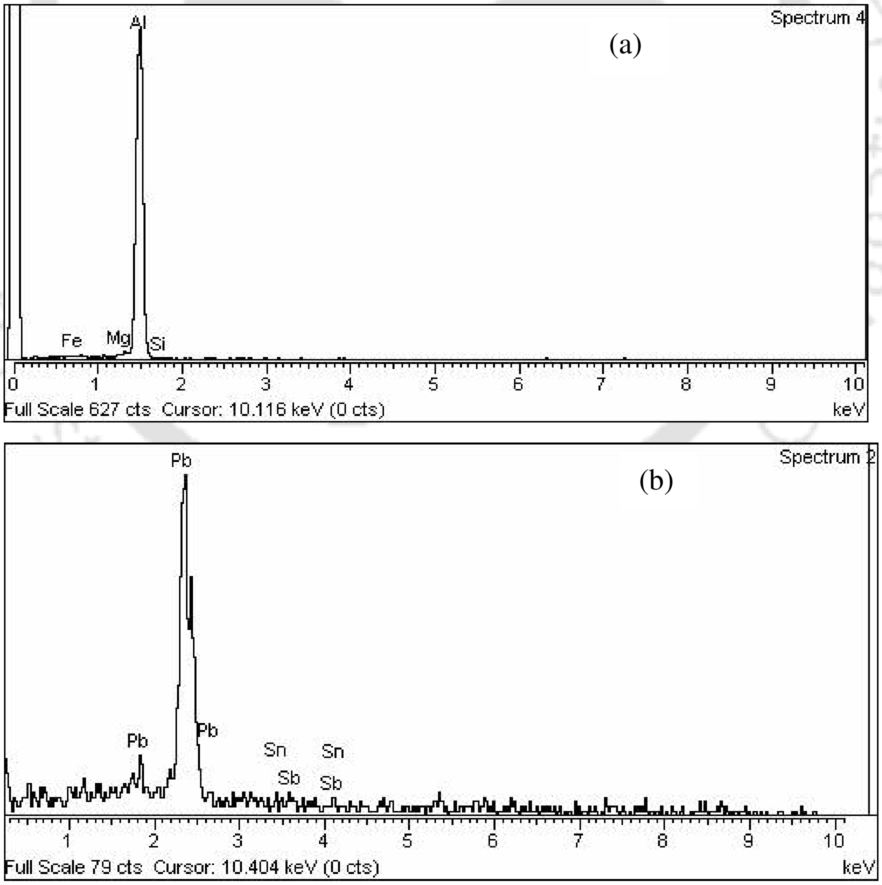


Figure 3.7. Composition spectrum of (a) aluminum (b) lead alloy

3.4 Measurement of Tensile Strength, Hardness and Surface Roughness

Micro tensile tester (Make: Deben UK LTD., Model: MICROTEST 5 kN) shown in Figure 3.8 is used to measure the tensile strength of the extruded products [Appendix A]. The extruded samples from different holes of the multi-hole dies were cut into the size of 30 mm length. The both ends of the tensile test specimen were applied with the mixture of acrylic powder (self-polymerizing resin) and acrylic liquid (self-polymerizing liquid) and allowed to dry properly. These gripping ends prevent the test specimen from the damage caused by the gripper of micro tensile tester and to avoid notch sensitivity. Samples are mounted horizontally and clamped in a pair of jaws, which are supported on stainless steel sliding bearings. A dual threaded lead screw drives the jaws symmetrically in opposite directions. The data of load-deflection curves were obtained experimentally and were converted to engineering stress-strain diagrams. The effects of extrusion ratio, die land length and lubrication of the dies on the hardening behavior of the extruded products were studied.

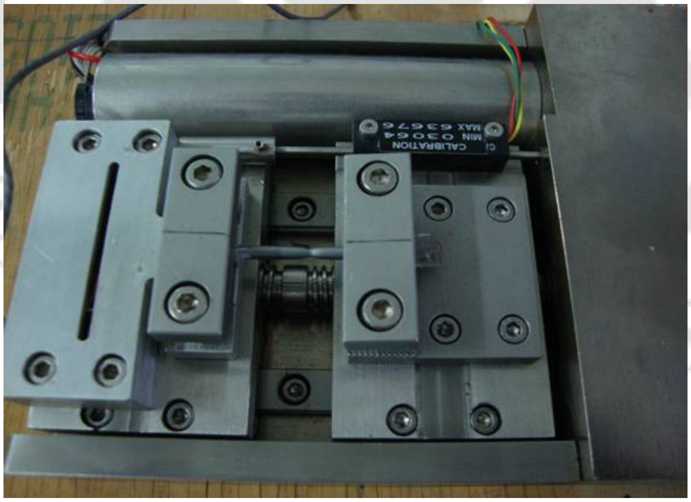


Figure 3.8. Micro tensile tester

Figure 3.9. Polishing machine for micro hardness sample preparation

Figure 3.10. Vickers Micro-hardness tester

Figure 3.11. Surface roughness measuring instrument

Micro-hardness tests of extruded products were carried out on extruded products coming out through different holes of 5-hole, 9-hole and 13-hole dies. Due to small diameter of extruded products (1.5 mm for lead products and 3 mm for aluminum), they could not be used directly for hardness measurement. The sample preparation was carried out to conduct the micro-hardness tests. A cold mounting method was used for the mounting of the extruded products with acrylic powder and acrylic liquid. The samples were polished with the help of polishing machine (Make: BUEHLER, Model: ECOMET-6) as shown in Figure 3.9 to avoid the surface effect in micro hardness testing [Appendix A]. For determining the micro-hardness Vickers Micro Hardness Tester (Make: BUEHLER, Model: MICROMET 2101) as shown is Figure 3.10 was used. Indentation was carried out with a load of 50 g for 10 seconds for the lead material and 100 g for 15 seconds for aluminum [Appendix A]. Pocket Surf (Mahr, GMBH) shown in Figure 3.11 was used to measure the surface roughness of the extruded products. Its measuring range is 0.03–6.35 µm and accuracy is ±0.01 micron. The surface roughness evaluation length and cut off length were 2.4 and 0.8 mm respectively [Appendix A].

3.5 Measurement of Radius of Curvature

Product quality is one of the major expectations with the final product in metal forming processes. The different process parameters sometimes play crucial role in producing better quality product. Many researchers have studied the bending of extruded products by simulations and experiments. In experiments, the extruded products are cut carefully and the curvatures are measured. The schematic of a curved extruded part is shown in Figure 3.12.

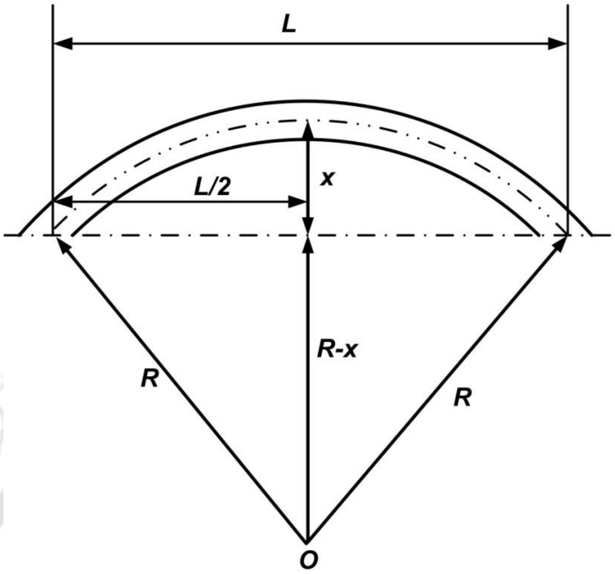


Figure 3.12. Schematic of radius of curvature of a curved product

From the geometry shown in Figure 3.11,

$$\left(\frac{L}{2}\right)^2 + \left(R-x\right)^2 = R^2 \; . \qquad (3.1)$$

Assuming x is very small as compared to radius of curvature, R

$$R = \frac{L^2}{8x} \; . \qquad (3.2)$$

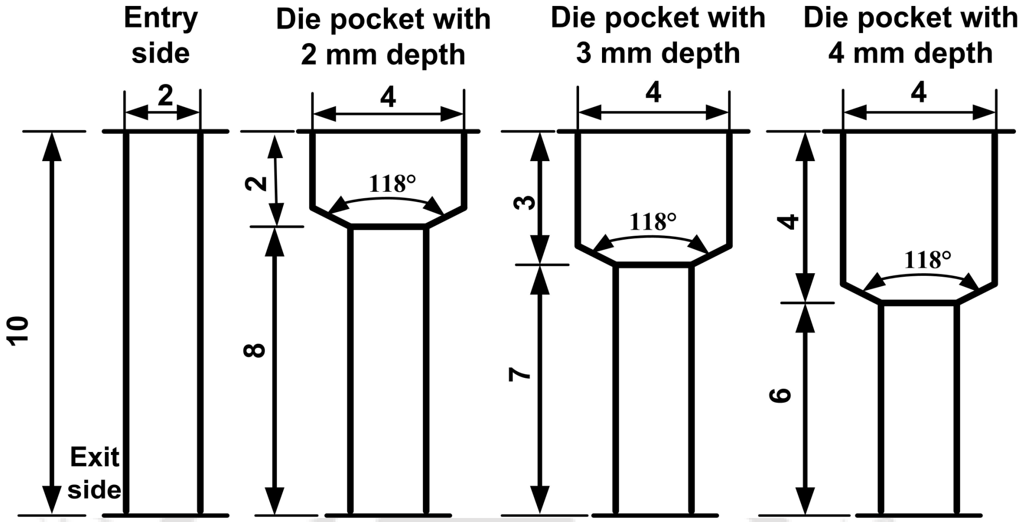
For the present study, Image J®, image processing software (Java based image processing program developed at National Institute of Health, USA) has been used to measure the radius of curvature of the extruded products. The procedure can be explained as follows. The extruded products are cut carefully without disturbing the profile. The photographs of the curved products are taken by the digital camera (Make: Sony Cyber-shot, Model: DSC-W220, 12.1 mega pixels). The distance in pixels, pixel aspect ratio, unit of length and scale are set in the software to transfer the camera photo into the global system of the Image J® software. The measurement of L and x are then taken directly. The values of L and x are put in Equation 3.2 to find out the radius of curvature.

3.6 Fabrication of Die Pockets in Multi-hole Die

The quality and accuracy of the extruded products in the multi-hole extrusion process depend on many factors such as extrusion ratio, die land length, lubrication, location of the holes and balanced metal flow in the multi-hole die. The requirement of pockets in extrusion process was found to be important in continuous extrusion process to have billet-to-billet welding. The pocket retains the metal from previous billet and then gets welded to the front of the new following billet. The different pocket design parameters are pocket entry angle, pocket volume, geometry of the pocket and offset of the pocket. To study the effect of the die pockets in multi-hole extrusion process, die pockets of different depth are produced on multi-hole dies.

Four types of dies are prepared as shown in Figure 3.13. In Die IV, one hole is located at centre and other four holes are at pitch circle diameter of 10 mm. In Die V, one hole is at centre and other four holes are at pitch circle diameter of 14 mm. In Die VI, one hole is at centre and other six holes are at pitch circle of 10 mm. In Die VII, one hole is at centre and other six holes are at pitch circle diameter of 14 mm. In all cases, the holes in the periphery are located symmetrically. The diameter of each hole is 2 mm. Die pockets of depth of 2, 3 and 4 mm are produced on each hole. The pocket diameter is 4 mm for all cases. The pockets are produced by drilling process. Utmost care has been taken to avoid the eccentricity of the pockets with the holes of multi-hole dies. Total sixteen dies are prepared for carrying out the experiments [Appendix B]. Figure 3.14 shows the schematic of the pockets which are produced on all four types of dies.

Figure 3.13. Four types of dies used to study the effect of die pocket



(All dimensions are in mm; drawing not to scale)

Figure 3.14. Schematic of the pockets produced on die

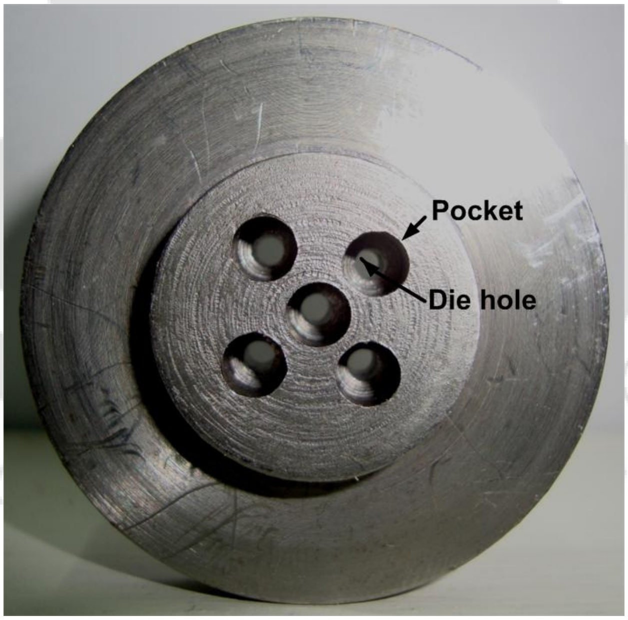


Figure 3.15. Pockets produced on Die IV

The photograph of Die IV with die pockets of 4 mm depth is shown in Figure 3.15 which gives clear idea about the die pockets in multi-hole dies. Similarly, die pockets of different depths are produced on other dies.

The experiments are carried out on a 2000 kN hydraulic press (Make: Lawrance & Mayo) [Appendix A]. The dies, container punch and die support base are prepared from H13 die steel. The commercially available lead alloy is used as billet material. The billet of 20 mm diameter and 20 mm height is used for the extrusion experiments. Extrusion is carried out at speed of 1 mm/min in order to eliminate the strain-rate effect. Commercially available grease is used as a lubricant during the multi-hole extrusion. The load and displacement are measured at particular interval of time. The extruded parts are carefully cut to measure the bending. Experiments are repeated twice to asses the repeatability of the process. The value of friction factor at the billet-container interface is 0.3.

3.7 Conclusion

In this chapter, the details of experiments are explained. Multi-hole extrusion set up and multi-hole dies were fabricated. A vibrator is attached to the container wall of the extrusion set up for the multi-hole extrusion experiments to impose vibrations. The billets preparation of lead alloy and aluminum alloy are discussed. The photographs of equipment used for measurement of tensile strength, hardness and surface roughness are shown and their working principles are explained. The radius of curvature of the extruded products is measured. The photographs of bent products are processed in Image J®. For the study of effect of die pockets in multi-hole extrusion process, pockets of 2, 3 and 4 mm depths are produced in four different dies. Multi-hole extrusion experiments are carried out with the fabricated dies and set up. Results are discussed in Chapter 4.

Chapter 4

Results of Experimental Study on Multi-hole Extrusion Process

4.1 Introduction

In multi-hole extrusion process, the number of holes and their location on the die decide the extrusion load and quality of the extruded products. Die land length is also an important process parameter which affects the extrusion load and the quality of the extruded products. The profile of the extruded product is one of the quality aspects. Extrusion ratio and die land length affect the mechanical properties of the extruded products. In multi-hole extrusion process, it is a challenging task to control the flow of the metal at die exit due to complex influencing factors. Use of die pocket offers an opportunity to control the metal flow. Lubrication is also an influential factor in reducing extrusion load and increasing surface quality of the extruded products. In the present work, experiments on multi-hole extrusion process were carried out to study the effect of different process parameters and externally imposed vibrations on ram force, bending of the extruded products, tensile strength and micro hardness of the extruded products. The effect of process parameters on surface roughness of the extruded products was studied. Lead and aluminum alloy were used for experiments. Commercially available grease (Balmerol grease autoplex, Balmer Lawri & Co Ltd) was used as lubricant. The ram force obtained in the extrusion of lead alloy for different lubricated and unlubricated dies are discussed. The compression test of the lead specimen was carried out in a universal testing machine to find out stress-strain relationship. The following relation is fitted from the stress-strain data obtained:

$$\sigma_y = 54.59\left(\varepsilon_{eq}\right)^{0.23}, \qquad (4.1)$$

where σ_y is the flow stress in MPa and ε_{eq} is the equivalent strain.

Multi-hole extrusion was carried out with the fabricated set up and dies. Ram forces were measured during the multi-hole extrusion of lead alloy at different ram speed. The billet of 20 and 30 mm were used in extrusion process. The effect of die pockets on ram force, length of the extruded products and bending of the extruded products were studied.

4.2 Ram Force Obtained for Different Dies in Extrusion of Lead Alloy

The ram force obtained in multi-hole extrusion process with different extrusion ratio dies is shown in Table 4.1. It is observed that lubrication and reduction in die land length reduce the ram force. Similar observations on effect of die land on extrusion load were also obtained by Ajiboye and Adeyemi [2008] in single hole extrusion. The smaller die land length reduces the chances of ironing effect; as a result the ram force reduces.

Table 4.1. Ram force comparison for multi-hole extrusion

Die land length (mm)	Ram force (kN)					
	5-hole Die		9-hole Die		13-hole Die	
	Lubricated	Unlubricated	Lubricated	Unlubricated	Lubricated	Unlubricated
10	125.5	133.8	109.5	118.0	103.5	111.5
3	123.0	129.5	105.5	115.3	101.7	107.5

4.3 Comparison of Ram Forces for Lubricated and Unlubricated Extrusion with 9-hole Dies

In order to carry out a detailed study of the effect of die land length of ram force and quality of the extruded products, nine-hole die is used. Different die land lengths are produced on 9-hole die. The details of the dies are given in Table 3.1 (Chapter 3). Extrusion of lead alloy was carried out with 9-hole dies (Die I, Die II and Die III). Tables 4.2 and 4.3 show the ram forces for 20 and 30 mm billet length extrusion respectively at different ram speeds with lubricated and unlubricated dies. The decrease in ram force with decrease in ram speed is observed for both lubricated and unlubricated dies. For Die II and Die III, there is a decrease in ram force as compared to Die I. This shows that the ram force decreases as the length of die land length decreases. In all the cases, lubricated dies provided lower ram force compared to unlubricated dies. It is observed that in all the cases, as the ram speed increases, the ram force also increases. The material properties, friction and flow losses are three important factors affecting the ram force. In order to make an assessment of change in material properties with speed, compression tests were carried out in the selected speed range (0.45–1.8 mm/min).

Table 4.2. Comparison of ram force for extrusion with 9-hole die for 20 mm billet length

Ram speed (mm/min)	Ram force (kN)					
	Die I		Die II		Die III	
	Lubricated	Unlubricated	Lubricated	Unlubricated	Lubricated	Unlubricated
1.5	112.65	122.75	109.55	121.20	111.55	119.95
1.2	104.25	118.15	105.25	122.70	100.50	116.15
0.9	100.05	115.15	96.90	114.00	96.00	111.60
0.45	99.80	107.50	92.35	103.50	93.90	103.55

Table 4.3. Comparison of ram force for extrusion with 9-hole die for 30 mm billet length extrusion

Ram speed (mm/min)	Ram force (kN)					
	Die I		Die II		Die III	
	Lubricated	Unlubricated	Lubricated	Unlubricated	Lubricated	Unlubricated
1.8	125.45	134.25	118.55	127.40	113.85	122.85
1.2	117.25	125.15	115.35	123.85	108.55	119.40
0.9	108.55	117.35	106.80	117.55	101.30	113.80
0.45	103.65	111.45	100.85	104.80	97..65	104.10

The compression test data for 20 and 30 mm billet length at different strain rate are shown in Table 4.4 and 4.5. Within the chosen speed range, constitutive relation remains almost same as given by Eq. (4.1). Hence, the increase in ram force is basically either due to increased friction or due to flow loss. The increased flow loss with increased ram speed is akin to minor losses in pipe flow, for example the pressure loss through an orifice. The loss through an orifice is proportional to the square of the flow velocity.

Table 4.4. Compression test data of lead for 30 mm billet length.

Velocity (mm/min)	Average strain rate (s^{-1})	Hardening behavior	Yield strength (MPa)
1.8	1.5×10^{-3}	$\sigma_y = 53.81\left(\varepsilon_{eq}\right)^{0.23}$	21.94
1.2	1.45×10^{-3}	$\sigma_y = 54\left(\varepsilon_{eq}\right)^{0.22}$	21.5
0.9	0.75×10^{-3}	$\sigma_y = 54.06\left(\varepsilon_{eq}\right)^{0.2}$	21.06
0.45	0.37×10^{-3}	$\sigma_y = 53.5\left(\varepsilon_{eq}\right)^{0.22}$	20.1

Table 4.5. Compression test data of lead for 20 mm billet length.

Velocity (mm/min)	Average strain rate (s^{-1})	Hardening behavior	Yield strength (MPa)
1.5	1.96×10^{-3}	$\sigma_y = 53.46\left(\varepsilon_{eq}\right)^{0.21}$	20.87
1.2	1.5×10^{-3}	$\sigma_y = 53.99\left(\varepsilon_{eq}\right)^{0.2}$	20.66
0.9	1.12×10^{-3}	$\sigma_y = 54.22\left(\varepsilon_{eq}\right)^{0.2}$	21.13
0.45	0.56×10^{-3}	$\sigma_y = 54.79\left(\varepsilon_{eq}\right)^{0.21}$	21.47

4.4 Variation in Radius of Curvature of Extruded Products Obtained from 20 mm Length Billet Extrusion with 9-hole Die of Different Die Land Length

Extruded products come out from centre hole as well as peripheral holes of the multi-hole die with different die lands during the extrusion. The bending of the products is not following axisymmetry. The variation of radius of curvature with extrusion speed of the product from centre hole of lubricated dies for 20 mm billet length is shown in Figure 4.1. For Die I and Die II, the ram speed is having some influence on the curvature of the product as compared to Die III. For Die III, the significant increase in curvature with speed is not observed. Figure 4.2 shows the variation in radius of curvature for pin extruded from centre with ram speed for unlubricated dies. The influence of speed for lubricated and unlubricated dies is different. For unlubricated die extrusion, radius of curvature of the extruded products in Die I increases with ram speed.

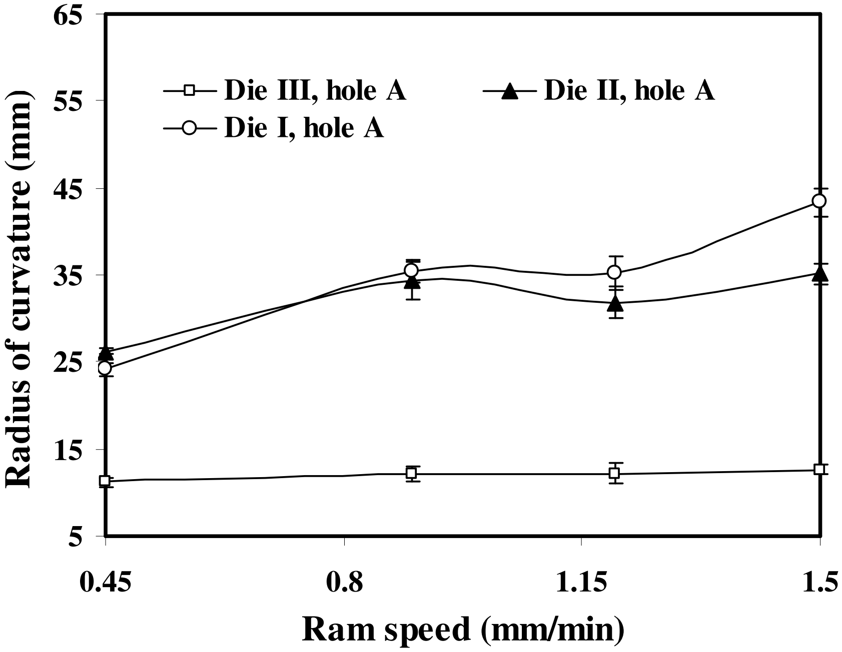


Figure 4.1. Radius of curvature for centre hole product from 20 mm billet length with lubrication.

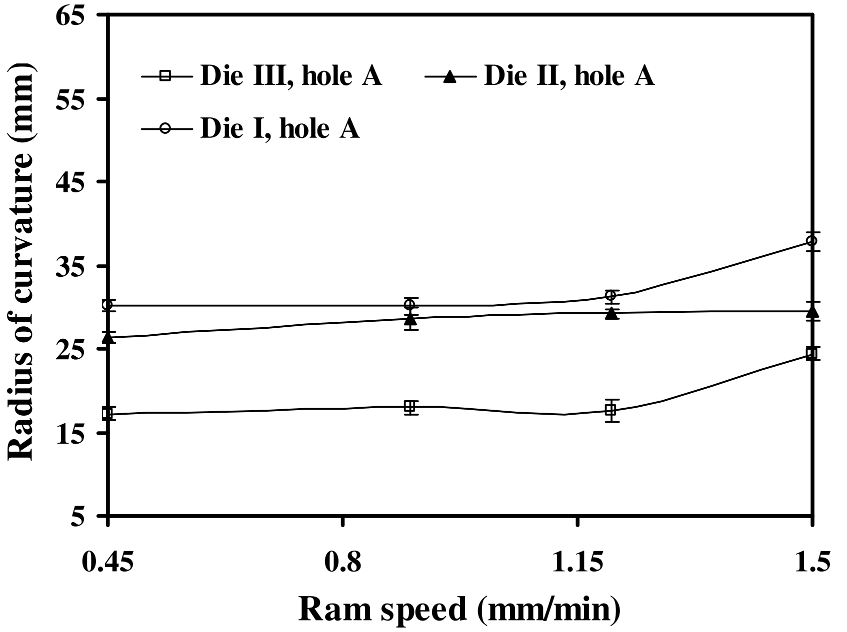


Figure 4.2. Radius of curvature for centre hole product from20 mm billet length without lubrication.

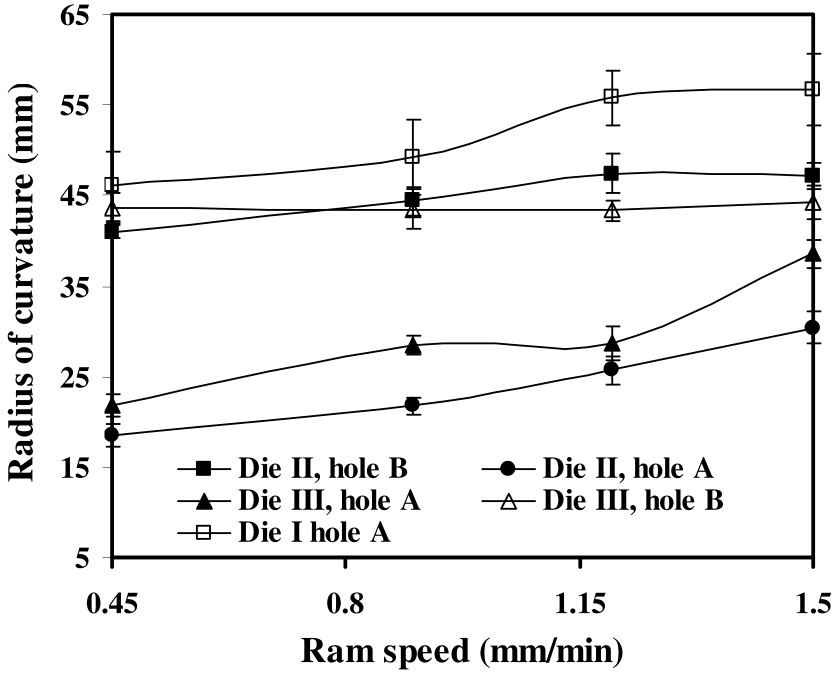


Figure 4.3. Radius of curvature for peripheral hole product from 20 mm billet length with lubrication.

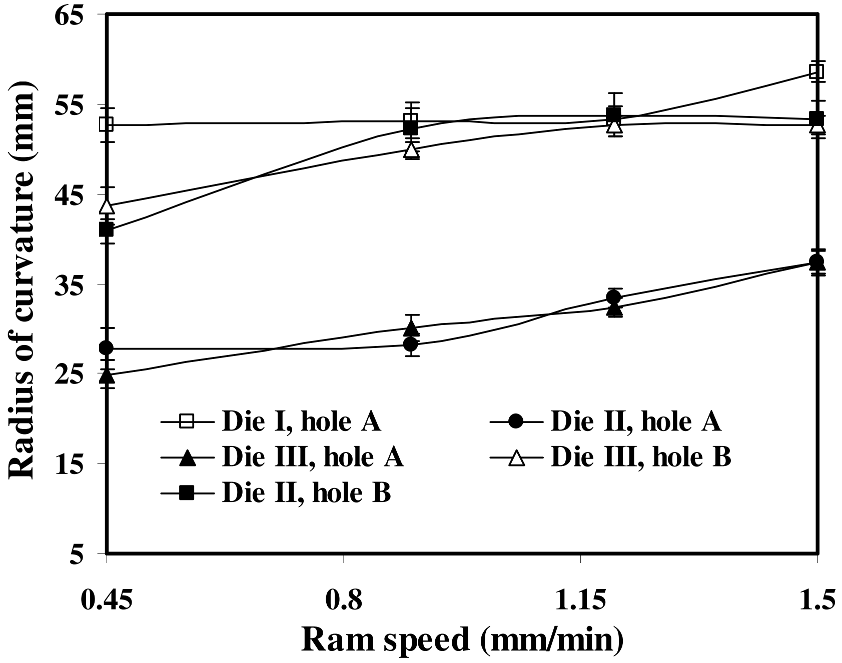


Figure 4.4. Radius of curvature for peripheral hole product from 20 mm billet length without lubrication

Figure 4.3 shows the variation of radius of curvature with respect to ram speed for peripheral products of 20 mm billet extrusion with different lubricated dies. The maximum radius of curvature was observed with Die I, holes 'A' (10 mm die land). Thus, lengthier die land produces less curved products. Figure 4.4 shows that unlubricated Die I, holes 'A' and Die II, holes 'B' produce the greater radius of curvature. Thus, generally, unlubricated die with high die land produces less curved products.

The flow behaviour of metal and die land length plays important role in producing either straight or bent profile. The die land length is more influential parameter compared to lubrication and ram speed for producing better and high radius of curvature. In the experiments, different die land lengths were produced on the alternate holes to observe the flow behavior and curvature of extruded products.

4.5 Variation in Radius of Curvature of Extruded Products Obtained from 30 mm Length Billet Extrusion with 9-hole Die of Different Die Land Length.

To study the effect of billet length on the radius of curvature, 30 mm billet length was extruded. Figures 4.5 and 4.6 show the variation of radius of curvature with extrusion speed of the product from centre hole of lubricated and unlubricated dies respectively for 30 mm billet length. It is observed that the most straight products are obtained from the unlubricated Die I. With increased ram speed, greater radius of curvature of the extruded products is obtained from unlubricated die. For the peripheral holes, as like 20 mm billet extrusion, the higher value of radius of curvature is observed with the die of 10 mm die land length and unlubricated condition. In general, the products extruded from 30 mm billet are less curved compared to those extruded from 20 mm billet. Larger contact length of the billet in the container helps in the uniform flow.

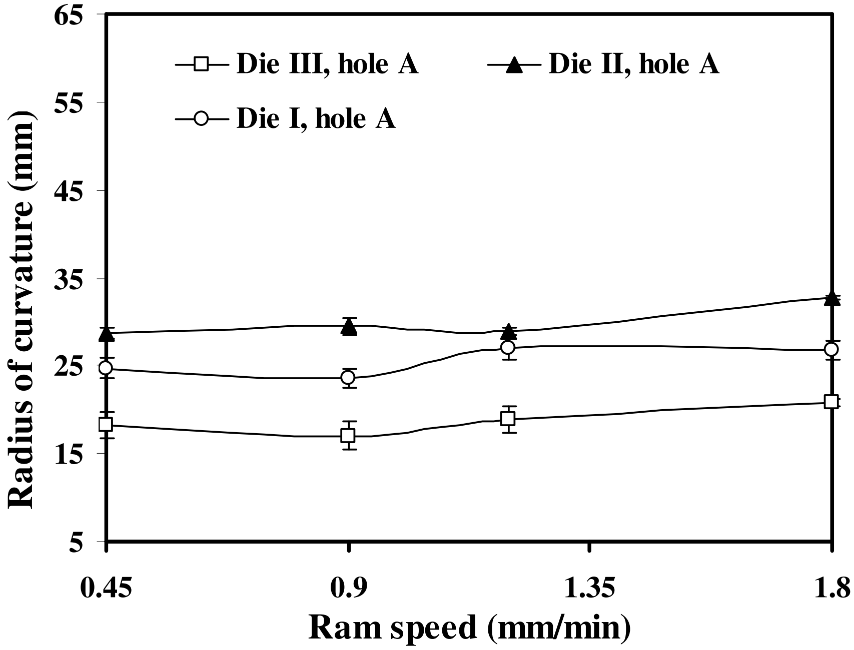


Figure 4.5. Radius of curvature for centre hole product of 30 mm billet length with lubrication

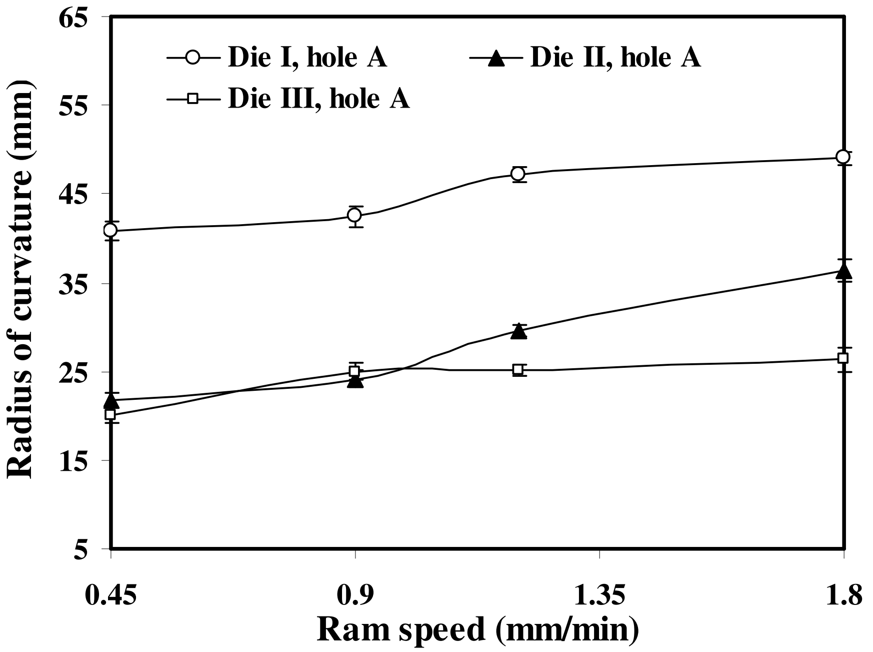


Figure 4.6. Radius of curvature for centre hole product of 30 mm billet length without lubrication.

Like the case of 20 mm billet extrusion, the dies with smaller die land length produces smaller radius of curvature for 30 mm billet length, which can be observed from Figures 4.7 and 4.8. The flow pattern and flow behavior changes with lubrication and subsequently change the bend profile of the extruded products. Interestingly, for same extrusion ratio condition, the effect of lubrication along with the die land length has much influence in producing larger radius of curvature of the extruded products. The present experimental results show that that the radius of curvature of the extruded product increases with increase in billet length, which matches with the results obtained by Ajiboye and Adeyemi [2006] for single-hole extrusion.

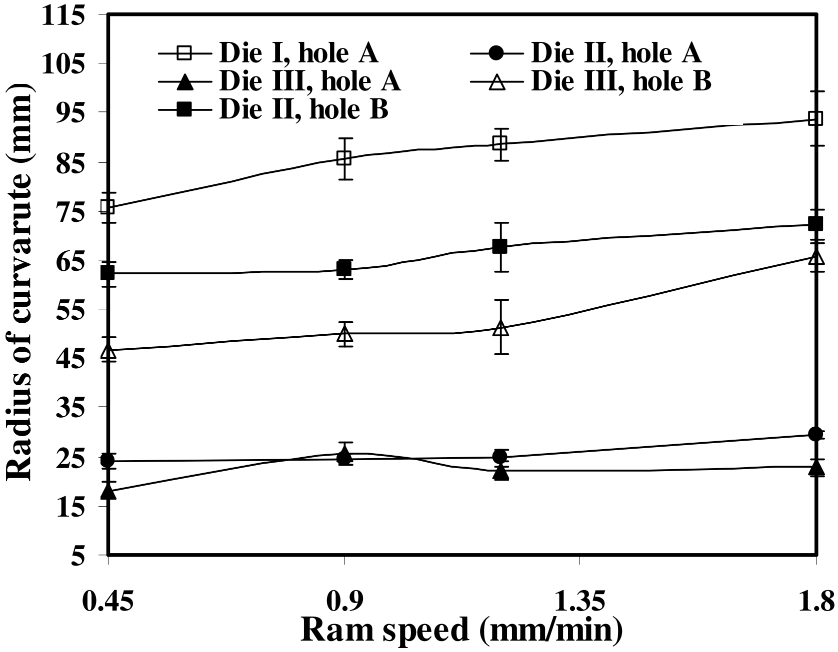


Figure 4.7. Radius of curvature for peripheral hole products of 30 mm billet length with lubrication

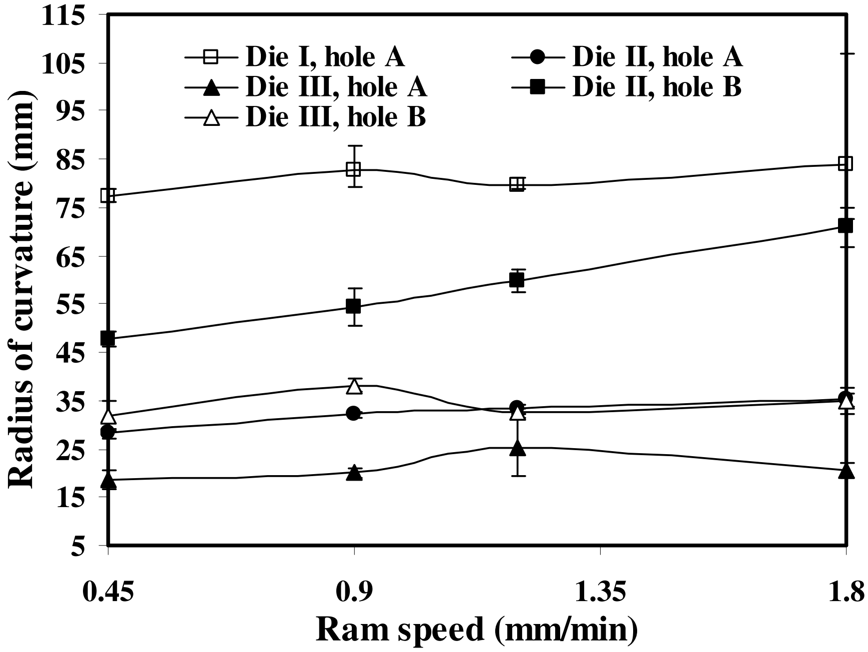


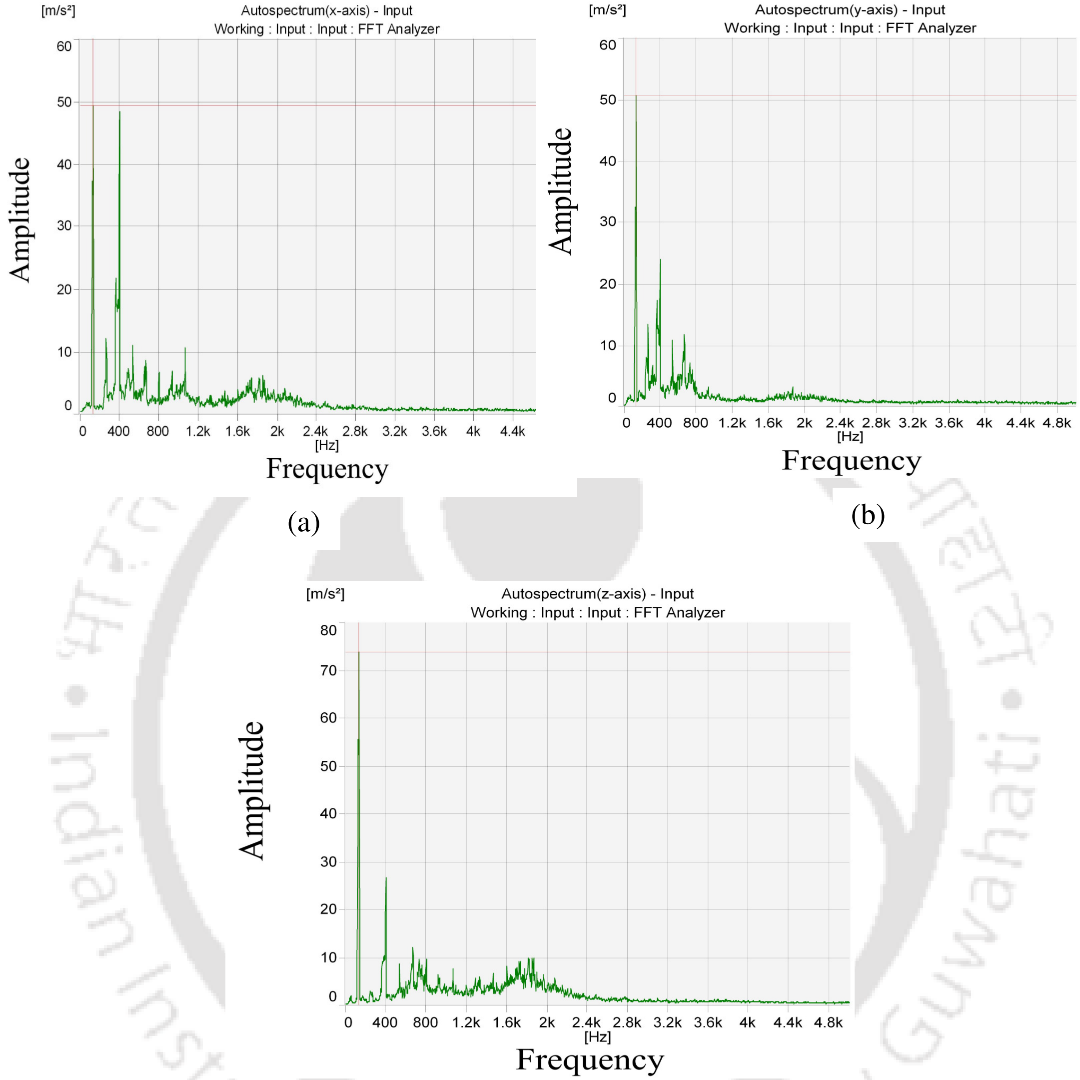
Figure 4.8. Radius of curvature for peripheral hole product of 30 mm billet length without lubrication

Some researchers have tried to establish relationship among the process parameters with the bending of the extruded products. Simulation works on multi-hole extrusion process carried out by Chen *et al.* [2008] show that extruded tube bend outward in two-hole extrusion and inward in three-hole extrusion and four hole extrusion. No such definite pattern is observed in present experimental study. In all cases, mix of inward and outward bending of the extruded products is observed.

4.6 Multi-hole Extrusion with Imposed Vibrations

It is observed that in the multi-hole extrusion process, the lubrication conditions in the interface of billet-container and at die land region affect the ram force. Literature review on the use of vibration in metal forming processes reveals that application of vibrations helps in reducing the friction conditions encountered. Reduction in frictional force is obtained when the oscillation direction is parallel to the direction of motion of the die. For this study, the experimental set up is developed and the procedure for imposing vibrations in multi-hole extrusion set up has been discussed in Section 3.2.

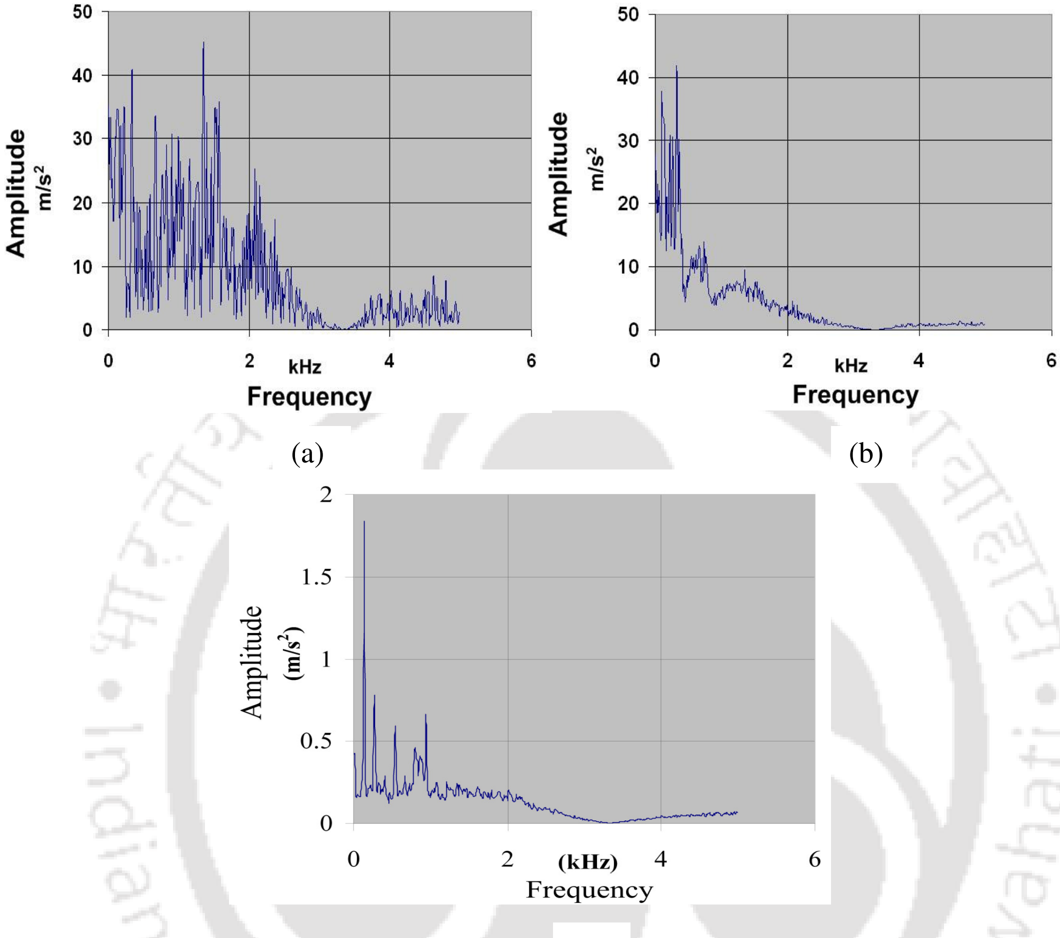
Extrusion of lead alloy was carried out with 9-hole die with 1.5 and 0.45 mm/min ram speed. Both lubricated and unlubricated dies were used. The vibration was imposed to the extrusion set up by a vibrator. A tri-axial accelerometer was used to measure the amplitude of acceleration generated by vibrator. Figures 4.9 (a, b and c) show the frequency versus amplitude of acceleration of the vibrations, when the extrusion was not carried out. The peak frequencies for all three axes during the extrusion are shown in Figure 4.10. Figure 4.10 shows the condition of vibration during extrusion which is measured along x, y and z-direction.



(a) (b)

(c)

Figure 4.9. Frequency and amplitude of acceleration of imposed vibration: (a) along x-axis, (b) along y-axis, (c) along z-axis



(a) (b)

(c)

Figure 4.10. Frequency and amplitude of acceleration of imposed vibration: (a) along x-axis, (b) along y-axis, (c) along z-axis during extrusion

4.6.1 Comparison of Ram Force for 20 mm Length Billet Extrusion with 9-hole Die with Imposed Vibration.

Table 4.6 shows the comparison of ram forces obtained during the multi-hole extrusion with vibration for lubricated and unlubricated dies. The vibration helps in reducing the friction between container and billet, due to which the ram force decreases. It was observed that there is not much difference in ram forces for lubricated die without vibration and unlubricated die with vibration. The elimination of lubrication contributes towards achieving a green manufacturing environment.

Table 4.6. Comparison of ram force for 20 mm billet length extrusion (with vibration)

Ram speed (mm/min)	Ram force (kN)			
	Lubricated Die I		Unlubricated Die I	
	No vibration	With vibration	No vibration	With vibration
1.5	112.65	101.75	122.75	115.38
0.45	99.80	88.42	107.50	98.35

4.6.2 Effect of vibration on Radius of Curvature of the Extruded Lead Alloy Products

It is well established that vibration assisted metal forming can result significant reduction in resistance of the forming of the material to deformation by combination of stress superposition and attenuation in interfacial friction. Vibration helps in reducing forming force, the flow stress and in friction between the die and work piece. As reported in Section 3.1, like the reduction in ram force with the imposed vibration, a considerable variation in the radius of curvature of the extruded products is observed in the experiments. Tables 4.7 and 4.8 show the variation of radius of curvature for the extruded products of 20 mm billet length extrusion through Die I. Vibrations were imposed during extrusion process with ram speed of 1.5 and 0.45 mm/min to study the effect of vibration on radius of curvature at different ram speed.

Table 4.7 shows that in 3 out of 4 cases, the vibration increased the radius of curvature of the centre hole product. For periphery holes, most of the products were found to be straight (as indicated by high radii of curvature in Table 4.8). For unlubricated die with ram speed of 1.5 mm/min, the average value of radius of curvature was found to be lesser when vibration was imposed on the extrusion process. In general, the proper imposition of vibration is capable of producing straight products.

Table 4.7. Comparison of radius of curvature of the extruded products from centre hole for 20 mm billet length extrusion

Ram speed (mm/min	Radius of curvature (mm)			
	Lubricated Die I		Unlubricated Die I	
	With vibration	Without vibration	With vibration	Without vibration
1.5	41.37	12.64	24.29	25.03
0.45	29.98	11.98	40.67	17.24

Table 4.8. Comparison of radius of curvature of the extruded products from periphery holes for 20 mm billet length extrusion

Ram speed (mm/min	Radius of curvature (mm)			
	Lubricated Die I		Unlubricated Die I	
	With vibration	Without vibration	With vibration	Without vibration
1.5	122.45	47.07	45.30	58.6
0.45	40.47	41.0	71.03	52.72

4.7 Tensile Strength of the Extruded Lead Alloy Products

As a part of the study on mechanical properties, the variations in tensile strength of the extruded products were studied for different extrusion ratio (ER), die land length and lubrication conditions. The unbalanced material flow takes place due to eccentricity of the holes in multi-hole dies. This causes the variation in length of the product as well as different degree of bent profiles. For the present study three different multi-hole dies viz. 5-hole die, 9-hole die and 13-hole die with extrusion ratio of 35.55, 19.75 and 13.67 respectively are used as given Table 3.2, Chapter 3. The engineering stress-strain curves of the products from the centre hole of the lubricated and unlubricated dies of 10 mm die land length are shown in Figure 4.11 (a) and (b) respectively. With unlubricated dies the tensile strength ranges from 28 to 34 MPa. For the lubricated dies, the tensile strength ranges from 26 to 28 MPa. This indicates that the lubrication helps in smooth material flow resulting less tensile strength of the extruded products.

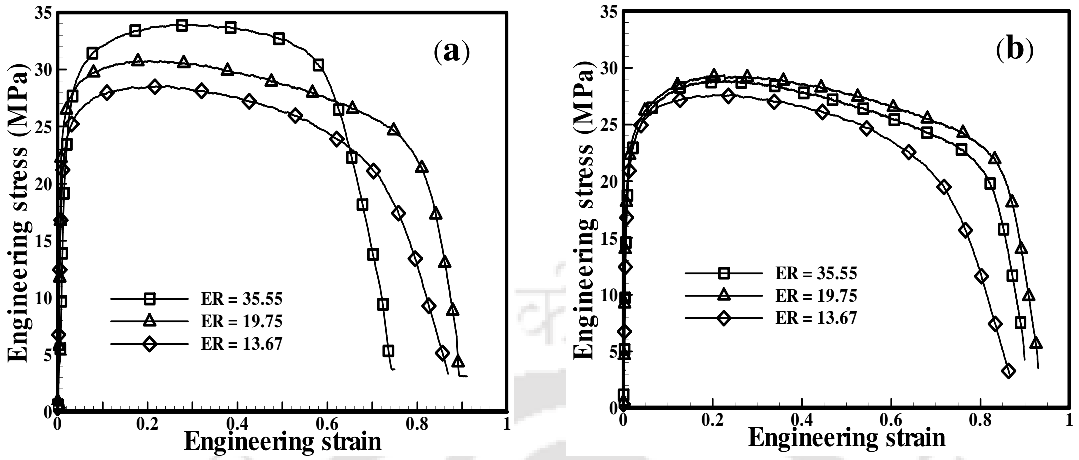


Figure 4.11. The engineering stress-strain curves for lead products from centre hole with 10 mm die land length (a) unlubricated die (b) lubricated die

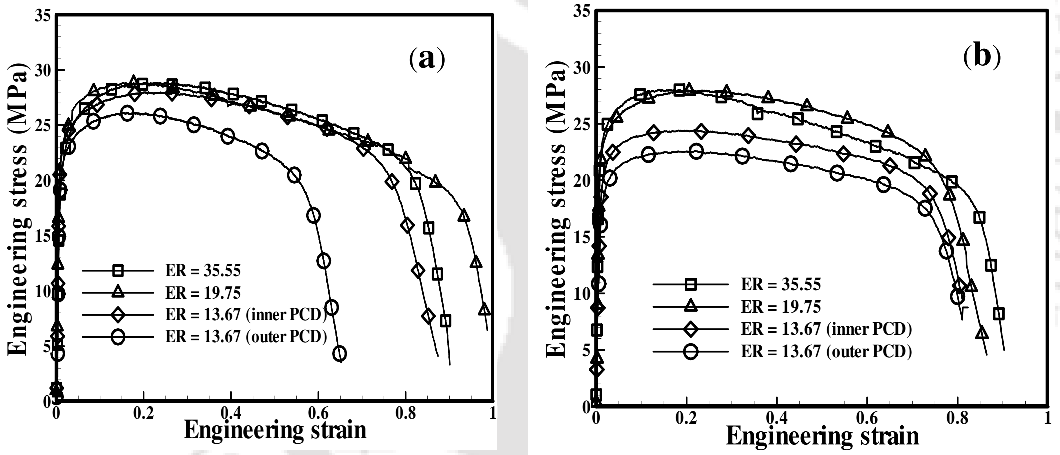


Figure 4.12. The engineering stress-strain curves for lead products from periphery holes with 10 mm die land length with (a) unlubricated die (b) lubricated die

The reduction in extrusion ratio also helps in decreasing strain hardening. Figures 4.12 (a) and (b) show the engineering stress-strain curves for the extruded products of the peripheral holes of the lubricated and unlubricated dies respectively with 10 mm die land length. The less variation in the tensile strength is observed for the extrusion ratio of 35.55 and 19.75 as compared to that of centre hole. At low extrusion ratio, less variation in engineering stress value is observed. The more number of holes in the periphery allow the material to flow easily. The proper position of the holes in periphery and lubrication can produce more uniform material property in multi-hole extrusion.

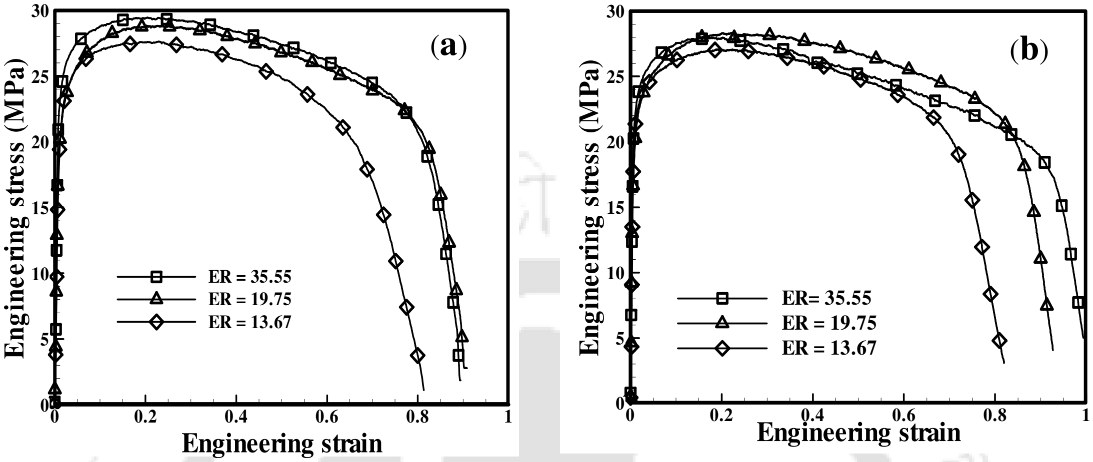


Figure 4.13. The engineering stress-strain curves for lead products from centre holes with 3 mm die land length (a) unlubricated dies (b) lubricated dies

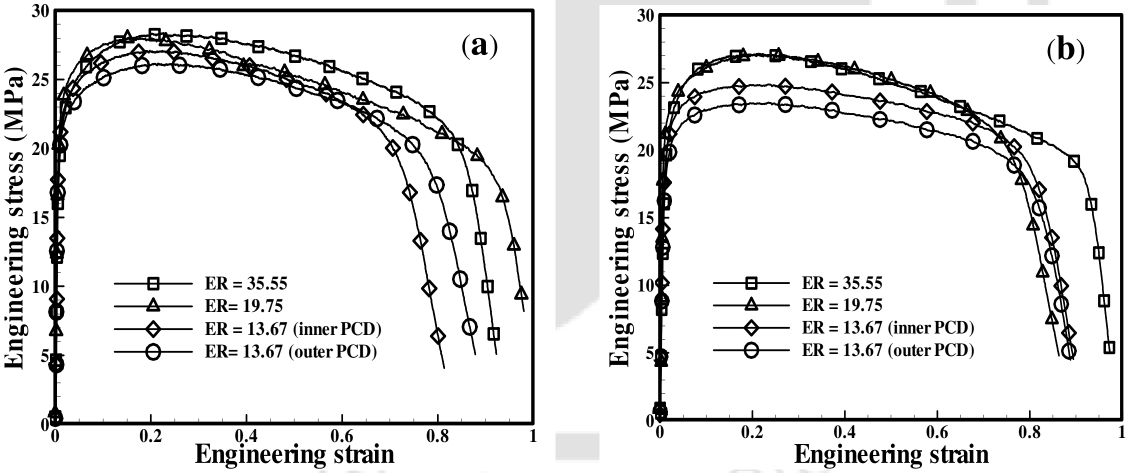


Figure 4.14. The engineering stress-strain curves for lead products from periphery holes with 3 mm die land length (a) unlubricated dies (b) lubricated die

The smaller die land length reduces strain hardening on the extruded products and this can be observed from Figures 4.13 (a) and (b).The tensile strength ranges from 26 to 29 MPa for unlubricated dies and 26 to 28 MPa for lubricated dies for all extrusion ratios. The lubrication has less effect in 3 mm die land length dies as compared to 10 mm die land length dies. Figures 4.14 (a) and (b) show the tensile strength of the peripheral products for different extrusion ratio with 3 mm die land length dies. The variation in tensile strength is much less for both lubricated and unlubricated dies as compared to 10 mm die land length dies. The difference in tensile strengths of the products from inner and outer pitch circle of the die of extrusion ratio of 13.67 is lesser for 3 mm die land length (Figure 4.14 (a)) as compared to 10 mm die land length (Figure 4.12 (a)). With lubricated dies, similar trend is observed with the extruded products with 10 and 3 mm die land length (Figure 4.12 (b) and Figure 4.14 (b)). This indicates that the proper die land design for the holes at different pitch circles of the die can control the mechanical properties.

4.8 Micro Hardness of Extruded Lead Products

As a part of the study on mechanical properties, the micro hardness tests of the extruded products were carried out. Three replicates were carried out at different conditions. At each replicate, micro hardness measurements were carried out at 4-5 places. The combined data of all measurements was used to make inference about the average quality attribute along with standard deviation. The average hardness values for the products from centre hole of the dies with 10 mm die land length are shown in Figures 4.15 and 4.16. For unlubricated dies, the average hardness value ranges from 10.58 to 10.88 VHN with different extrusion ratio and for lubricated dies, it ranges from 10.55 to 10.75 VHN. The lubrication has no significant effect for the centre hole. More deviations in hardness values are observed for the extrusion ratio of 35.55 as compared to 19.75 and 13.67 for both lubricated and unlubricated conditions, which is expected as high extrusion ratio causes more strain hardening and proportionately more non-uniformity.

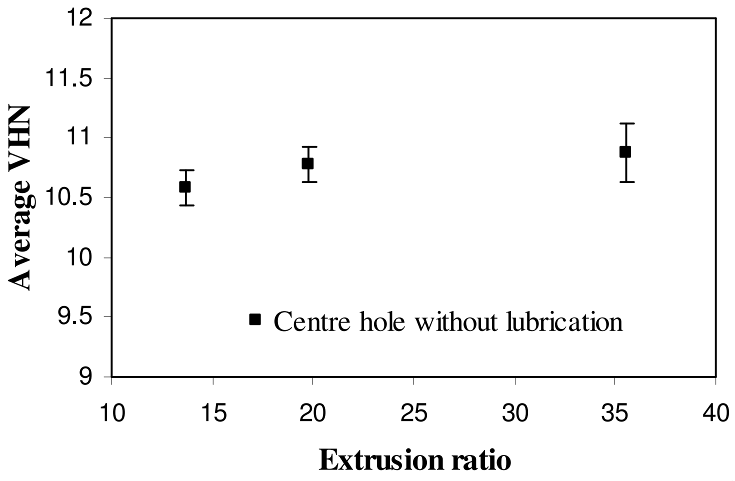


Figure 4.15. The hardness value (mean± standard deviation) for lead products from centre holes of unlubricated dies with 10 mm die land length

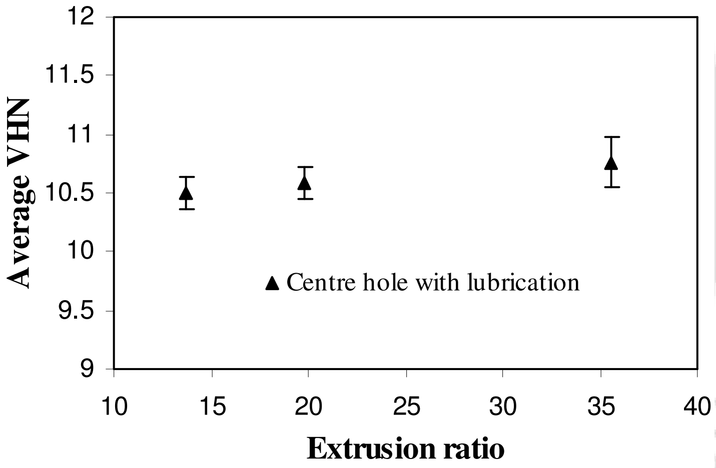


Figure 4.16. The hardness value (mean± standard deviation) for lead products from centre holes of lubricated dies with 10 mm die land length

The hardness values of the products from the peripheral holes of dies of 10 mm die land length are shown for different overall extrusion ratios in Figures 4.17 and 4.18. It is seen that the micro-hardness of peripheral extrudates is less sensitive to extrusion ratio in comparison to extrudates from central hole. It is observed experimentally that the metal flows more easily from the peripheral holes than from central hole, causing increased extrudate length from peripheral holes compared to central hole.

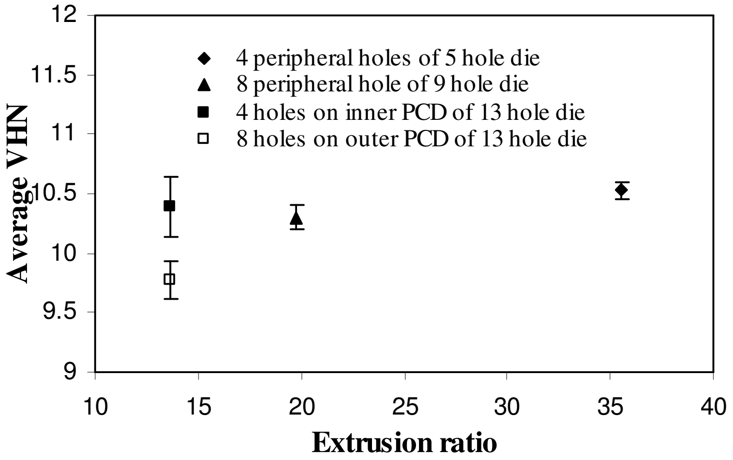


Figure 4.17. The hardness value (mean± standard deviation) for lead products from peripheral holes of unlubricated dies with 10 mm die land length

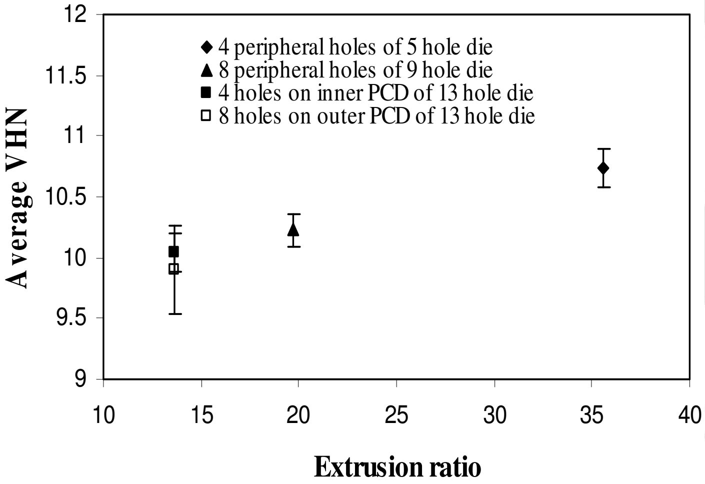


Figure 4.18. The hardness value (mean± standard deviation) for lead products from peripheral holes of lubricated dies with 10 mm die land length

A rigorous analysis by FEM can reveal the flow pattern. However, it appears that presence of many holes on periphery helps in the easy flow of metal, while in the centre, the metal observes obstruction and forms a wider dead metal zone. As a consequence, extrudate coming out from the central hole undergoes more strain hardening as compared to extrudate coming out from a peripheral hole. Hence, the effect of varying the extrusion ratio is experienced more by central hole than peripheral holes. This is the reason of lower variability of micro-hardness of peripheral extrudates with change of overall extrusion ratio as compared to central extrudate. In 13-hole die, micro-hardness of inner peripheral extrudates is found to be greater than the micro-hardness of the outer peripheral extrudates. This further confirms that the more number of holes near the container wall offer lesser resistance to flow, causing lesser amount of strain hardening. For the same PCD also, the amount of strain hardening on the extruded products obtained from different holes shows slight deviation.

The deviation in the hardness value for peripheral holes is less as compared to centre hole for different extrusion ratio with both lubricated and unlubricated conditions. For example, the variation in the hardness for the centre hole is more (maximum of 11.9 VHN and minimum of 10 VHN) as compared to peripheral holes (maximum of 10.66 VHN and minimum of 10.32 VHN) for the extrusion ratio of 35.55 in lubricated condition. This may be attributed to complex flow behavior at the centre due to formation of dead metal zone.

Figures 4.19 and 4.20 show the average hardness values for extruded products through the dies with 3 mm die land length. The deviations in hardness values of the extruded products form the 3 mm die land length dies are less as compared to 10 mm die land length dies. Low die land length also produces less variation in hardness value in the products coming through the peripheral holes in both lubricated and unlubricated conditions as shown in Figures 4.21 and 4.22. The lower die land length produces less straining and work hardening on the extrudates. Consequently, the effect of extrusion ratio is less significant on hardness of the extruded products obtained from smaller die land length (3 mm) as compared to the products from higher die land length (10 mm).

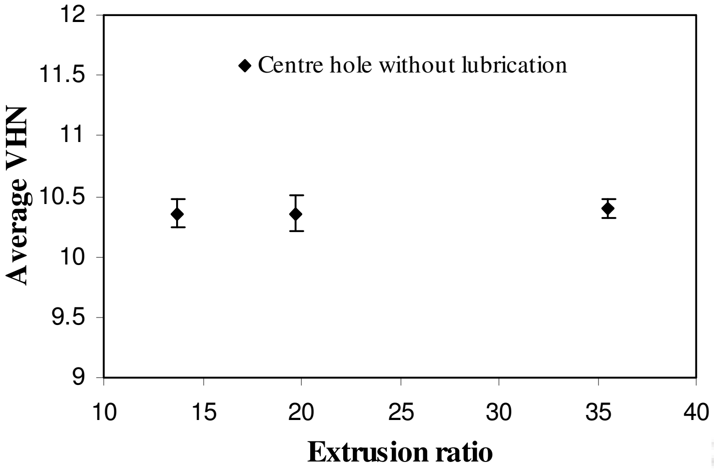


Figure 4.19. The hardness value (mean± standard deviation) for lead products from centre holes of unlubricated dies with 3 mm die land length

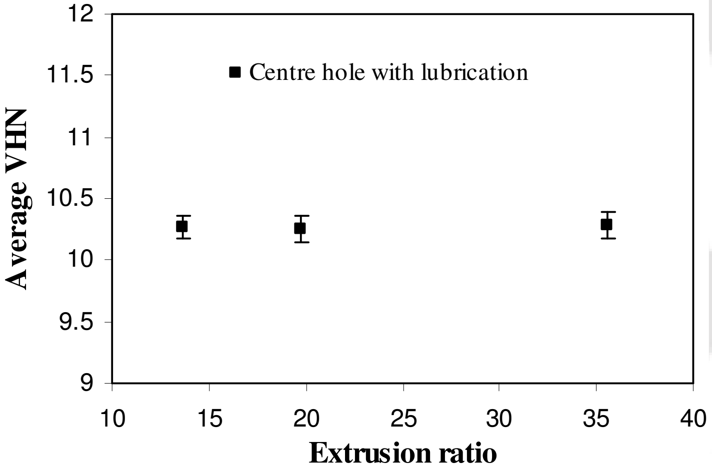


Figure 4.20. The hardness value (mean± standard deviation) for lead products from centre holes of lubricated dies with 3 mm die land length

In the replication of experiments some variations in average hardness value are observed. To assess the repeatability of the experiments, hypothesis testing is employed. A brief description of the application of hypothesis testing in manufacturing is available in [Dixit and Dixit, 2008]. At 95% confidence level, the variation in the average hardness among the replicates is insignificant [Appendix C].

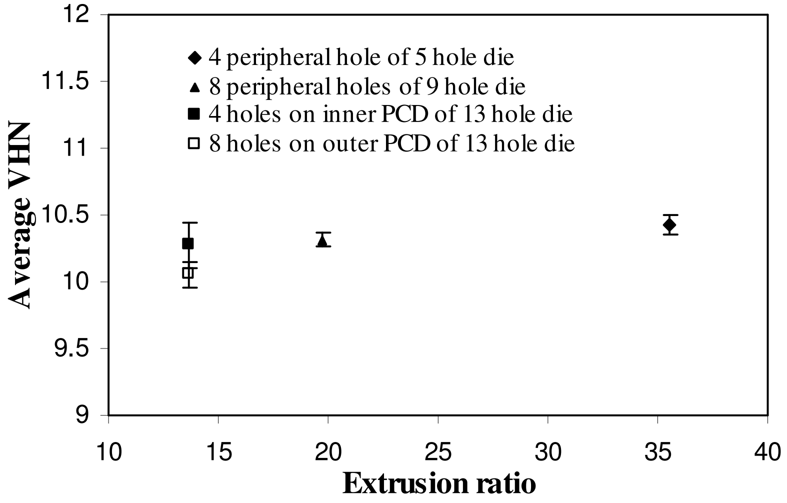


Figure 4.21. The hardness value (mean± standard deviation) for lead products from peripheral holes of unlubricated dies with 3 mm die land length

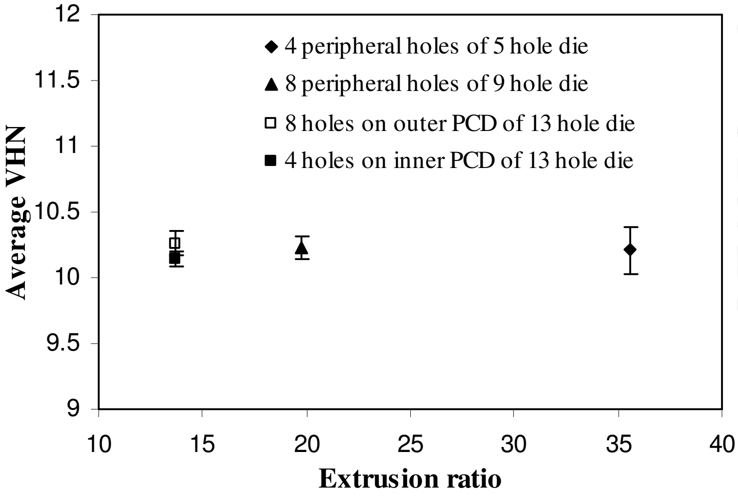
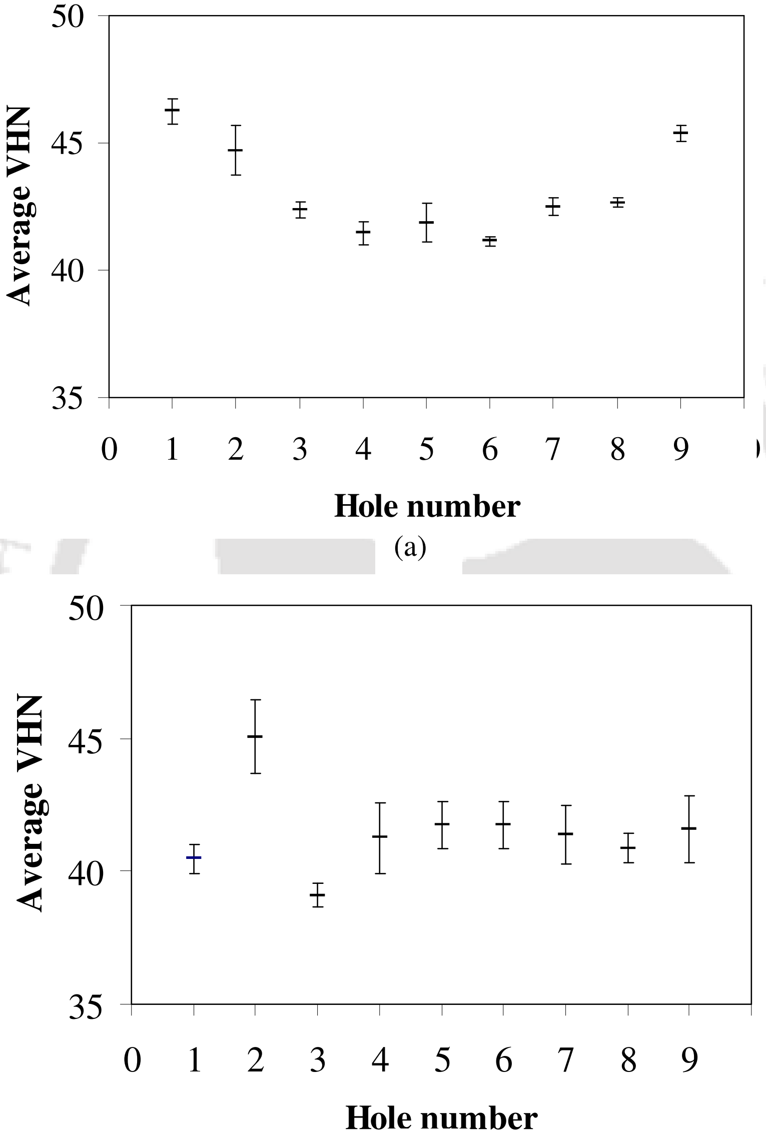


Figure 4.22. The hardness value (mean± standard deviation) for lead products from peripheral holes of lubricated dies with 3 mm die land length

4.9 Micro Hardness of Extruded Aluminum Products

The multi-hole extrusion of aluminium was carried out with a die having 9 holes of 3 mm diameter each using MoS_2 (Molykote, GmbH, Germany) as lubricant. Two dies one with die land lengths of 10 mm and another with die land lengths of 15 mm were fabricated.

The average micro hardness values of the extruded products obtained from 15 and 10 mm die land lengths dies are shown in Figures 4.23 (a) and 4.23 (b) respectively.



(a)

(b)

Figure 4.23. Micro hardness value (mean± standard deviation) of the extruded aluminum from the lubricated 9-hole die (hole number 9 is the centre hole) (a) 15 mm die land length (b) 10 mm die land length

In case of multi-hole extrusion of aluminium with die having 15 mm die land length, the maximum and minimum hardness value of the extruded products are found to be 46.25 and 41.15 VHN respectively. For the die with 10 mm die land length, the maximum and minimum hardness values of the extruded products are found to be 45.05 and 39.5 VHN respectively. Average hardness values of the extruded products coming out from the dies with 15 mm die land length is 43.13 VHN, which is about 5% higher than the average hardness value of 41.32 VHN of the extruded products coming out from the dies with 10 mm die land length. A hypothesis testing using Student's *t*-test showed that the process has good repeatability at 95% confidence level [Appendix C].

4.10 Surface Roughness of Extruded Lead Products

From the past research work it was found that several process parameters like extrusion ratio, extrusion speed, type of lubrication etc. affect the surface quality of the extruded products. However, for multi-hole extrusion, the extruded products coming out from different holes located at different pitch circle diameter of the die experience the process parameters differently. This affects the surface quality of the products. Surface roughness of the extruded products is measured using the surface roughness measuring instrument (Pocket Surf). The centre line average value (CLA) surface roughness value (R_a) is measured for three replicates. The surface roughness was measured along the length of the product. In each replicate, the measurement was taken at 4-5 points. The combined data of all measurements was used to make inference about average quality attribute along with the standard error in the estimate. Tables 4.9 and 4.10 show the surface roughness values of the extruded products of lead. Lubricated dies always produce better surface quality i.e., low roughness value.

The products coming out from centre hole of dies with 3 mm die land length have lower surface roughness value in lubricated condition. It is interesting to observe that extrusion ratio is also a parameter, which affects the surface roughness of an extruded product. From Table 4.9 it can be seen that for unlubricated die with 10 mm die land length, there is about 50% difference in roughness value for high and low extrusion ratio. For unlubricated die with 3 mm die land length, there is about 30% difference in roughness value for high and low extrusion ratio.

Table 4.9. Average surface roughness value of the extruded products from the centre holes of multi-hole dies with different extrusion ratio. (The values in bracket are standard errors)

Extrusion ratio	Surface roughness, R_a (μm)			
	No lubrication		Lubrication	
	10 mm die land length	3 mm die land length	10 mm die land length	3 mm die land length
35.55	0.608 (0.085)	0.501 (0.045)	0.5 (0.045)	0.35 (0.05)
19.75	0.396 (0.027)	0.465 (0.04)	0.403 (0.118)	0.385 (0.06)
13.67	0.405 (0.054)	0.371 (0.076)	0.371 (0.067)	0.346 (0.089)

Table 4.10. Average surface roughness value of the extruded products from the peripheral holes of multi-hole dies with different extrusion ratio. (The values in bracket are standard errors)

Extrusion ratio	Surface roughness, Ra (μm)			
	No lubrication		Lubrication	
	10 mm die land length	3 mm die land length	10 mm die land length	3 mm die land length
35.55	0.521 (0.086)	0.378 (0.017)	0.488 (0.063)	0.352 (0.062)
19.75	0.522 (0.086)	0.318 (0.097)	0.402 (0.061)	0.333 (0.055)
13.67 (Inner PCD)	0.434 (0.011)	0.373 (0.063)	0.4 (0.065)	0.365 (0.080)
13.67 (Outer PCD)	0.443 (0.08)	0.423 (0.049)	0.391 (0.05)	0.348 (0.071)

For the extruded products of the peripheral holes, with lubricated dies having 3 mm die land length, the effect of extrusion ratio is also quite significant (Table 4.10). It seems that increase in plastic deformation, increases the surface roughness of the extrudate. Mahadevan (2006) has observed the similar behaviour in axisymmetric cold forging process, where the surface roughness increased with increase in compression.

4.11 Surface Roughness of Extruded Aluminum Products

The effect of die land length and lubrication on the surface roughness of the extruded products of aluminium is studied and the average roughness values are reported in Table 4. The extruded products coming out from the holes of 9-hole die show variation in average surface roughness. With smaller die land lengths, *i.e.*, 10 mm, the difference between the maximum and minimum roughness value is about 60%. For the die with 15 mm die land length, the difference between the maximum and minimum roughness value is about 30%. But on an average, the lower roughness value is observed for the extruded products coming out from the die with 10 mm die land length. Variation in the surface roughness of extrudates coming out from different holes is due to variation in flow pattern and lubrication.

Table 4.11. Average surface roughness of the extruded aluminum from lubricated 9-hole dies with different die land length

Hole No.	15 mm die land length		10 mm die land length	
	Average roughness (μm)	Std. error in roughness (μm)	Average roughness (μm)	Std. error in roughness (μm)
1	0.35	0.02	0.3	0
2	0.355	0.015	0.255	0.015
3	0.29	0.02	0.345	0.015
4	0.345	0.025	0.32	0.02
5	0.345	0.015	0.26	0.01
6	0.36	0.02	0.315	0.015
7	0.28	0.01	0.305	0.015
8	0.345	0.025	0.415	0.015
9 (center)	0.32	0.02	0.365	0.015

The process parameters like extrusion ratio, die land length, the location of holes in the die and lubrication affect the surface roughness of the extruded products. Selection of the dominating parameter(s) and/or their combination must be done properly in order to obtain the best surface finish.

4.12 Effect of Die Pockets in Multi-hole Extrusion Process

The quality and accuracy of the extruded products in the multi-hole extrusion process depend on many factors such as extrusion ratio, die land length, lubrication, location of the holes and metal flow pattern in the multi-hole die. Die pockets design is an important process parameter which has been studied by many researchers to obtain balanced flow of metal during extrusion. Pocket volume, stepped pocket and eccentricity of pocket have also been investigated. In the present work, the die pockets are produced on the holes of multi-hole dies to study their effect on extrusion load, length of the extruded products and bending of the extruded product. The details of multi-hole dies fabricated to carry out experiments are explained in Section 3.6, Chapter 3. The extrusion load, bending of the extruded products and variation in extruded product lengths are discussed here.

4.12.1 Comparison of Extrusion Load Obtained from Experiments for Dies without and with Die Pockets

Due to the different number of holes on die, the location of holes and pocket geometry, the variation in extrusion load is observed as shown in Table 4.12. The extrusion load is found to be less when the peripheral holes are located nearer to the centre. The holes away from the centre experience higher effective extrusion ratio, due to which the extrusion load increases. This is observed experimentally as well as in FEM simulations that will be discussed in Chapter 5. The least extrusion load is observed for the die pocket depth of 2 mm. Die pocket depths of 3 and 4 mm provide an increased load compared to pocket depth of 2 mm. This may be due to the increase in dead zone height in die pocket.

For a particular die design, the optimum die pocket depth helps in reducing the extrusion load. Similar observations also can be seen with the results obtained from finite element modelling explained by Li *et al.* [2003]. For a particular profile width, there exits an optimum pocket width beyond which the effect of pocket on metal flow control is ineffective. The die pocket depth can be considered as an important parameter to reduce the extrusion load. The pocket design in the aspect of pocket depth, pocket width and pocket angle can produce an optimum extrusion load along with quality product in multi-hole extrusion process.

Table 4.12. Comparison of extrusion load

Die pocket depth (mm)	Extrusion load (kN)			
	Die IV	Die V	Die VI	Die VII
0	108	116	102	106
2	103	107	100	104
3	106	112	104	108
4	110	114	107	110

4.12.2 Bending of the Extruded Products from the Dies without and with Die Pockets

The different process parameters and their effect on the bending of the extruded products are not known exactly. In this investigation, the cross section of the extruded product is solid and circular. Radii of curvature of the extruded products are calculated for the extruded products obtained from experiments. The bending of the extruded products is also observed in simulations. However, simulation assumes a homogeneous material and perfectly co-axial movement of the punch, which may not be possible in actual practice. Table 4.13 shows the radii of curvature of the extruded products coming out from the centre hole of the different dies obtained from experiments.

The dies with high pocket depth produce more bent products. The proper guiding of the extruded parts is found to be more important than making metal flow easy in multi-hole extrusion in order to minimize bending. In this regard, die land length is the important parameter. As the pocket depth increases, the die land decreases in the present work. The reduced die land length is the main factor for the decrease of the curvature.

Table 4.13. The radii of curvature of the extruded products coming from centre hole (Values in bracket are standard deviations)

Die pocket depth (mm)	Radius of curvature (mm)			
	Die IV	Die V	Die VI	Die VII
0	29.4 (2.35)	31.43 (1.37)	28.84 (1.09)	31.13 (1.2)
2	23.87 (1.24)	27.13 (1.23)	25.52 (1.69)	30.82 (1.28)
3	21.95 (1.24)	24.35 (1.52)	25.5 (1.83)	27.98 (1.21)
4	21.16 (2.29)	22.46 (1.68)	22.46 (1.70)	25.6 (1.81)

Table 4.14. The radius of curvature of the extruded products coming from peripheral hole (Values in bracket are standard deviations)

Die pocket depth (mm)	Radius of curvature (mm)			
	Die IV	Die V	Die VI	Die VII
0	29.75 (2.97)	41.73 (2.54)	27.94 (2.1)	34.7 (0.92)
2	27.8 (1.49)	37.65 (1.38)	25.41 (1.85)	33.61 (1.04)
3	27.5 (1.28)	36.46 (2.11)	25.49 (1.82)	24.65 (1.37)
4	23.5 (1.78)	26.49 (1.89)	25.05 (2.28)	24.3 (2.26)

Table 4.14 shows the average radius of curvature values of the extruded products coming out from the peripheral holes of different dies. It is clear that the die having no die pockets produces less bent products as compared to the dies with different pocket depth. As the flow of metal is not uniform with multi-hole extrusion, it is difficult to achieve an optimal pocket design in order to reduce the bending of the extruded products. The die land lengths get reduced when pockets are made. To minimize the bending, more attention is needed on die land length than the pocket design. The location of the holes must be taken care of as the exiting profiles coming out from the holes located near the centre influence each other and more bending and/or distortion occurs. This has been observed from the experiments as well as FEM simulations that will be described in next chapter.

4.12.3 Variation in Length of the Extruded Products from the Dies without and with Die Pockets.

The extruded products lengths obtained from experiments are measured and the variation among them is studied. The coefficient of variation for length of the product is calculated using the following formula,

$$\text{Coefficient of variation} = \frac{s}{\bar{x}} \times 100\% \qquad (4.2)$$

where s is standard deviation and $\bar{x}$ is average value.

It is observed that increase in die pocket depth helps in balancing the non-uniform metal flow and as a result, lesser variation in the length of the extruded products is observed as shown in Figure 4.24. With higher die pocket depth, less difference in length of the extruded products from both centre and peripheral holes is observed. The die pocket geometry must be selected properly to obtain less variation in lengths of the extruded product.

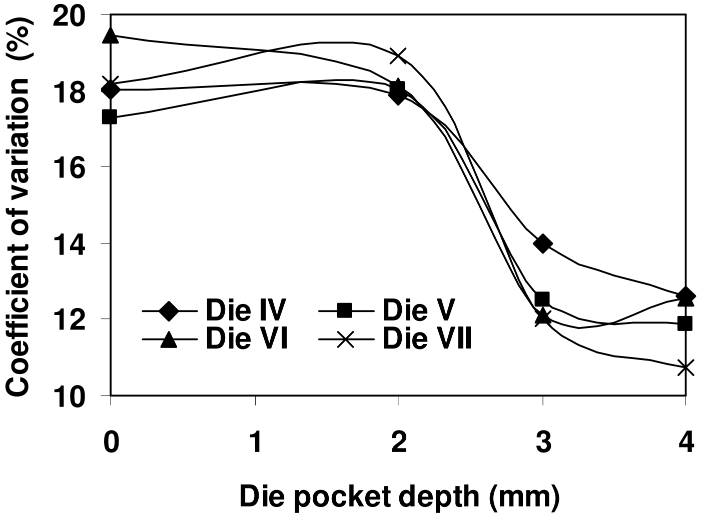


Figure 4.24. Coefficient of variation of the extruded product length

4.13 Conclusion

In this work, the effects of extrusion ratio, lubrication, die land length, vibration and die pockets in a multi-hole extrusion process are studied experimentally. The following conclusions are drawn:

- The ram forces for different types of dies are experimentally found out. As expected, larger billet length requires higher extrusion force for both lubricated and unlubricated dies. The reduction in die land length helps in reducing the total load during extrusion process. Friction between die container and billet plays an important role in increasing the ram force during extrusion.
- With imposed vibration, considerable amount of decrease in ram force is observed. The application of vibration may eliminate the necessity of lubrication, thus helping in achieving green manufacturing.
- The radii of curvature of the extruded products of different lubricated and unlubricated dies for different billet length are studied for different ram speeds. The peripheral holes produce less curved extruded products compared to the centre hole in the multi-hole die extrusion.
- The unlubricated dies produce less curved products as compared to lubricated ones. The higher die land length guides the extruded products to get less curved when extruded through lubricated and unlubricated dies. The vibration also helps to produce less curved products.
- It is observed that higher die land length produces products of better strength as compared to smaller die land length.
- For extrusion of lead with the dies having 10 mm die land length, the micro hardness value of the extruded products coming out from the centre hole is found to increase with increase in extrusion ratio. However, much variation in hardness is not observed with the extruded products coming out from 3 mm die land length dies as compared to 10 mm die land length dies.
- Extrusion ratio is found to be insignificant for causing the variation in micro hardness of the extruded lead products coming out from dies having 3 mm die land length. In the extrusion of aluminum, about 5% increase in average

hardness is observed with the extruded products coming out from die with 15 mm die land length as compared to die with 10 mm die land length.

- For lead extrusion, extrusion ratio, die land length and lubrication are found to be significant factors for surface roughness. For aluminium, high die land length produces high roughness.
- Die pockets are also important process parameter in reducing extrusion load. Die pockets help in balanced material flow, which helps in producing more uniform length of the extruded products. In the multi-hole extrusion process it is observed that for a given extrusion ratio, the least extrusion load is observed with the die having die pocket depth of 2 mm. Increase in die pockets depth produces more bent products due to reduction in die land. However, the variation in length of the extruded products can be minimized by using die pockets.

Chapter 5

Results of Finite Element Simulations of Multi-hole Extrusion process

5.1 Introduction

It has been widely accepted that finite element method (FEM) is a powerful numerical tool for design and analysis of metal forming processes. Simulations of manufacturing processes reduce the need of costly shop floor trials and redesign of tooling and accessories. Finite element methods for simulations of metal forming processes are classified into elastic-plastic and rigid plastic simulations. In the elastic-plastic simulation, material is modelled as elastic-plastically deforming. Rigid plastic simulation assumes material to deform only plastically. In comparison to elastic-plastic simulations, it takes shorter computational time. In the present work finite element simulations have been carried out using DEFORM–3D® (Version 10.1) developed by Scientific Forming Technologies Corporation (SFTC). DEFORM is a finite element method (FEM) based simulation software designed for various forming processes. It is used by metal forming industries and research organizations. DEFORM–3D® is capable of modelling complex three dimensional material flow patterns and ideal for those processes that can not be modelled with two dimensional analyses. DEFORM–3D® consists of following three major components:

(i) Pre-processor: It creates the part geometry, assembles the part geometries, generates mesh, inputs the material data and processes the data required to analyse the simulation for generating the required database file.

(ii) Simulation engine: It performs the numerical calculations required to analyze the process and writing the results to the database file. It performs the actual simulation calculations. It is the main processor.

(iii) Post processor: It reads the database file from the simulation engine and displays the results graphically, extracts the numerical data and derivative quantities like stresses.

5.2 Finite Element Simulation of Multi-hole Extrusion Process with 9-hole Die of Different Die Land Lengths

Rigid-plastic finite element DEFORM–3D® software has been used to investigate the deformation behavior and bending of the lead billet during the multi-hole extrusion process. The solid 3D modeling of die, billet, container and punch were made with same dimensions as used for experiments (explained in Chapter 3, Section 3.2).

The 3D models of the container with die, punch and billet material were modeled in NX 3 Unigraphics®, advanced CAD/CAM/CAE software developed by Siemens PLM Software. The stereolithography (STL) files of the models were transferred to finite element program DEFORM to establish the finite element mesh. The STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes. The following assumptions were made for the analysis. The container and dies were considered as rigid bodies. The lead billet was considered as a rigid plastic material. DEFORM provides different methods of defining the flow stress. For the present simulations, the power law has been used which can be defined as:

$$\bar{\sigma} = K\bar{\varepsilon}^{n}, \tag{5.1}$$

where $\bar{\sigma}$ is the flow stress of the material, K is the material constant, $\bar{\varepsilon}$ is the effective plastic strain and n is the strain exponent. The compression test of the lead specimen was carried out in a universal testing machine to find out stress-strain relationship. From the compression test, the following values are obtained and used for the present simulations, material constant, K is 54.59 MPa, strain exponent, n is 0.23. Friction factor m is taken 0.3 at all the interfaces. To determine the friction factor the method followed is explained as follows. Extrusion experiments are carried out with two billets of different lengths. Then the friction factor, m is calculated as [Bakhshi-Jooybari, 2002]

$$m = \frac{\sqrt{3}\Delta F}{\pi \bar{\sigma} d_o \Delta L_C}, \tag{5.2}$$

where m is friction factor, $\bar{\sigma}$ is the normal flow stress of the billet material, d_o is internal diameter of the container, ΔF is the difference in punch load and ΔL_c is difference in billet length.

The billet material follows von Mises yield criteria and strain hardening is assumed to be isotropic. Tetrahedral mesh with 19948 elements and 4138 nodes is used to uniformly discretize the billet material. Although the setting of mesh density at the deformation zone can be altered according to the strain and strain rate distribution, in the present work uniform mesh density is considered for simplicity. A constant incremental punch displacement of 0.3 mm is imposed during the simulation process. Punch speed of 1.5 and 1.8 mm/min are considered for 20 and 30 mm billet length respectively. Stopping criteria is selected as 10 mm of ram traverse.

5.2.1 Comparison of Extrusion Load Obtained from Experiments and Finite Element Simulations for 9-hole die with Different Die Land Length

Finite element simulation of the multi-hole extrusion with nine-hole die was carried out. The maximum extrusion loads obtained from the simulations are compared with the experimental data. The comparative results of extrusion load are shown in Table 5.1 and Table 5.2 for extrusion of 20 mm and 30 mm length billets respectively.

Table 5.1. Comparison of extrusion load obtained from experiments and FE simulations for 20 mm billet length

Die Type	Extrusion Load (kN)	
	Experiment	FE Simulation
Die I (10 mm die land)	112.65	125
Die II (10/6.5 mm die land)	109.55	119
Die III(10/3 mm die land)	111.55	113
Die with no die land length	–	110

Table 5.2. Comparison of extrusion load obtained from experiments and FE simulations for 30 mm billet length

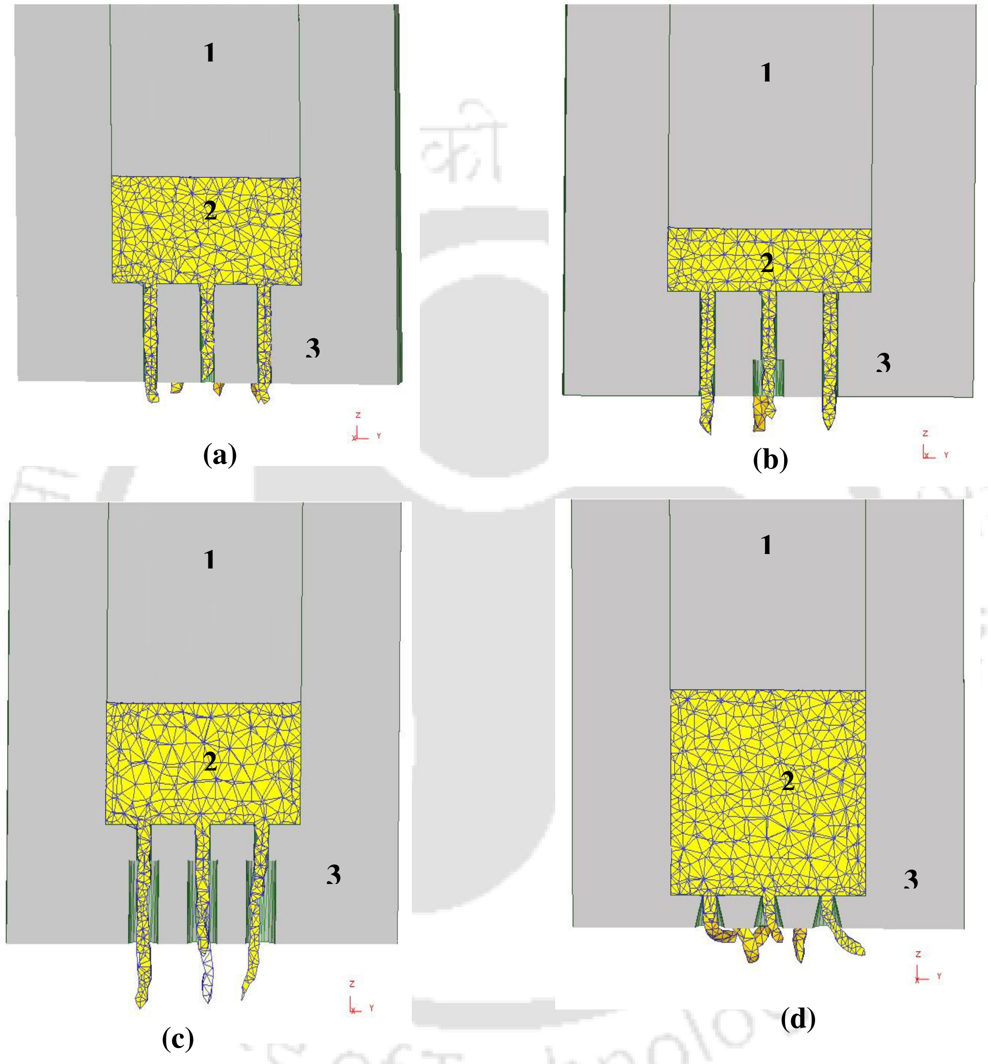
Die Type	Extrusion Load (kN)	
	Experiment	FE Simulation
Die I (10 mm die land)	125.45	131
Die II (10/6.5 mm die land)	118.55	126
Die III (10/3 mm die land)	113.85	121
Die with no die land length	–	112

There is a good agreement between the experimental and simulation results for 20 and 30 mm billet extrusion. The minimum extrusion load is observed with the dies having no die land length and maximum extrusion load with the dies having 10 mm die land length (Die I). Extrusion load increases with increase in die land length and billet length for same extrusion ratio. (There is an exception in Table 5.1. Here, the experimental load for Die III is more than that of Die II, although the difference is small and may be attributed to uncontrollable experimental errors.) From simulations, it can be observed that the extrusion load reduces by 15% when the die land length reduces from 10 mm to zero for 30 mm billet length extrusion. The extrusion load reduces by 12% when the die land length reduces from 10 mm to zero for 20 mm billet length extrusion.

5.2.2 Finite Element Simulations on Bending of Extruded Products of 9-hole die

Radius of curvature of the extruded product has been studied using finite element simulations. Rigid-plastic finite element DEFORM- 3D software has been used to investigate the deformation behavior of the lead billet during the multi-hole extrusion process. Figure 5.1 shows the extruded products with different bend profile during the extrusion process. Maximum bending of the extruded product is observed with the products coming out from the die without die land length. The least bent product is observed with the die of the largest die land length i.e. 10 mm. The experimental radius of curvature of the extruded products obtained from experiments with Die I, Die II and Die III has been discussed in Sections 4.4 and 4.5 (Chapter 4).

A good qualitative agreement between the experiments and simulations is observed. Higher extrusion load due to high die land length can be compromised for the better quality of the extruded products.



(a) (b) (c) (d)

1: Punch, 2: Deformable workpiece and 3: Die

Figure 5.1. Finite element simulation: extruded products from (a) Die I (b) Die II (c) Die III and (d) 9-hole die without die land.

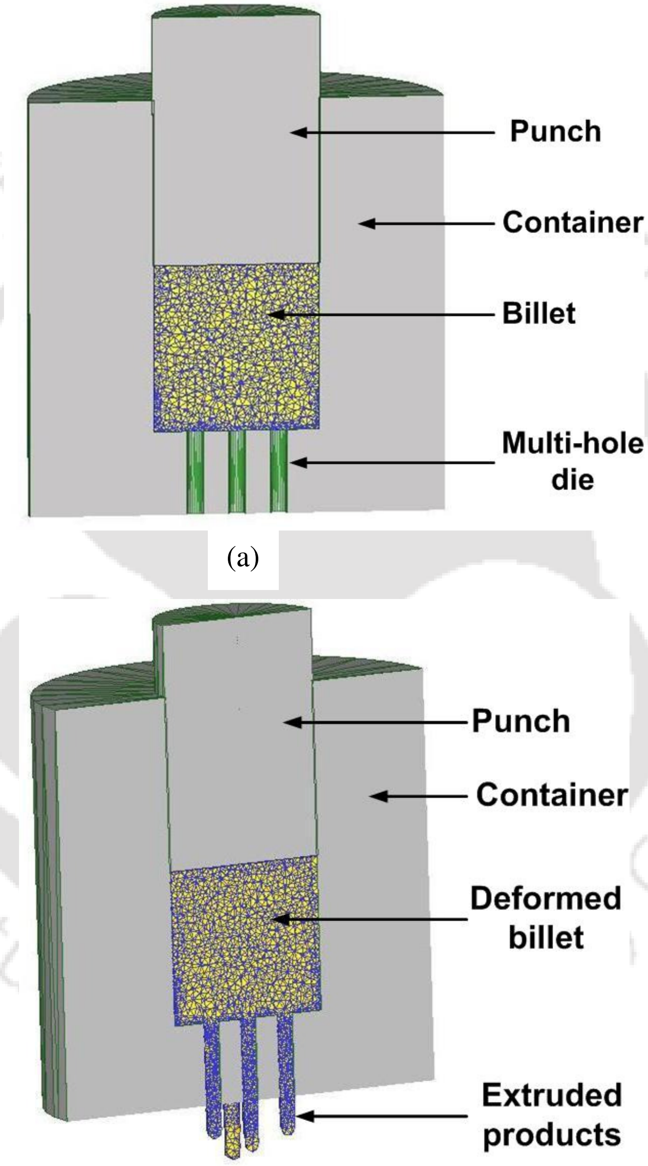
5.3 Finite Element Simulations on Effect of Die Pockets in Multi-hole Extrusion Process

The quality and accuracy of the extruded products in the multi-hole extrusion process depend on many factors such as extrusion ratio, die land length, lubrication, location of the holes and metal flow pattern in the multi-hole die. The requirement of pockets in extrusion process was found to be important in continuous extrusion process to have billet-to-billet welding. The pocket retains the metal from previous billet and then gets welded to the front of the new following billet. The different pocket design parameters are pocket entry angle, pocket volume, geometry of the pocket and offset of the pocket. Here, the effect of the die pockets in multi-hole extrusion process has been studied. Finite element simulations using DEFORM-3D is carried out to obtain the extrusion load and effective strain distribution. The simulation results of extrusion loads are compared with experiments.

The dies were modelled in NX 3 Unigraphics® and STL file of the models were transferred to DEFORM-3D geometric modelling pre-processor. The dimensions of the container with die, punch and billet were kept same for modelling as for experiments. Details of the dies are explained in Section 3.6 (Chapter 3). For the present study, the compression test of the lead billet is carried out and the material constants are calculated. From the compression test, the following values are obtained and used for the simulations. The material constant, K is 53.46 MPa and strain exponent n is 0.21. Friction factor m is taken 0.3 at all the interfaces. Tetrahedral mesh with 18000 elements is used to uniformly discretize the billet material. A constant incremental punch displacement of 0.3 mm and a total displacement of 10 mm are imposed during the simulation process. Figure 5.2 shows the finite element mesh before and after extrusion for Die IV.

5.3.1 Comparison of Extrusion Load Obtained from Experiments and Finite Element Simulations for Dies without and with Die Pockets

Comparison of extrusion load obtained from experiments and simulations are given in Table 5.3. Due to the different number of holes on die, the location of holes and pocket geometry, the variation in extrusion load is observed. The extrusion load is found to be less when the peripheral holes are located nearer to the centre. The holes away from the centre experience higher effective extrusion ratio, due to which the extrusion load increases.



(a)

(b)

Figure 5.2. Finite element mesh (a) before extrusion (b) after extrusion for Die IV

A good agreement between the extrusion load obtained from experiments and simulations is observed. The least extrusion load is observed for the die pocket depth of 2 mm. Die pocket depths of 3 and 4 mm provide an increased load compared to pocket depth of 2 mm, although the die land length reduces with increase in pocket depth in the present design. This may be due to the increase in dead zone height in die pocket. For a particular die design, the optimum die pocket depth helps in reducing the extrusion load. Similar observations also can be seen with the results obtained from finite element modelling explained by Li *et al.* [2003] for single hole extrusion. For a particular cross-section of extruded profile, there exits an optimum pocket width beyond which the effect of pocket on metal flow control is ineffective.

Table 5.3. A comparison of extrusion load

Die pocket height (mm)	Extrusion load (kN)							
	Die IV		Die V		Die VI		Die VII	
	Experiment	FEM	Experiment	FEM	Experiment	FEM	Experiment	FEM
0	108	118	116	125	102	111	106	115
2	103	106	107	112	100	106	104	106
3	106	108	112	117	104	108	108	110
4	110	112	114	118	107	109	110	112

The die pocket depth can be considered as an important parameter to reduce the extrusion load. The pocket design in the aspect of pocket depth, pocket width and pocket angle can produce an optimum extrusion load along with quality product in multi-hole extrusion process.

5.3.2 Effective Strain

Study of the effective or von Mises strain and its evolution during extrusion process provides the in depth information about the work hardening behavior or the extent of deformation of the deformable billet material. More the effective strain, the more is the deformation. In the present study, the effective strains of the extruded products are obtained from the finite element simulations. As an example, a typical effective strain distribution on the billet and extruded part during multi-hole extrusion through Die II is shown in Figure 5.3. Effective strain is found to be more at the entry to the die land region. Surprisingly, FE simulation shows decrease in the effective strain in the extrudates along the flow direction! The effective strain should not be decreasing in a rigid plastic model.

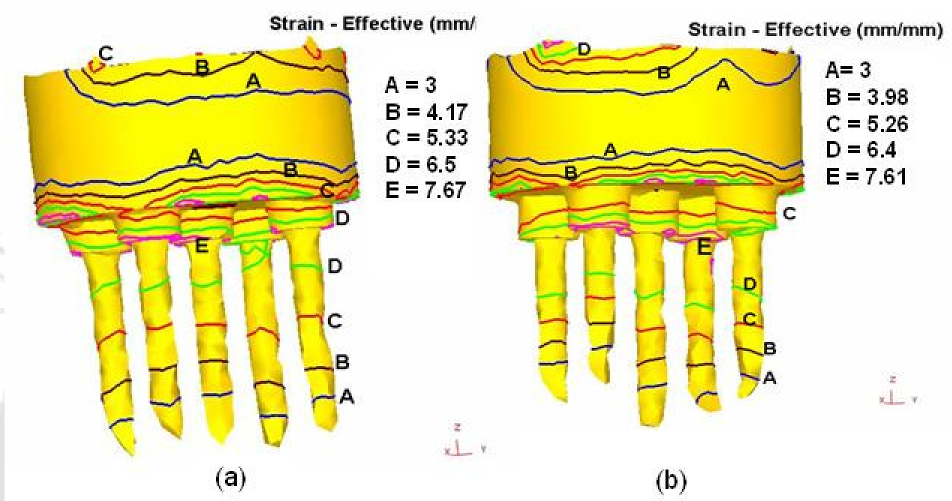


Figure 5.3. Effective strain distribution for Die V with die pocket depth of (a) 2 mm (b) 3 mm

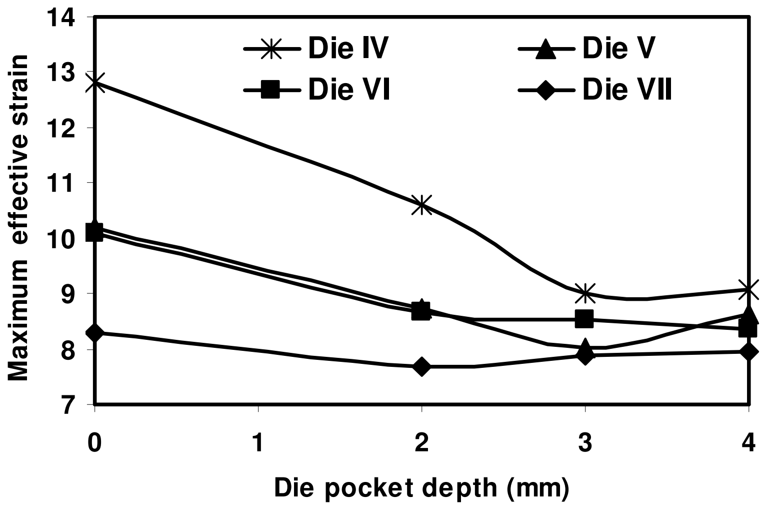


Figure 5.4. The maximum effective strain obtained during extrusion with dies of different die pocket depth.

The maximum effective strain produced during the extrusion process has been shown in Figure 5.4. It is observed that for Die IV and Die VI (having peripherals hole nearer to the centre), the maximum effective strain values decrease with increase in die pocket depth. There is a slight difference in this pattern for Die IV and Die V. It is inferred that the pocket design should be based on the location of holes in order to obtain the uniform flow of the material.

5.4 Conclusion

Finite element simulation of multi-hole extrusion process was carried out. The extrusion loads obtained from experiments are in good agreement with the simulation results. The effect of die land length on extrusion load is also significant in reducing extrusion load. Die pockets are found to be important process parameter in reducing extrusion load. For a given extrusion ratio, the least extrusion load is observed with the die having die pocket depth of 2 mm. The same was obtained in experimental study. The effective strains are maximum at the entry of the die land region and tend to decrease with increase in the pocket depth. In general, die pockets increase the curvature of extruded products due to reduction in die land. However, the variation in length of the extruded products can be minimized by using die pockets. There is a good qualitative agreement between the experimental and simulation results.

Chapter 6

An Experimental Study on a Constrained Multi-hole Extrusion Process

6.1 Introduction

Demand for extruded products having high accuracy and quality has increased considerably in the recent past. The focus of the extrusion studies has shifted from the extrusion load to product quality. One important quality attribute is maintaining the straightness or the desired curvature of the extruded products. Several researchers have studied the process of bending of the extruded products with a motivation to have a control on the bending. Experimental studies on cold extrusion of aluminum and lead alloys prove the effect of extrusion ratio, die angle and extrusion speed on the quality of the extruded products. The complexity in metal flow in the plastic region increases with the increase in die aperture offset. The proper die aperture offset causes the uniform velocity of metal flow, which also effectively controls the bending of the extruded products.

Recently, several researchers have investigated the bending of extrudates in multi-hole extrusion process. Controlled velocity of extrusion, temperature at the die bearing exit and metal flow were the main focus in research to improve the quality of the extruded products. Although the proper die design, particularly the die pocket design can help to control the bending of extrudates, it requires a thorough theoretical and/or experimental understanding of the process, which is not an easy task. Moreover, the design of pocket is highly sensitive to materials to be extruded and process conditions. Thus, there is a need for a robust method of producing straight products.

Near net shape is an innovative concept in industrial manufacturing. The main focus of this technology is to produce parts, as near as possible, close to the final shape and contour, implementing non-chipping techniques. In this way, manufacturing gives the possibility to obtain a final product with minimal cutting. Near net shape technology also generates the opportunity to reduce the productive steps for a given process and low cost of production. Forging processes have gained a wide area of research in producing near net shape products. Production of gears, splines and other such kind of products has been studied by both experiments and finite element simulations. Along with the good shape and quality, improving productivity is also important. Among the different processes, multi-hole extrusion process is an option to improve productivity.

It was found to be more interesting to have a kind of multi-hole extrusion set up to produce the product of equal length with minimum or no bending. Here, a constrained multi-hole extrusion process has been proposed for getting equal lengths of the extruded products without bending. A number of experiments have been carried out to assess the suitability of the constrained multi-hole extrusion process. Mechanical properties such as tensile strength and micro-hardness of the extruded products obtained through constrained and free extrusion are also studied. It is found that the constrained extrusion process produces better quality product than the free extrusion.

6.2 Concept of Constrained Extrusion Process

In the conventional direct extrusion, the material moves freely after exiting from the die. Such type of extrusion can be called free extrusion and is prone to produce bending of the extruded products. In order to avoid the bending, the material can be guided in a hole, which in effect increases the die land. However, in multi-hole extrusion, there is a need to guide the material in a blind hole instead of in a through hole to control the length of the extruded products. Guiding of the extruded products in the blind holes not only controls their lengths, but also improves their mechanical properties due to application of a forging type compressive load.

In the proposed constrained multi-hole extrusion, the extrusion load is expected to be considerably greater than the extrusion load for free extrusion, but compared to a single-hole free extrusion, the increased load may not be very high. On the other hand, the quality of extruded products in terms of its curvature and mechanical properties is much better compared to free single or multi-hole extrusion processes. As the extruded products are guided in blind holes, the length of the extruded products does not have any significant effect on the bending and mechanical properties.

6.3 Experimenrtal Procedure

Figure 6.1 shows the experimental setup. A 100 kN capacity universal testing machine (Make: Instron, Model: 8801) was used as an extrusion press. The specifications of this machine are provided in Appendix A. The container, die, punch and fixture were made of die steel (H13). The 5-hole and 9-hole dies with hole diameter of 2 mm were used. Figure 6.2 shows the top and front view of die & fixture assembly of the constrained multi-hole extrusion set up. In the fixture the blind holes constrain the free flow of the extrudates from the die exit. Commercially available lead alloy was used to prepare billets of 20 mm height and 20 mm diameter. This material was chosen due to limitation of the load capacity of the available presses and also satisfies both commercial and technological (rheological and thermomechanical conditions of aluminum alloy and copper, extruded at hot condition) conditions. The compression test of the specimen was carried out in a universal testing machine to find out stress-strain relationship. The following relation is fitted from the stress-strain data obtained,

$$\sigma_y = 53.46(\varepsilon_{eq})^{0.22} , \tag{6.1}$$

where σ_y is the flow stress in MPa and ε_{eq} is the equivalent strain. The Vickers micro-hardness test was carried out on the sample of billet material and the average hardness was found to be 10.2 VHN. The fixture with blind holes allows the extruded materials to go into the blind holes in order to get the equal length of the product. Proper fastening was made to prevent misalignment of the die and fixture during extrusion process. For each extrusion test, the container wall, die, punch and the specimen were first cleaned with ethanol and lubricant was then applied on the die, punch and container.

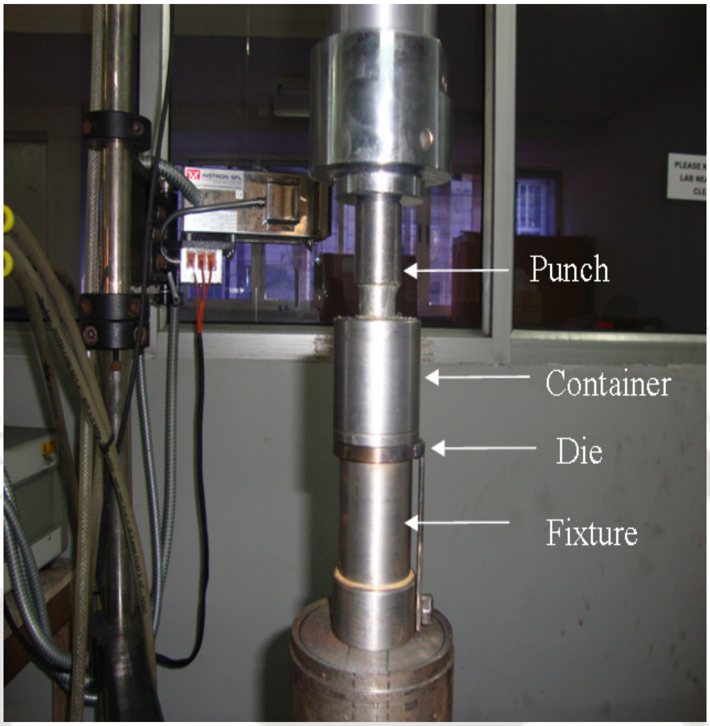


Figure 6.1. Experimental set up photograph of constrained multi-hole extrusion

After each test, the entire set up was removed from the machine and the extruded products were cut carefully for measurement of length. Micro-hardness tests were carried out for extruded products through different holes on 5-hole and 9-hole dies. Three replicate experiments were conducted for each case and the average hardness of the product was recorded. Tensile tests were carried out for the extruded products on micro-tensile tester (Make: DEBEN, Model: MICROTEST, 5 kN capacity). As the dimensions of the extruded products were small, they could not be used directly to find the mechanical properties. The sample preparation was carried out for both tensile and micro-hardness test. Sample preparation procedure has been explained in Section 3.2.2.

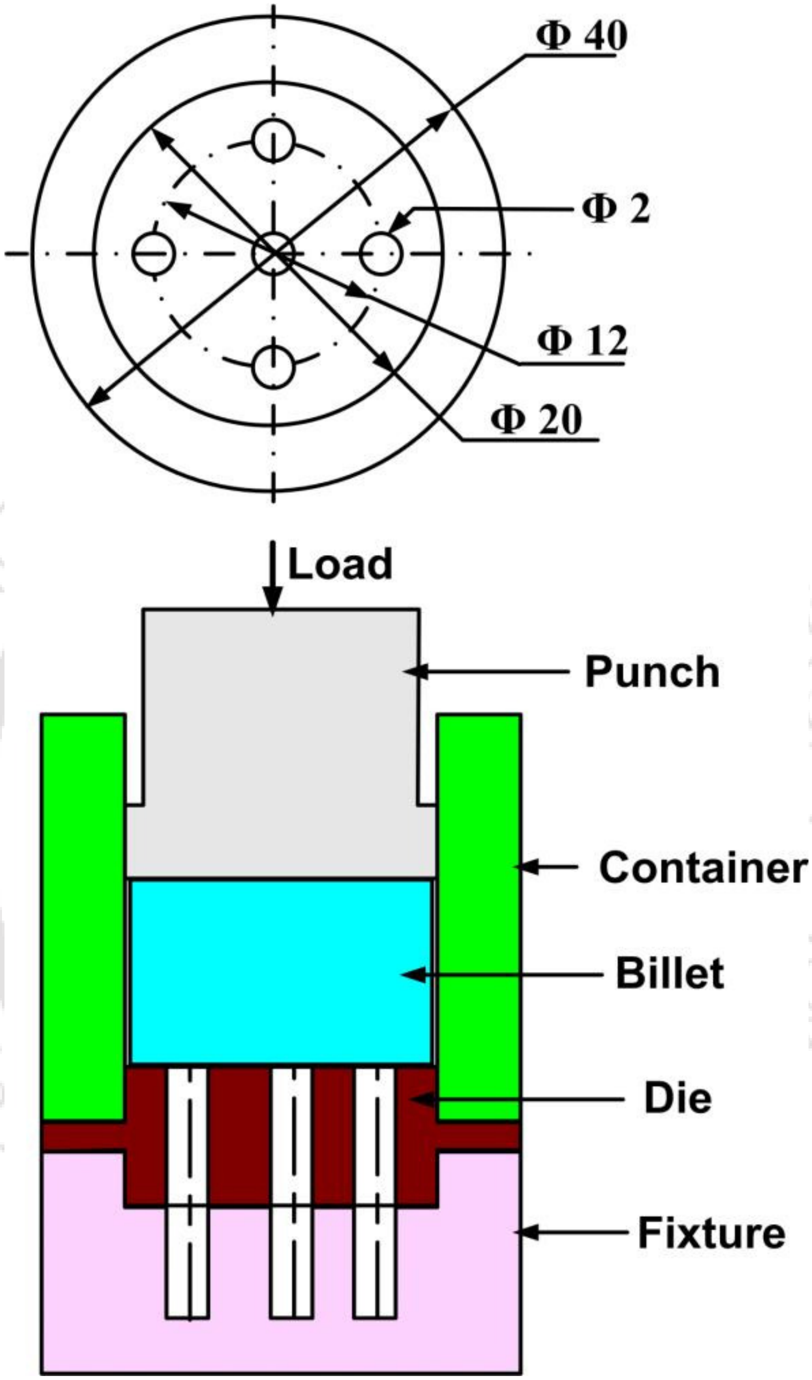


Figure 6.2. Schematic of constrained multi-hole extrusion

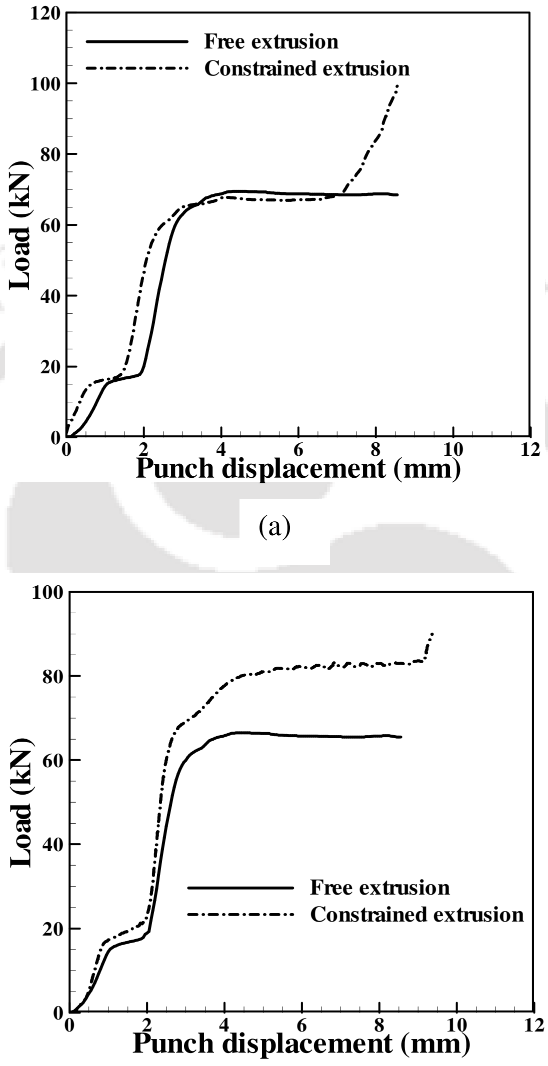
6.4 Results and Discussion

In this section, the results of a comparative study of free and constrained extrusion are reported. Load-displacement curve, extruded lengths, comparison of bending of the extruded products, tensile strength and micro hardness of the extruded products are discussed.

6.4.1. Load–Displacement Curves

The load-displacement curve for free and constrained extrusion with five-hole and nine-hole dies is shown in Figures 6.3 (a) and (b) respectively (In the constrained extrusion cases, the load-displacement curve could not be plotted up to full load due to limitation of the equipment.). Initially there is a continuous increase in load till the material reaches plastic stage, where after the load remains almost constant till the outer surface of the billet touches the inner wall of the container. After this load keeps on increasing till the material does not come out of the holes of the die. In free extrusion, once the extrusion starts, load keeps on reducing slightly due to reduction in the friction between the billet and container.

The constrained extrusion process could be completed in a hydraulic press (Make: Lawrence & Mayo, 2000 kN capacity). In constrained extrusion, once the extrusion through a hole is complete, the load further increases. This is due to the increased effective extrusion ratio. The maximum load for 9-hole die extrusion was found to be 240 kN, which is about four times more than the load required for free extrusion at similar process conditions. For 5-hole die constrained extrusion, maximum load of 180 kN was observed, which is about three times more than the load required for free extrusion. The higher load is the only drawback of constrained multi-hole extrusion process. For comparison, corresponding single-hole extrusion was carried out. The extrusion load was 135 kN, about 44% less than the maximum load of 240 kN obtained in the constrained extrusion with 9-hole die. The 5-hole die constrained extrusion required only about 33% greater maximum load compared to single-hole extrusion. The benefits in the form of improved geometric and mechanical properties offset the disadvantage of some increase in the load. While carrying out the multi-hole extrusion, it is better to make an estimate of the load and set the pressure relief valve setting in the hydraulic press accordingly for the safety of the die, ram and machine.



(a)

(b)

Figure 6.3. Load-displacement curves for free and constrained extrusion for (a) 5-hole (b) 9-hole dies

6.4.2 Length of the Extruded Products from Free Extrusion

In the constrained multi-hole extrusion, there is no variation in the length of the extrudates. In case of free multi-hole extrusion, the variation in the length of the extrudates is observed. The length of the extrudates obtained from different holes located at same pitch diameter and also from the same hole with replicate experiments for 5-hole and 9-hole dies are shown in Tables 6.1 and 6.2.

The coefficient of variation for length of the extrudates is calculated using the following formula:

$$\text{Coefficient of variation} = \frac{s}{\bar{x}} \times 100\% , \tag{6.2}$$

where s is standard deviation and $\bar{x}$ is average value.

Table 6.1. Length of the extruded products in free extrusion with 5-hole die

Sl. No.	Length of extruded products (mm)					Coefficient of variation
	Centre hole	Peripheral holes				
		1	2	3	4	
1	65	73	60	88	77	14.98 %
2	74	80	73	96	80	11.42 %

Table 6.2. Length of the extruded products in free extrusion with 9-hole die

Sl. No.	Length of extruded products (mm)									Coefficient of variation
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	27	47	49	45	50	36	50	45	44	17.35 %
2	25	43	45	41	43	37	45	42	44	15.58 %

The unbalanced material flow causes variations in length of the extruded products. In replicates, the differences in length of the extruded products from the same hole are more for 5-hole die as compared to 9-hole die. More number of holes on same pitch circle of the die provides lesser variation in length of the products as material flows easily through the holes with fewer gaps in between.

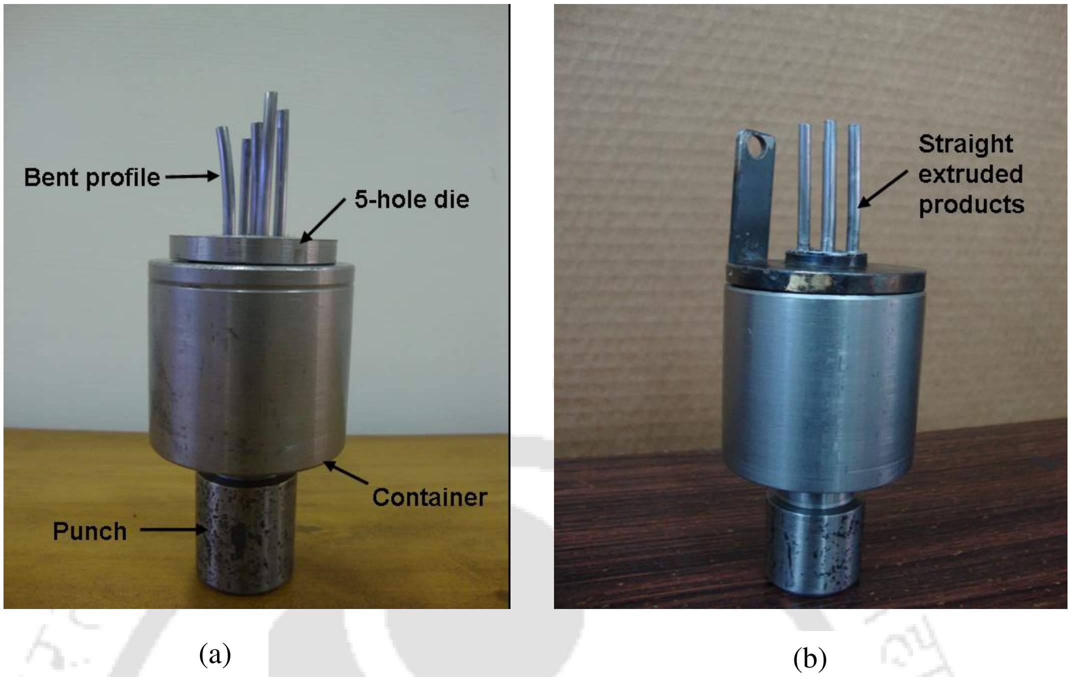


Figure 6.4. Extruded products from 5-hole die (a) free extrusion (b) constrained extrusion

It has been reported earlier by some researchers that the parameters like die pockets, eccentricity and die land length help in reducing the bending of the products [Onuh *et al.*, 2003; Li *et al.*, 2003a and Li *et al.*, 2010]. The proper process and die design is a difficult task. The typical bent products obtained from free extrusion and straight products from constrained extrusion with a 5-hole die are shown in Figures 6.4 (a) and (b) respectively. Extruded products from free and constrained extrusions with 9-hole die are shown in Figure 6.5. Figure 6.5 (a) shows the extruded products coming out from free extrusion. Bending is observed with some extruded products in free extrusion.

During the constrained extrusion process, the extruded products of some holes are controlled to the length of the blind holes and other products flow to fill the subsequent blind holes there after. Figure 6.5 (b) shows the extruded products at some instance of constrained multi-hole extrusion process with a 9-hole die. The variations in the length of the extruded products can be clearly observed. As the extrusion process continues, all the blind holes get filled up. Figure 6.5 (c) shows the extruded products of equal length. It is also observed that side flow of the material takes place after the blind holes are getting filled up. The side flow is due to the improper tolerance in design of fixture and bottom of the die.

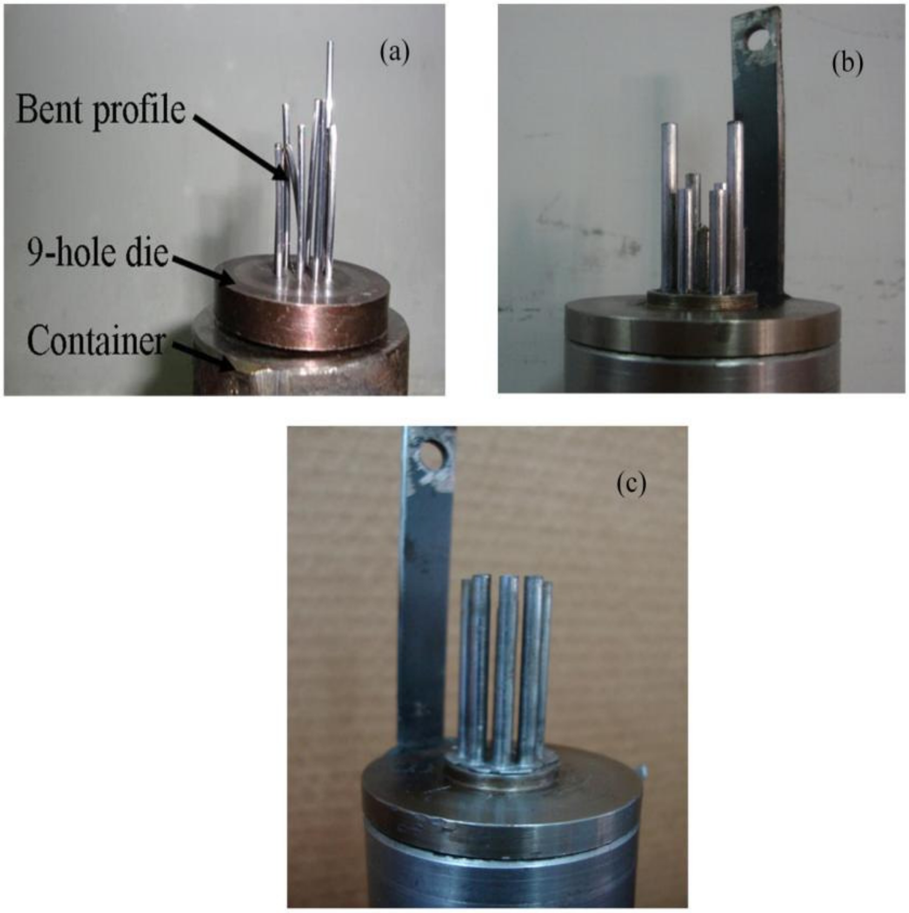


Figure 6.5. Free and constrained extrusion through 9-hole die (a) free extrusion (b) constrained extrusion at some instance (c) at the end of constrained extrusion

A simple calculation of volume constancy gives the required punch displacement. From Equation 6.3 the approximate punch displacement can be calculated.

$$\frac{\pi}{4}D^2L=\frac{\pi}{4}d^2\left(l_1+l_2\right)n, \tag{6.3}$$

where

D = diameter of the container in mm

L = billet length in mm

d = diameter of the extruded product in mm

l_1 = die land length in mm

l_2 = depth of blind hole in mm

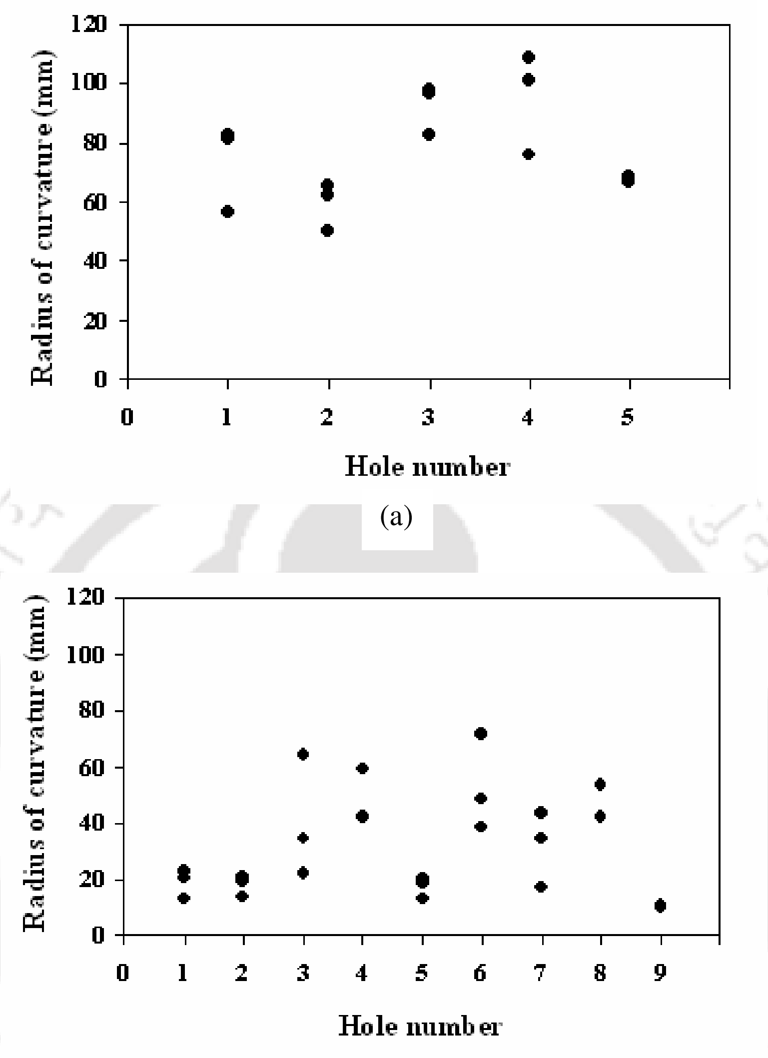
n = number of holes in multi-hole die

Theoretically it is assumed that the punch displacement is equal to the reduction in billet length during extrusion process. But before the extrusion starts, the container and billet gap gets filled up. Therefore, a little higher value of punch displacement is applied during experiments.

6.4.3 Comparison of Bending of the Extruded Products in Free Extrusion

The different radii of curvature were observed with the extruded products coming out from different holes in free extrusion. Moreover, the repeatability in bending pattern is poor with replicate experiments. Thus, it is difficult to get straight product with free extrusion. It is observed from Figures 6.6 (a) and (b) that significant bending occurs in free multi-hole extrusion process. The radius of curvature for the extruded products from 5-hole die is found to be higher than that of 9-hole die.

It has also been observed during the experiment that the extruded products coming out from the holes located nearer to each other in same pitch circle or in different pitch circle obstruct each other during their progression. This causes unnecessary more bending of the extruded products. The surface quality of the extruded products also gets affected. The proposed constrained multi-hole extrusion eliminates the bending of extruded products without optimizing the process parameters.



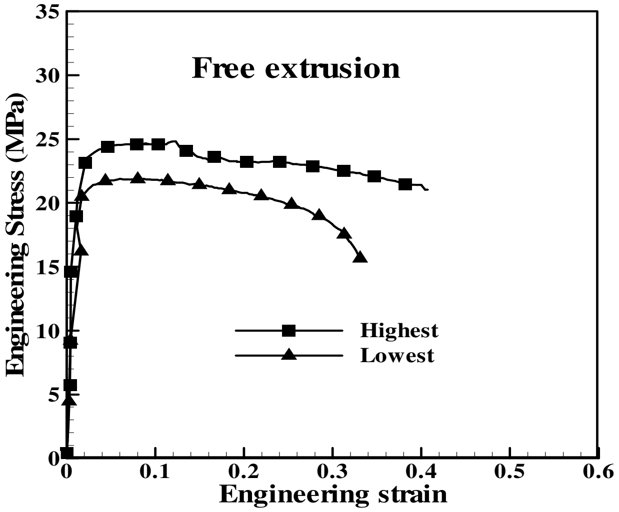
(a)

(b)

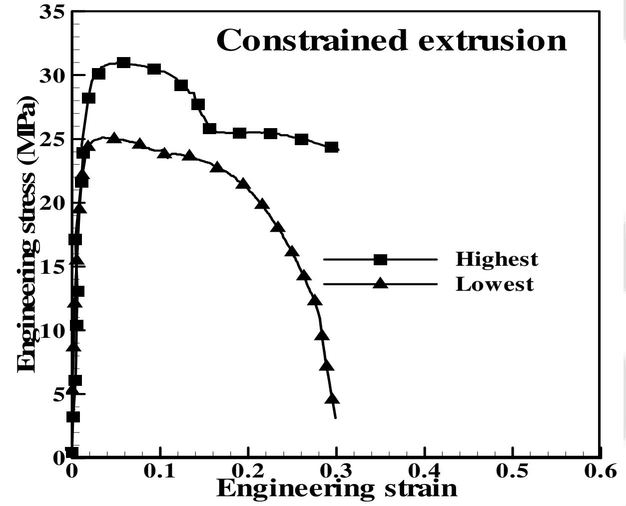
Figure 6.6. Radius of curvature of the extruded products from free extrusion (a) 5-hole die (hole number 5 is the centre hole) (b) 9-hole die (hole number 9 is the centre hole)

6.4.4 Comparison of Tensile Strength of Extruded Products

Tensile tests are carried out for the extruded products obtained from both free and constrained extrusion with 5-hole and 9-hole die and the maximum and minimum engineering stresses (among 3 replicates) are shown in Figures 6.7 and 6.8 respectively.

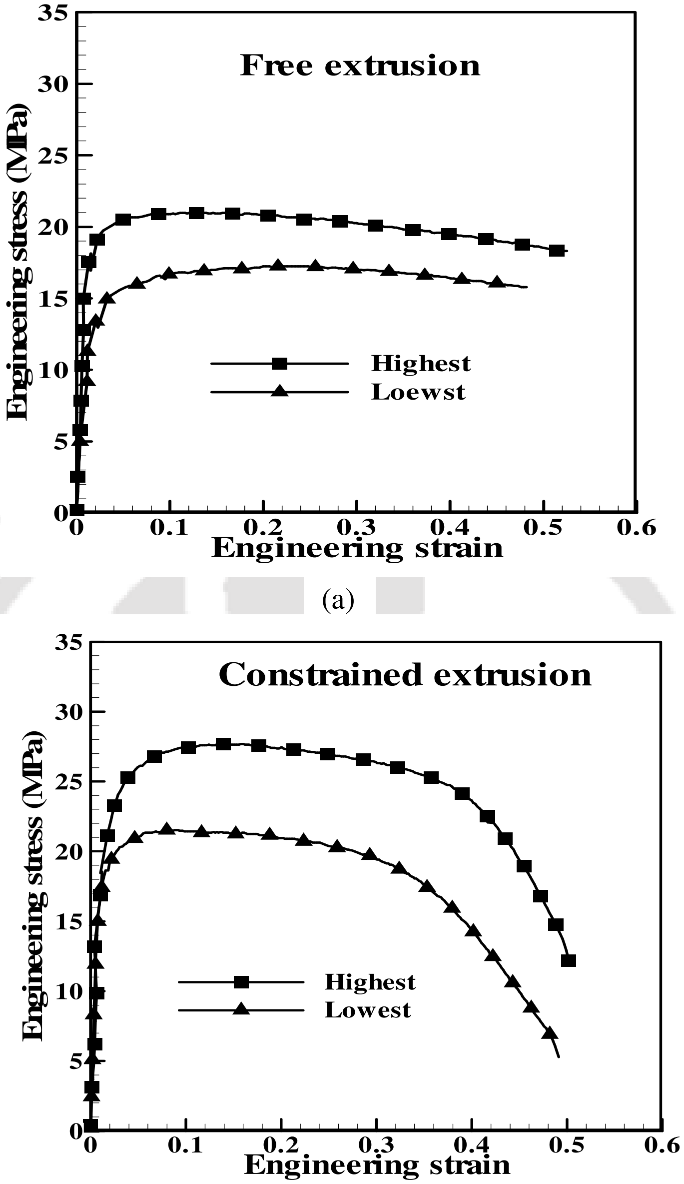


(a)



(b)

Figure 6.7. Engineering stress-strain curves of the extruded products through 5-hole die (a) free extrusion (b) constrained extrusion



(a)

(b)

Figure 6.8. Engineering stress-strain curves of the extruded products through 9-hole die (a) free extrusion (b) constrained extrusion

For both 5-hole and 9-hole extrusion, higher tensile strength is observed for the products from constrained extrusion. The ultimate tensile strengths of the extruded products from free extrusion are shown in Tables 6.3 and 6.4. Due to non-uniform material flow, the extruded products form different holes of the same die get work hardened by different amounts. As a result of this tensile strength are found to be different. In case of 9-hole extrusion, the ultimate tensile strength of the extruded products is less as compared to that of 5-hole extrusion. In the repetition of experiments, the extruded products of each hole are kept separately and tensile tests are carried out on them.

Table 6.3. Ultimate tensile strength of extruded products in free extrusion from 5-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	23.65	25.99	25.11	20.17	21.89	10.12
2	23.4	25.69	25.39	20.71	22.21	9.00

Table 6.4. Ultimate tensile strength of extruded products in free extrusion from 9-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	19.46	16.20	17.01	17.88	20.15	19.31	20.15	20.97	18.93	8.32
2	19.95	16.61	16.43	17.84	20.08	19.94	20.16	20.85	18.09	8.80

The constrained multi-hole extrusion produces high strength products. This can be observed from Tables 6.5 and 6.6. For both 5-hole and 9-hole die extrusion, higher strength products are obtained in constrained extrusion compared to free extrusion. This is due to more work hardening in constrained extrusion. Comparing Tables 6.3 and 6.5, it is observed that on an average ultimate tensile strength of extrudates from constrained extrusion is about 14% greater than the ultimate tensile strength from free extrusion. Also, there is a lesser variation in the ultimate tensile strengths of extrudates in constrained extrusion compared to extrudates in free extrusion. Comparing Tables 6.4 and 6.6, it is observed that on an average ultimate tensile strength of extrudates from constrained extrusion is about 22% greater than the ultimate tensile strength from free extrusion. However, in this case, the constrained extrusion is providing slightly more variation in the ultimate tensile strengths of the extrudates in comparison to ultimate tensile strengths of the extrudates in free extrusion. This is due to different amount of straining experienced by the extruded products.

In the experiments it is observed that the extruded product having higher tensile strength gets extruded first and experiences more mechanical working by the compressive force when it fills up in the blind hole of the fixture. The higher hardness value is also observed for that particular product. The variation in the mechanical properties among extruded products may not matter much in many situations as long as the mechanical properties are better than a threshold limit. It is also possible to reduce the variation in the mechanical properties by applying the higher extrusion load, which will ensure proper compaction of all extrudates. Altinbalik and Can (2006) also noted that in lateral extrusion of splines a higher forming load attains better die filling. The complete die filling is achieved with high forming load.

Table 6.5. Ultimate tensile strength of extruded products in constrained extrusion from 5-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	28.29	25.50	25.11	30.03	25.11	8.35
2	27.58	25.70	25.64	29.14	25.61	5.88

An interesting observation is that multi-hole extrusion from 5-hole die provides higher average ultimate tensile strength of the extrudates compared to multi-hole extrusion from 9-hole die, in free as well as constrained extrusion. This can be observed by comparing Tables 6.3 with Table 6.4 and Table 6.5 with Table 6.6. This is due to the fact that effective extrusion ratio in 5-hole die in greater than the effective extrusion ratio in 9-hole die. Consequently, extrudates from a 5-hole die are strain hardened more than the extrudates from a 9-hole die.

Table 6.6. Ultimate tensile strength of extruded products in constrained extrusion from 9-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	23.75	27.5	20.34	22.15	24.65	21.62	21.90	22.77	22.51	9.27
2	24.49	27.1	20.08	22.93	24.42	22.15	22.08	21.98	22.12	8.81

6.4.5 Micro-Hardness of the Extruded Products

Micro hardness tests are carried out for the extruded products coming out from the free and constrained extrusion through 5-hole and 9-hole dies. Tables 6.7 and 6.8 show the micro hardness values measured for the extruded products coming out from 5-hole dies in free and constrained condition. Extruded products from constrained extrusion are harder (about 6%) than products from free extrusion. Average micro hardness and coefficient of variation, obtained for free and constrained extrusion with 9-hole die are shown in Tables 6.9 and 6.10. Here also extrudates from constrained extrusion are harder (about 5%) than products from free extrusion.

Table 6.7. Micro hardness of the extruded products in free extrusion through 5-hole die

Sl. No.	Micro hardness of extruded products (VHN)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	12.8	11.9	12.6	12.56	12.9	3.11
2	12.43	12.4	12.03	11.96	12.53	2.09

Table 6.8. Micro hardness of the extruded products in constrained extrusion through 5-hole die

Sl. No.	Micro hardness of extruded products (VHN)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	13.33	13.1	12.86	12.83	13.23	1.69
2	13.67	13.1	12.76	13.1	13.26	2.5

Table 6.9. Micro hardness of the extruded products in free extrusion through 9-hole die

Sl. No.	Micro hardness of extruded products (VHN)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	12.16	12.8	12.23	12.1	11.93	12.06	12.63	12.43	11.93	2.5
2	12.43	12.56	12.16	11.96	12.33	12.33	12.67	12.26	12.2	1.73

Table 6.10. Micro hardness of the extruded products in constrained extrusion through 9-hole die

Sl. No.	Micro hardness of extruded products (VHN)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	12.76	12.63	12.96	13.23	13.16	12.83	12.56	12.90	12.96	1.72
2	13.10	13.00	12.73	13.00	12.73	13.16	13.20	13.03	13.06	1.29

Comparing Tables 6.9 and 6.10 with Tables 6.7 and 6.8, it is observed that lower hardness products are obtained from 9-hole die as compared to 5-hole die, for free as well as constrained extrusion. This is expected as the effective extrusion ratio in a 5-hole die is greater than the effective extrusion ratio in a 9-hole die. Onuh *et al.* (2003) also observed that the average hardness value of the extrudate increases with increase in reduction. Surprisingly, the coefficient of variation in hardness value is less for 9-hole die extrusion as compared to 5-hole die. This is contrary to the observations in case of ultimate tensile strength. This indicates that there may not be a strong correlation between the increase in micro-hardness and increase in ultimate tensile strength. There is a scope to carry out further investigation on this aspect for different materials.

6.5 Conclusion

In the present work, a constrained multi-hole extrusion process is proposed and its performance is compared with the free multi-hole extrusion process. The process is somewhat similar to a combination of extrusion and closed-die forging. The constrained multi-hole extrusion process is found to produce straight and equal length extrudates. The extruded products have better mechanical properties in constrained extrusion than in free extrusion. The micro-hardness and ultimate tensile strength of extrudates from 9-hole die are lesser than micro-hardness and ultimate tensile strength of extrudates from 5-hole die. This is expected as the extrudates from 5-hole die undergo more straining than the extrudates from 9-hole die.

The developed process is suitable for small-length components. For the longer components, the fixture size will be more and creating a deep hole with very high length to diameter ratio poses problems. The major drawback of constrained extrusion process is that it consumes more power than the free extrusion process. However, when a multi-hole constrained extrusion process is compared with a single-hole free extrusion process, this fact gets undermined. At the same time, improvement in geometric accuracy and mechanical property of the extrudates makes a strong case for the use of this process, in spite of some increase in the extrusion load and power.

Chapter 7

Study on Multi-hole Microextrusion Process

7.1 Introduction

The growth of market demand for small sized components to be used in various electronic and mechanical gadgets like computers, cell phones and small robots has increased in recent years. The trends of miniaturization are now the challenging tasks to produce miniature parts. The processes like micro-EDM, micro-electrochemical machining, lithography, LIGA and laser technology were used for fabrication of micro components. In recent years, the use of micro forming process has become an interesting area of research to produce near net shape products with required quality. The know-how of the conventional forming processes can not simply be applied to the micro scale forming processes due to size effect. The conventional manufacturing processes like deep drawing and extrusion have been adapted by many researchers to produce micro parts. Components like micro gears, cups having wall thickness of micron size and micro pins are being produced using extrusion process. Micro-forming processes are suitable for mass production.

Recently, micro-extrusion has been considered as a feasible manufacturing process to produce metallic micro components. The most crucial part in the design and fabrication of a micro-extrusion machine is the fabrication of die and ram. The small size of the die and ram along with the stringent accuracy requirement needs suitable manufacturing processes. The conventional technology may not be compatible for manufacturing of miniature/micro products. It is necessary to reduce the size of the equipment to reduce the energy consumption and to reduce the equipment costs. Some traditional forming machine designs can be scaled down for micro forming needs, as long as the machines can operate with micro-tools of acceptable quality and efficiency. Micro-dies, container, punch and the actuators are the major parts to be designed and fabricated for the micro-extrusion process. Depending on the level of miniaturization, different processes are used to fabricate the micro-dies. Limited work on micro extrusion is available in literature. Recent studies on microextrusion process have been carried out by Cao *et al.* (2004), Krishnan *et al.* (2007), Parasiz *et al.* (2007) and Wu *et al.* (2010). The studies include micro die fabrication, micro-machine development, extrusion load, die wear, surface quality of the extruded products and mechanical properties of the extruded products. None of these work deal with multi-hole extrusion process.

In the present work, multi-hole microextrusion has been carried out to study the feasibility of the process in producing products in micron size. The difficulties encountered during the experiments are discussed and some modifications have been made to the microextrusion set up. Wax has been extruded to obtain preliminary concept on the effect of different process parameters. Lead extrusion also has been carried out and the effects of different process parameters are studied.

7.2 Experimenrtal Procedure

The fabrications of components of microextrusion set up and micro die are explained. The modifications made to the container, punch and die holder by reducing the dimensions are presented with schematics and pictures. The causes of failure of the modified components are discussed. The multi-hole micro die fabrication using micro electric discharge machining is discussed. The extrusion of wax and lead alloy are explained

7.2.1 Fabrication of Container, Punch and Die holder

For the present study, the die, punch, container and die holder are made of die steel (H-13). Figure 7.1 shows the container, punch and die of meso extrusion set up used for extrusion of 2 mm products from 20 mm diameter billet with 5-hole die. This will give a clear idea on the reduction in size of container, punch and die fabricated for microextrusion.

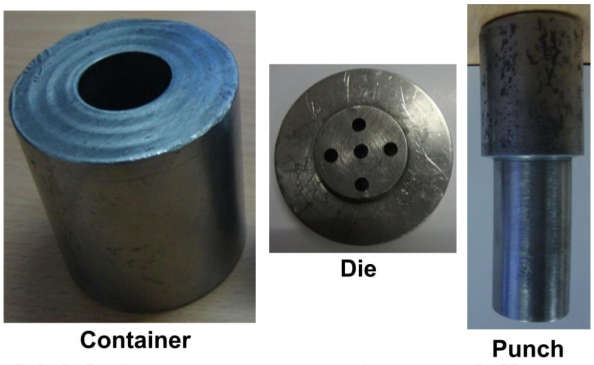


Figure 7.1. Components of meso extrusion set up for extrusion of 20 mm billet to produce 2 mm diameter products

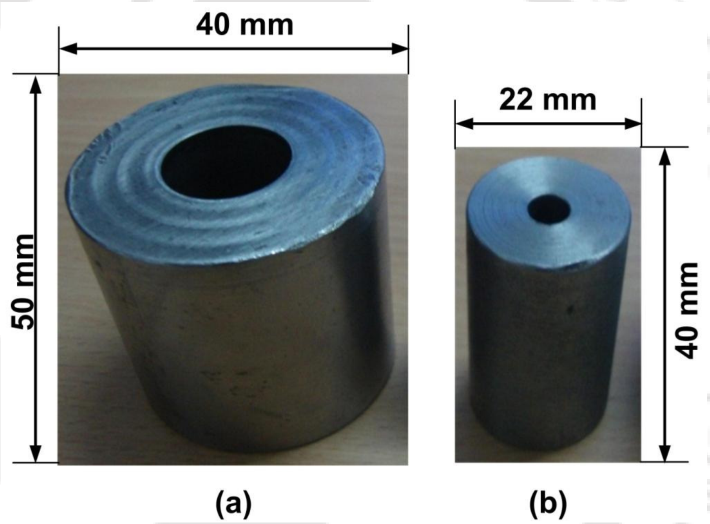


Figure 7.2. Containers used for (a) meso extrusion (b) microextrusion

The container dimensions are reduced for the multi-hole micro extrusion as shown in Figure 7.2. The container is made by turning and drilling operations. Hand lapping is carried out to improve the surface quality of the inner wall of the container. The punch dimensions are also reduced from the meso size as shown in Figure 7.3. The punch is made by turning process. The average surface finish produced is about 1 μm. The detailed die drawings are provided in Appendix D.

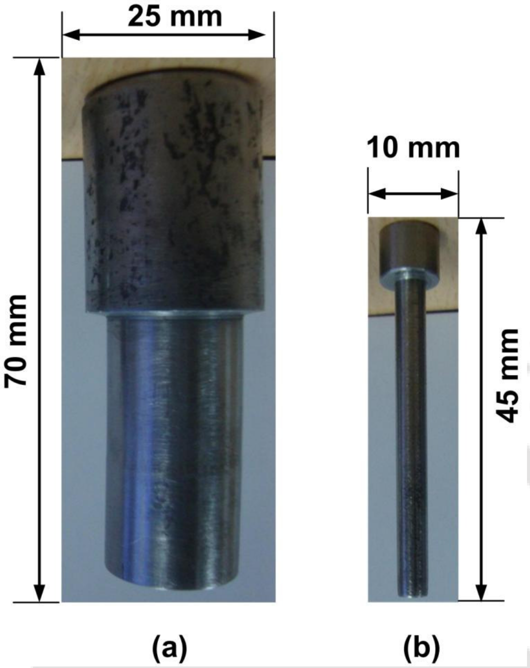


Figure 7.3. Punch used for (a) meso extrusion (b) microextrusion

The photographs of meso and multi-hole micro die are shown in Figure 7.4. The multi-hole micro die is first machined by turning process and micro-electrical discharge machining (μ-EDM) is carried out to produce micro holes. The top side of multi-hole micro die shows the die pockets produced to reduce the die land length. The micro holes of approximate diameter of 350 μm can be seen in the bottom side (Figure 7.4 (b)).

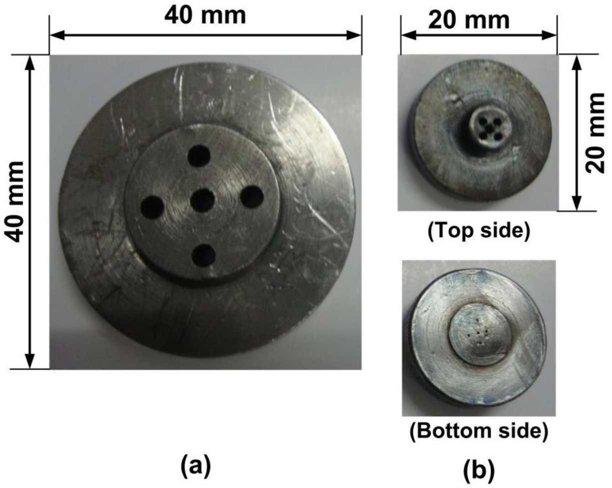


Figure 7.4. Die used for (a) meso extrusion (b) microextrusion

With the fabricated components of microextrusion, the set up is made. Wax and lead are extruded. During extrusion of wax, the container tends to lift up from the die holder. This is due to the more friction encountered during the extrusion at higher extrusion ratio. In lead alloy extrusion with the same set of container, die and punch, the punch failed by buckling. Thus, it is evident that just scaling down of the set up is not enough for carrying out extrusion at micro level successfully.

The photographs of modified container die holding block and punch dimensions are shown in Figure 7.5. Four holes are drilled on the periphery of container and die holding block (which holds the die). Fastening of container and die holding block is done with four M6 bolts. This arrangement stops the lifting of container from the die. The punch head is tapered to apply the extrusion pressure more uniformly and avoid buckling.

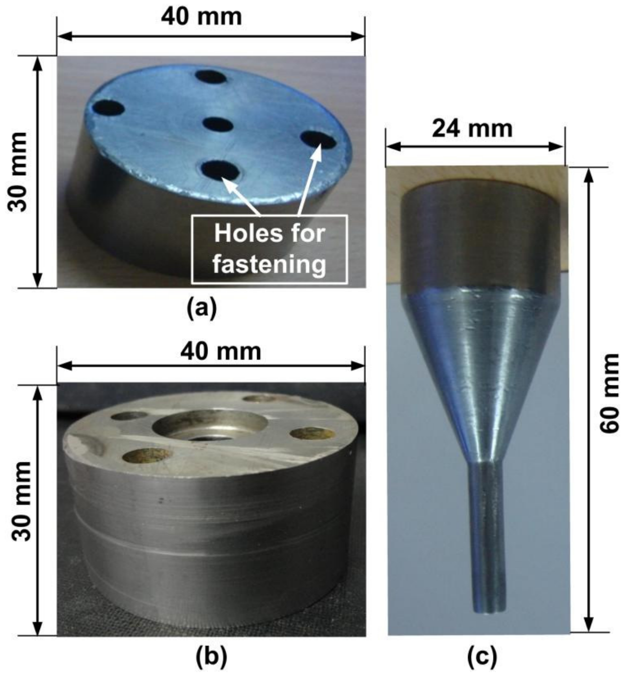
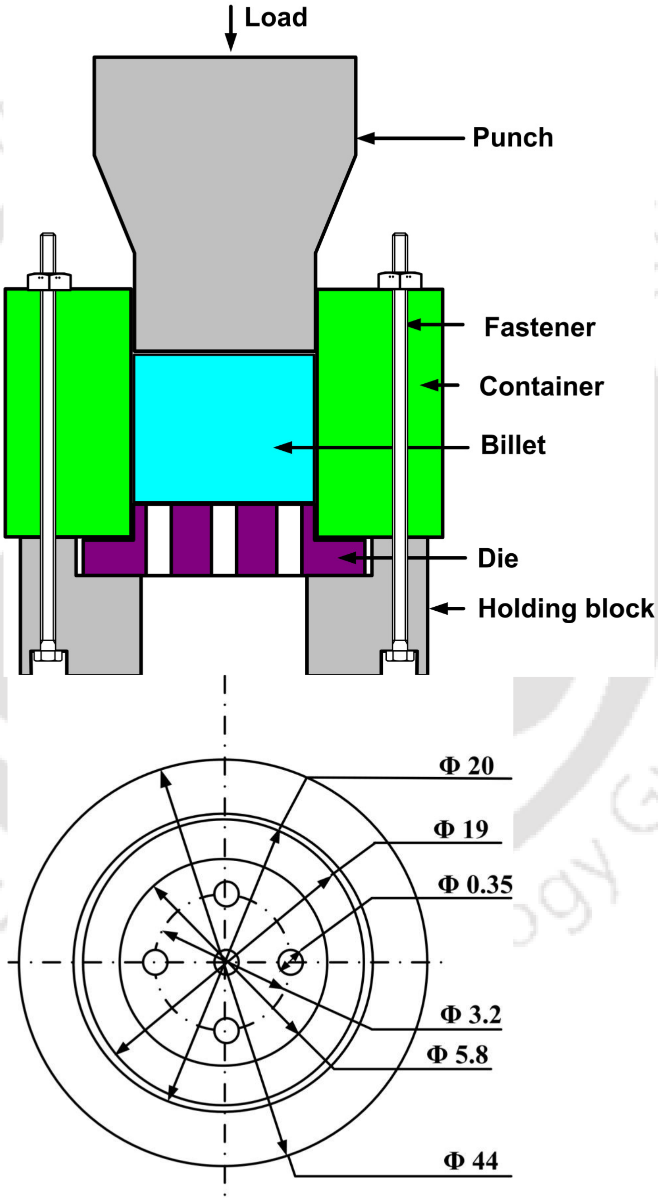


Figure 7.5. Modified components of microextrusion set up (a) container (b) die holding block (c) punch

A schematic of the modified microextrusion set up is shown in Figure 7.6. The top view shows the dimensions of micro holes and their locations on the die. Some trial experiments are carried out with the modified set up and both wax and lead alloy products are obtained successfully.



(All dimensions are in mm; drawing not to scale)

Figure 7.6. Schematic of modified microextrusion set up

7.2.2 Fabrication of Micro Multi-hole Die

Fabrication of the multi-hole die with hole diameter in micron is a challenging task. For carrying of microextrusion of pins Parasiz et al. (2007) fabricated the extrusion die (segmented die block in order to facilitate the removal of micropin after extrusion) of base diameter of 756 micron and extruded diameter of 568 micron by micro-electrical discharge machining (μ-EDM). For the present study, the multi-holes of average diameter of 350 μm with standard deviation of 19.45 μm are produced using the conventional μ-EDM process. The Electric Discharge machine available at Tool Room, Central Institute of Plastic Engineering and Technology, Changsari, Guwahati, India is used to produce micro hole on the 5-hole die is shown in Figure 7.7. The details of Electric Discharge Machine are given in Table 7.1.

Figure 7.7. Electric Discharge Machine (CNC Precision Die-sinking EDM)

Table 7.1. Electric Discharge Machine specifications

Machine Type	CNC Precision Die-sinking EDM
Model	ACT SPARK (SP1)
Make	AGIE CHARMILLES, CHINA
Dielectric fluid	Rsutlik EDM-30

For machining of micro holes, the operating parameters are selected for the electrode-workpiece combination (copper-steel). The pulse duration, pulse gap and work current are selected for maximum material removal and minimum tool wear condition from the operating instructions manual available with the machine. Commercially available electric copper wire of average diameter of 340 micron is used as the tool to produce micro holes. Initially die land length of 8 mm is produced on the multi-hole micro die.

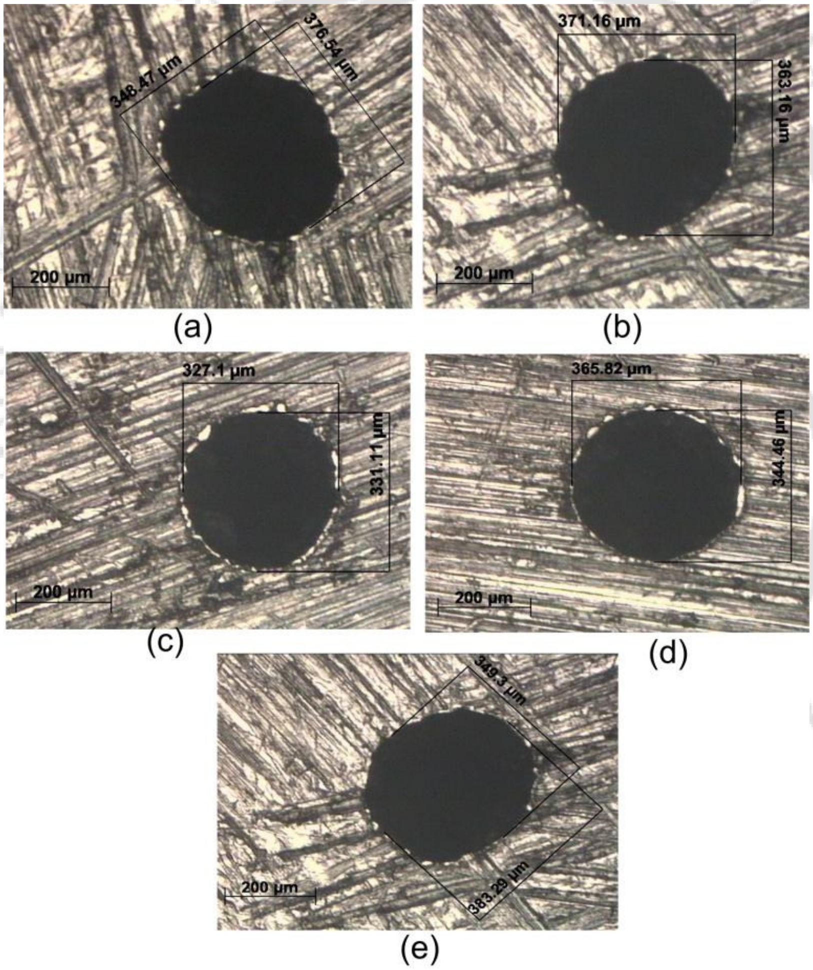


Figure 7.8. Dimensions of micro holes (a) centre hole and (b)-(e) peripheral holes

The micro photographs of the micro-holes produced are shown in Figure 7.8. The micro-hole sizes are measured and some variations in dimension are observed. The average hole size is found to be 350 microns. To study the effect of die pockets and die land length, further the pockets of 1 mm diameter and depth of 2 mm and 6 mm are produced. The pockets on the multi-hole micro die are made by drilling process using 1 mm twist drill bit. The schematic of the die pockets produced is shown in Figure 7.9.

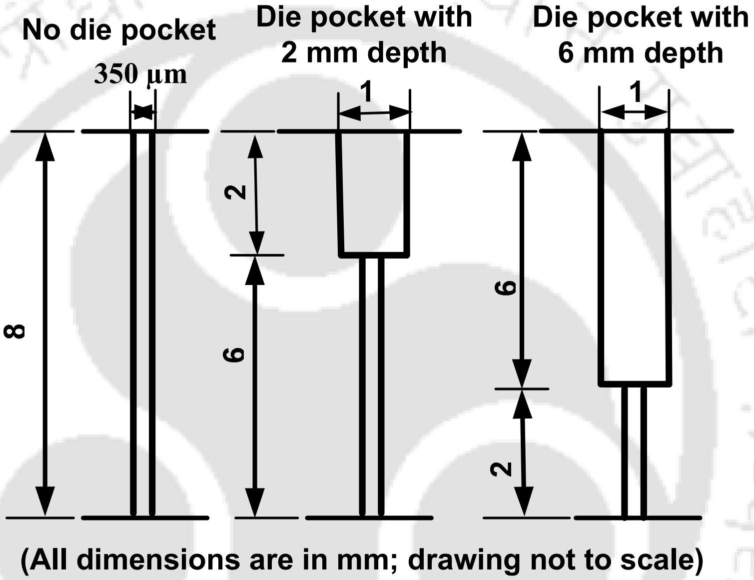


Figure 7.9. Schematic of pockets produced on micro holes

The universal testing machine (Make: INSTRON, Model: 8801; Capacity: 100 kN) shown in Figure 7.10 is used as the press for micro-extrusion of both wax and lead alloy. Wax and lead alloy are used for multi-hole microextrusion. The wax billets are prepared by melting and then solidifying the commercially available candle wax in a mould of 5.8 mm diameter and 50 mm height. The billet of 10, 15 and 20 mm length are produced. Lead alloy billets of 10 mm length and 5.8 mm diameter are prepared by machining the cast piece of 10 mm diameter and 50 mm length. Annealing of the lead billets is carried out by putting them in boiling water for one hour and then cooling down to room temperature to make them stress free.

Figure 7.10. Universal Testing Machine (INSTRON-8801)

At the beginning, the experiments are carried out for wax with 5-hole die. Wax is a strain and temperature sensitive material. The extrusion is carried out at room temperature (22 °C) with ram speed of 2, 1.5, 1 and 0.5 mm/min. Two replicates are carried out to observe the repeatability of the process. Removal of the extruded material from the die land regions of the multi-hole die was found to be difficult because of very small holes. After each experiment, the set up is removed from the press and then the die is removed. The die is heated to remove the wax by melting. The die is later cooled to room temperature and the experiments are repeated. The value of friction factor at the die-billet interface was experimentally determined as 0.87 for lead extrusion and 0.2 for wax extrusion. The procedure for determining the friction factor has been described in Section 3.3.

An extruded micro component of lead is shown in Figure 7.11 as an example of the present experiments carried out with the multi-hole micro die. The extruded product shown here has been extruded with the die having 2 mm die land length.

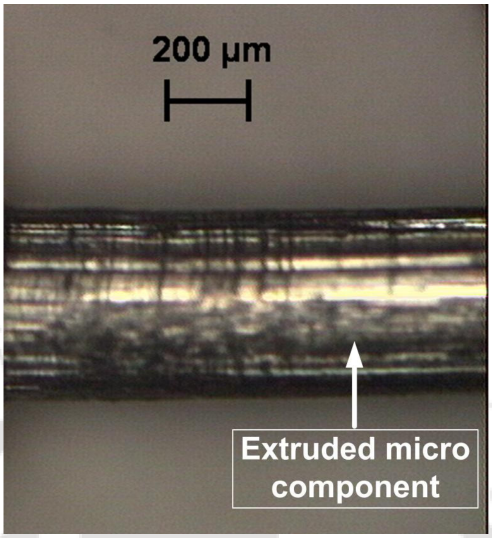


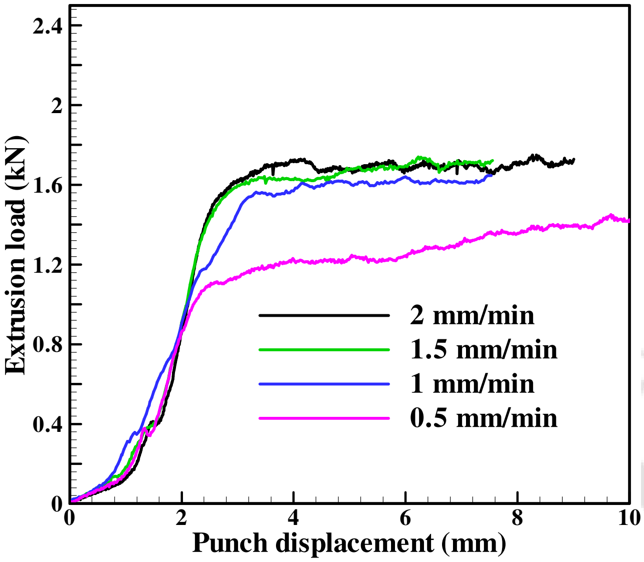
Figure 7.11. Extruded lead product from micro die

7.3 Results and Discussion

Extrusion of wax and lead alloy are carried out with the multi-hole micro die. The effects of ram speed, billet length and die land length on the extrusion load are studied. The lengths of the extruded lead alloy products are studied and variation in product length is discussed. The microhardness and micro tensile strength of the extruded lead products are studied. Comparisons of the microhardness of the extruded products are made for the extruded products of centre and peripheral holes.

7.3.1 Extrusion Load for Wax Extrusion

Micro extrusion of wax is carried out with 5-hole die. Three different billet lengths of 20, 15 and 10 mm are used. Each experiment is repeated twice. The extrusion load obtained from the extrusion of 20, 15 and 10 mm wax billet at different ram speed are shown in Figures 7.12, 7.13 and 7.14 respectively. For all three billet lengths, the extrusion load is found to be the least for 0.5 mm/min ram speed.



Figute 7.12. Load displacement curve for 20 mm length wax billet extrusion

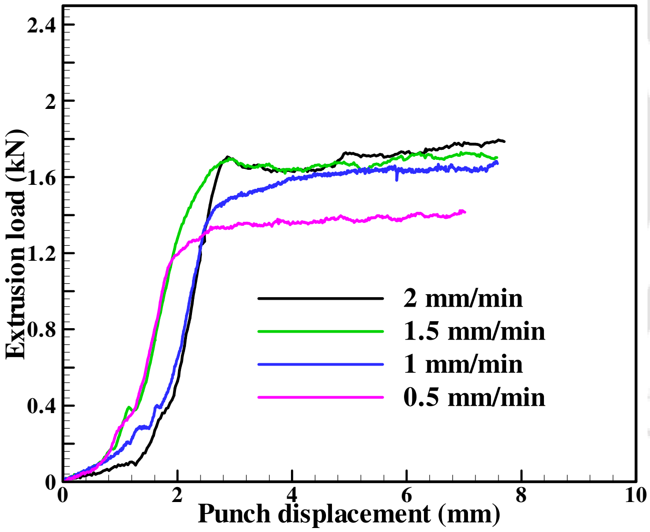


Figure 7.13. Load displacement curve for 15 mm length wax billet extrusion

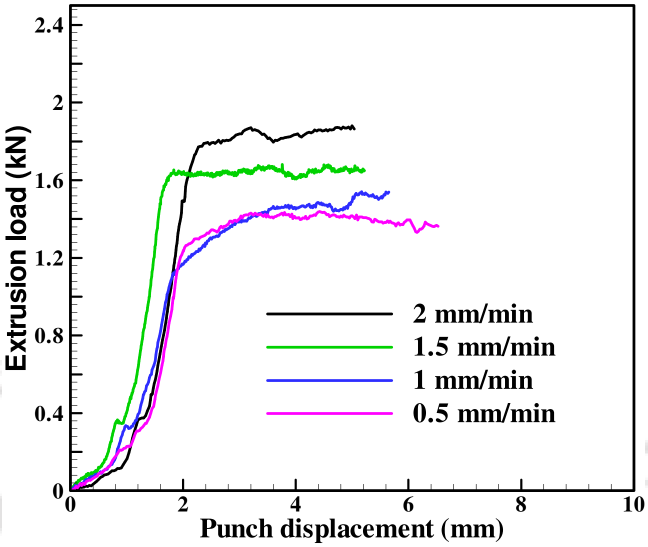


Figure 7.14. Load displacement curve for 10 mm length wax billet extrusion

Average extrusion load and standard deviations for wax extrusion are shown in Table 7.2. Differences in average extrusion load obtained for different billet length at same extrusion speed is insignificant. About 20% less extrusion load is obtained for the ram speed of 0.5 mm/min when compared to 2 mm/min. Extrusion speed is found to be more dominating process parameter than the billet length in wax extrusion.

Table 7.2. Average extrusion load for wax extrusion (values in bracket are standard deviation)

Ram speed (mm/min)	Average extrusion load (kN)		
	Billet length 20 mm	Billet length 15 mm	Billet length 10 mm
2	1.82 (0.07)	1.79 (0.06)	1.8 (0.07)
1.5	1.77 (0.04)	1.69 (0.36)	1.74 (0.06)
1	1.68 (0.04)	1.62 (0.46)	1.63 (0.83)
0.5	1.47 (0.06)	1.46 (0.45)	1.48 (0.47)

Table 7.3. Average extrusion load for wax obtained in experiment for dies having different die land length (values in bracket are standard deviation)

Die pocket depth (mm)	Die land length (mm)	Extrusion load (kN)
0	8	1.48 (0.47)
2	6	1.40 (0.32)
6	2	1.26 (0.21)

Table 7.3 shows the extrusion load obtained from the dies having different die land lengths. Reduced die land length helps in reduction of extrusion load. Die land length of 2 mm is having 15% less extrusion load compared to 8 mm die land length.

7.3.2 Extrusion Load for Lead Alloy Extrusion

The billet lengths of 10 mm for lead alloy extrusion is taken for extrusion experiments with a ram speed of 0.5 mm/min. Extrusion was carried out with dies having different die land length. The experiments were repeated twice.

Table 7.4. Average extrusion load obtained from micro-extrusion lead (values in bracket are standard deviation)

Die pocket depth (mm)	Die land length (mm)	Extrusion load (kN)
0	8	21.97 (1.28)
2	6	21.74 (0.59)
6	2	18.6 (0.26)

The average extrusion loads obtained for the extrusion of lead are shown in Table 7.4. The least extrusion load is obtained with die land length of 2 mm. The reduced die land length helps in reducing the extrusion load. It can also be noted that no significant difference in average extrusion load for lead extrusion and wax extrusion is observed for 8 and 6 mm die land lengths as in the case of wax extrusion.

7.3.3 Length of the Extruded Products of Wax and Lead Alloy

The lengths of the extruded products from different holes of a multi-hole die mainly depend on extrusion ratio, the friction factor and die land length. For meso scale extrusion with low extrusion ratio, the variations in length of the extruded products are quite less as discussed in earlier chapters. In microextrusion process, the grain size of the material also plays an important role in producing the product with different lengths and degrees of bending [Krishnan *et al.*, 2007 and Mori *et al.*, 2007]. It is observed that in wax extrusion (Figure 7.15), the extruded products are of almost same length. The effect of billet length and the different ram speeds on extruded product length are found to be insignificant.

Figure 7.16 shows wax and lead extrudates. It is observed that the extruded products of lead have large difference in the lengths. The extruded product length from the centre hole is more than the peripheral ones. The high friction between the billet and container wall in extrusion of lead alloy restricts the material flow through peripheral holes as compared to centre hole. Flow behavior of material affects the extruded length. The flow of metal through micro hole is not similar to flow through larger hole diameter.

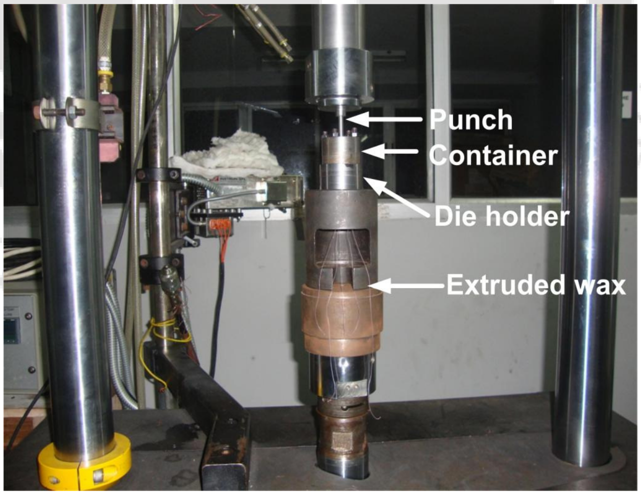
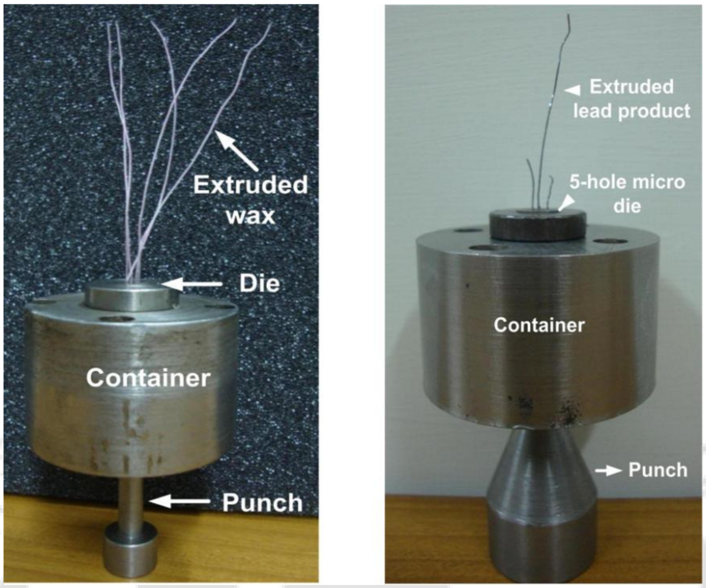


Figure 7.15. Microextrusion of wax



(a) (b)

Figure 7.16. Extruded products (a) wax and (b) lead alloy from 5-hole micro die

The lengths of the extruded products are measured carefully for the further studies. It is found necessary to find out the coefficient of variation in the extruded product lengths. The coefficient of variation for length of the product is calculated using the following formula:

$$\text{Coefficient of variation} = \frac{s}{\bar{x}} \times 100\% \,, \tag{7.1}$$

where s is standard deviation and $\bar{x}$ is average value

Table 7.5. Coefficient of variations (based on 3 replicates) of extruded lead products obtained from dies with different die land lengths

Die pocket depth (mm)	Die land length (mm)	Coefficient of variation (%)	
		Extrudates from centre hole	Extrudates from peripheral holes
0	8	14.6	18.86
2	6	13.15	11
6	2	6.5	11.2

Table 7.5 shows the coefficient of variations of the extruded lead products. It is observed that small die land length produces less variation in extruded products.

7.3.4 Micro Hardness Test of the Extruded Lead Alloy

Micro hardness tests are carried out on extruded products coming out from different holes of micro die. The measurement of micro hardness is carried out for the extruded product along axial and radial direction as shown in Figure 7.17. Some replicates were conducted and the range of variation was less than 0.2 VHN. The average values of micro hardness values are plotted.

For determining the micro-hardness, Vickers Micro Hardness Tester (Make: BUEHLER, Model: MICROMET 2101) is used. Due to small diameter of extruded products, they cannot be used directly for micro hardness measurement. The sample preparation is carried out to conduct the micro-hardness tests. A cold mounting method is used for the mounting of the extruded products with acrylic powder (self-polymerizing resin) and acrylic liquid (self polymerizing liquid). The samples are then polished to half of the diameter (for hardness measurement along axial direction) to avoid the surface effect in micro hardness testing. Indentation is carried out with a load of 50 g for 10 seconds during the test.

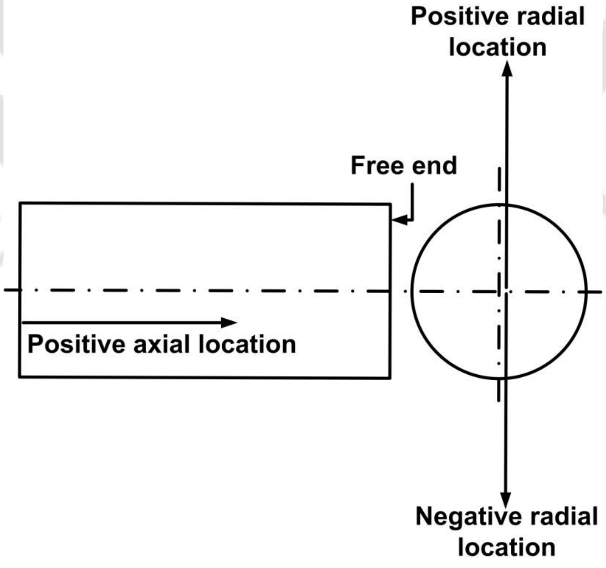
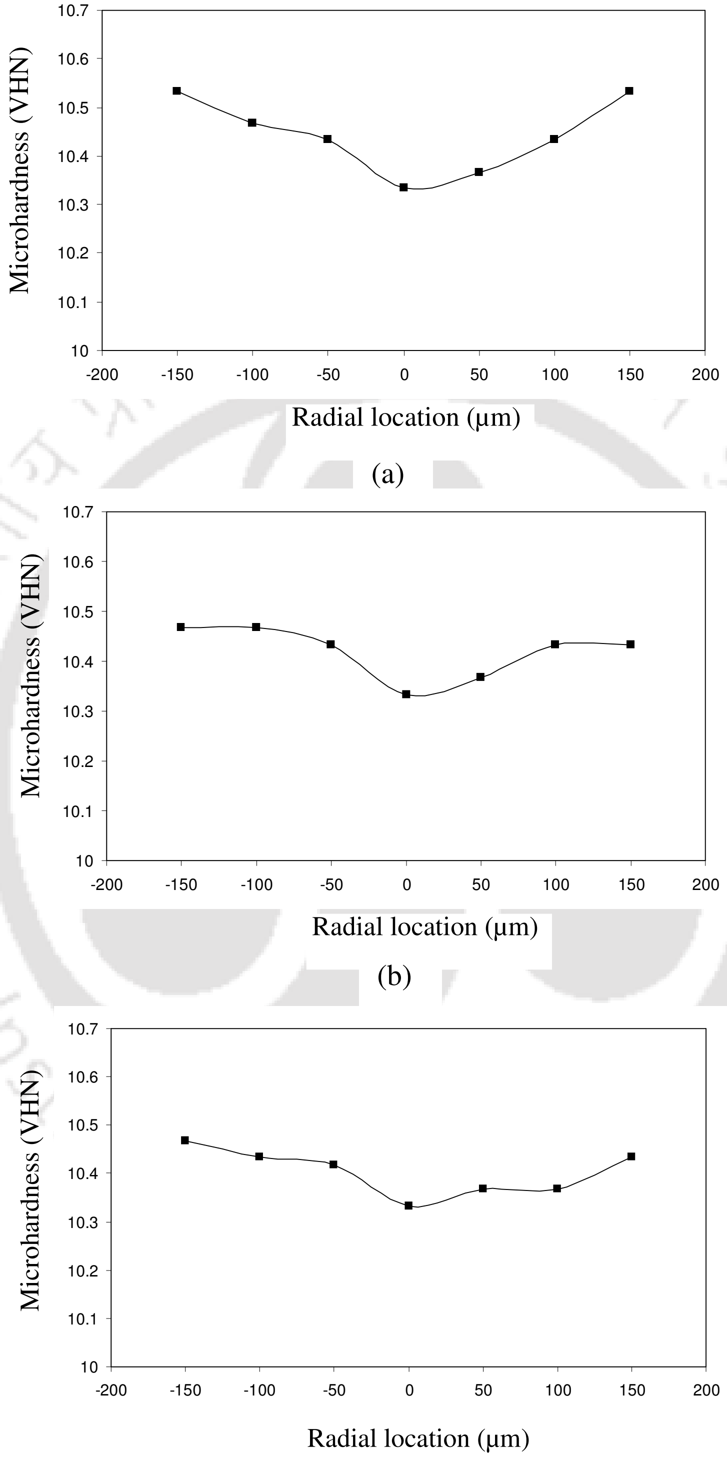


Figure 7.17. Axial and radial location of the extruded product for measurement of micro hardness

Micro hardness of the extruded products from centre hole and peripheral hole along radial direction is shown in Figure 7.18 and 7.19 respectively. In Figure 7.18 (a) for 8 mm die land lengths, high hardness value is observed at the locations away from the centre. It indicates that more work hardening takes place on the surface of the extruded products and it gradually decreases towards the centre. With reduction of die land length, the variation in average hardness value also reduces. More uniform hardness values of the extruded products are observed along the radial direction in the case of 2 mm die land length (Figure 7.18 (c)). The die pockets produced to reduce die land length also help in uniform material deformation during extrusion process. It is also observed that during extrusion process, the extruded product from the centre hole gets extruded easily as compared to the peripheral ones due to less frictional resistance. The more strain hardening results in high hardness value for the extrudates of peripheral holes. The hardness vales of the extruded products from peripheral holes are shown in Figure 7.19. Smaller die land length also helps to reduce strain hardening and lesser variation in hardness values is observed (Figure 7.19 (c)).

The hardness values are also measured along the axial direction (in the direction of extrusion). These are shown in Figures 7.20 and 7.21. Along the axial direction, a slight decrease in average hardness value is observed. There are no experimental results on microhardness of the extruded products in multi-hole microextrusion. Parasiz et al., 2007 have carried out single hole microextrusion and described the hardness distribution on the extruded micro pin. The present observations on the hardness distribution are similar to the observations made by them.



(c)

Figure 7.18. Micro hardness values of the products from centre hole along radial direction for different die land length (a) 8 mm (b) 6 mm and (c) 2 mm

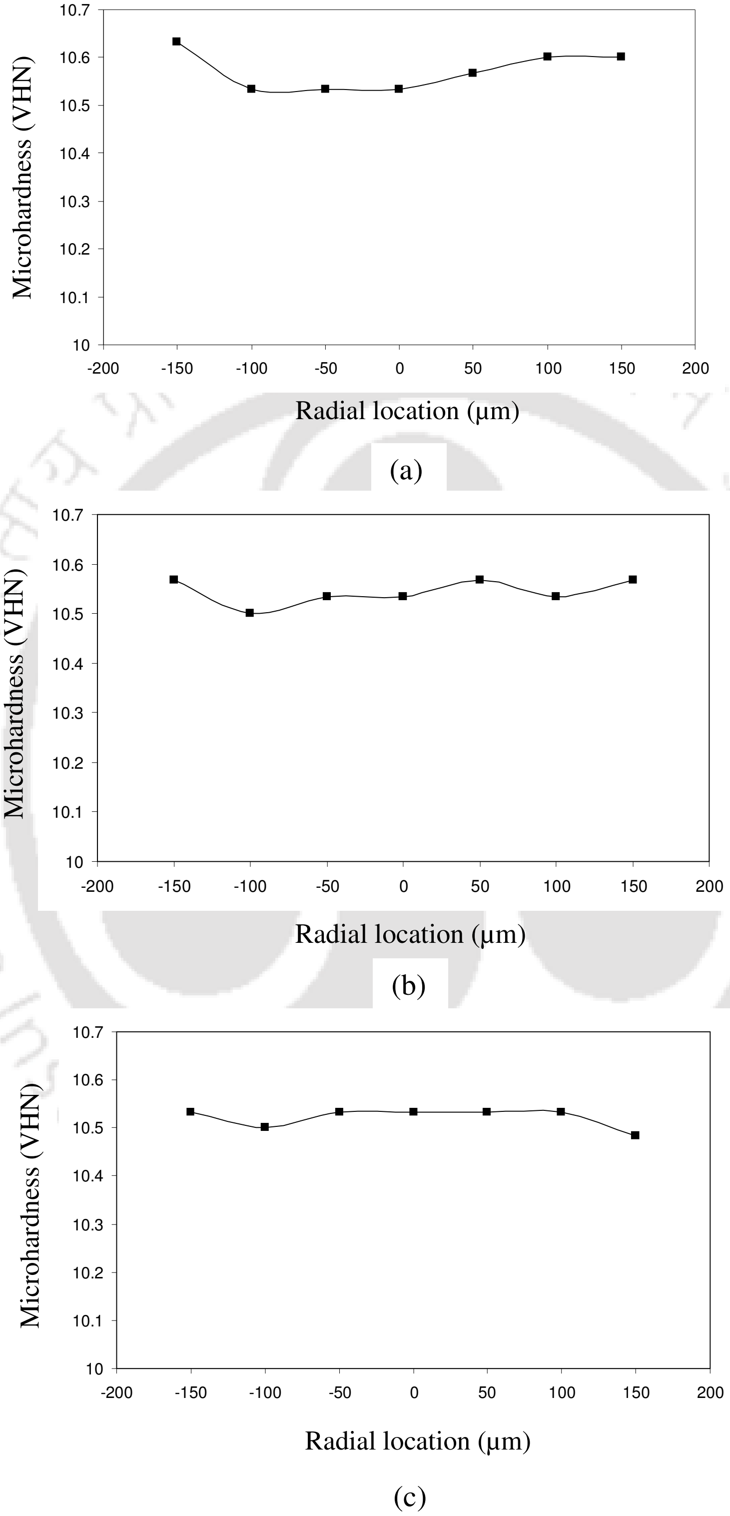
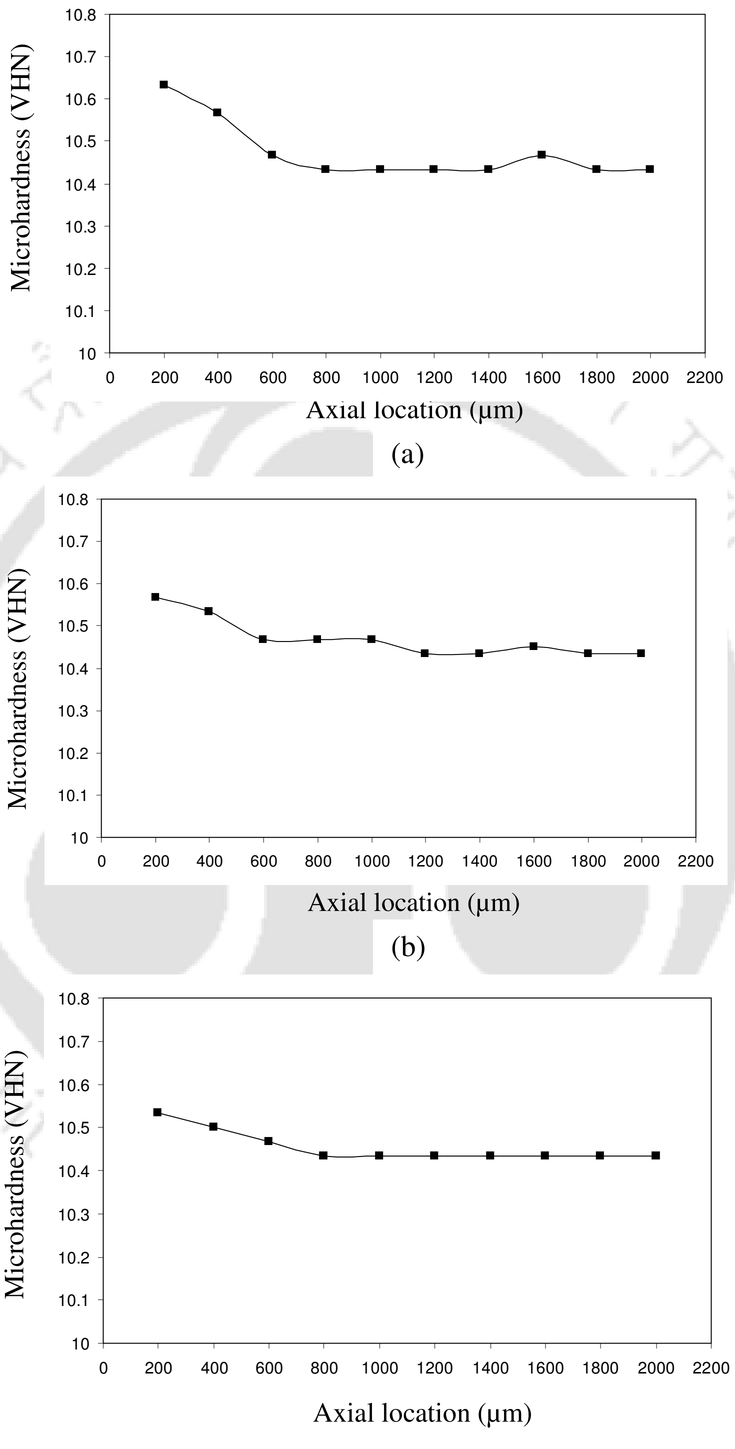


Figure 7.19. Micro hardness values of the products from peripheral holes along radial direction for different die land length (a) 8 mm (b) 6 mm and (c) 2 mm



(a)

(b)

(c)

Figure 7.20. Micro hardness values of the products from centre hole along axial direction for different die land length (a) 8 mm (b) 6 mm and (c) 2 mm

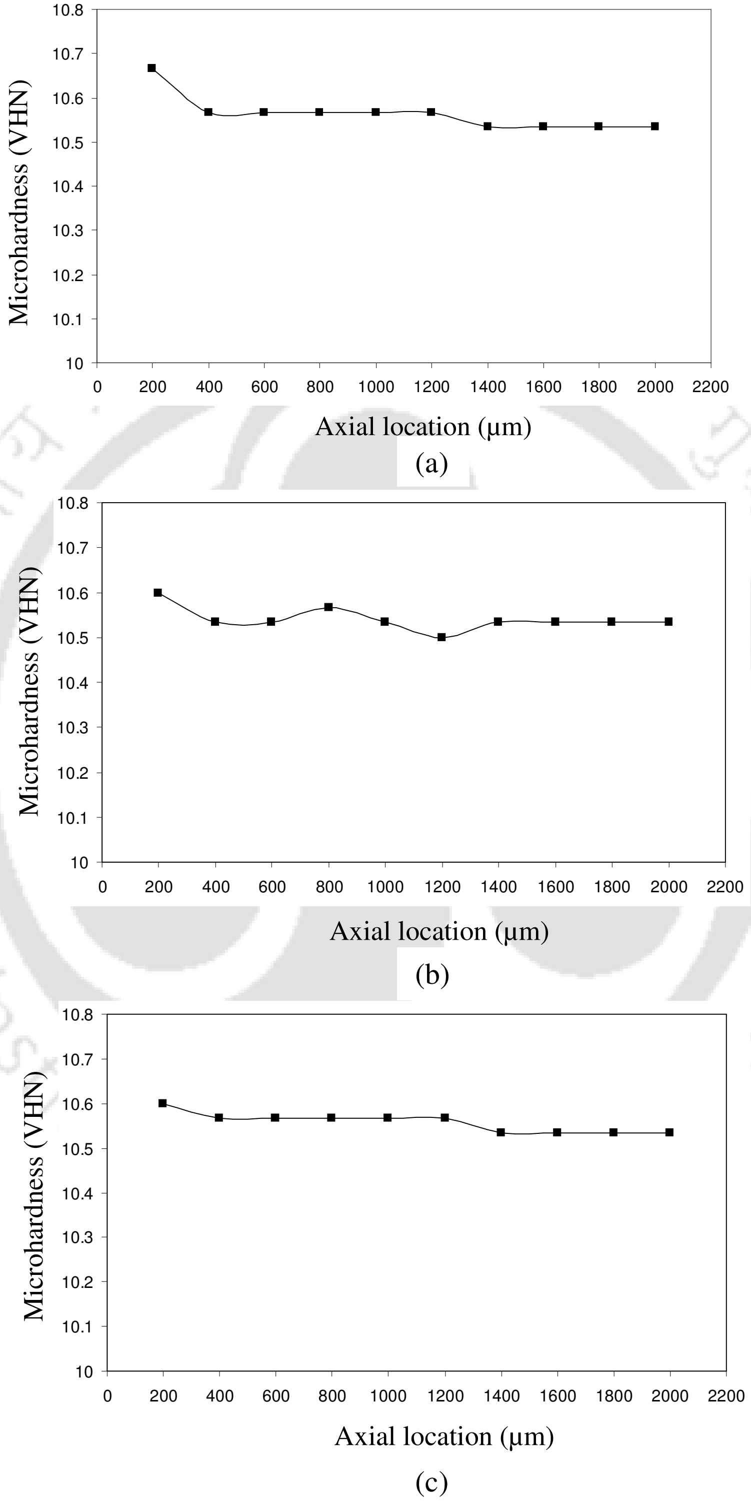


Figure 7.21. Micro hardness values of the products from peripheral holes along axial direction for different die land length (a) 8 mm (b) 6 mm and (c) 2 mm

7.3.5 Tensile Test of the Extruded Lead Alloy

Tensile tests of the extruded products of lead alloy from the micro-hole die are carried out. Experiments are repeated twice. The extruded products are cut to the required gauge length required for micro tensile tester (Make: DEBEN, Model: MICROTEST, 5 kN capacity). Both ends of the test specimen are applied with the mixture of acrylic powder (self-polymerizing resin) and acrylic liquid (self-polymerizing liquid) and allowed to dry properly. These gripping ends prevent the test specimen from the damage caused by the gripper of micro tensile tester and to avoid notch sensitivity. Utmost care has been taken in handling and fixing the specimen in the gripping end during tensile test. The load-displacement curves obtained from the data acquisition system of the micro tensile tester are then converted to engineering stress–strain curves.

The engineering stress-strain curves obtained for the extruded products of centre and peripheral holes are shown in Figures 7.22 and 7.23 respectively. The maximum engineering stress-strain values obtained during the tests are shown here. Figure 7.22 shows that the engineering stress value for the product coming out from the die with 2 mm die land length is about 25% lesser than that for the product coming out from the die with 8 mm die land length. However no significant difference in the tensile stress values are observed for the products of dies with 8 and 6 mm die land length. Figure 7.23 shows the engineering stress and strain curves for the products of peripheral holes. About 10% lesser engineering stress value is observed with the products from die with 2 mm die land length as compared to the products from die with 8 mm die land length. For both centre and peripheral holes, die pockets help in reducing the tensile strength of the products.

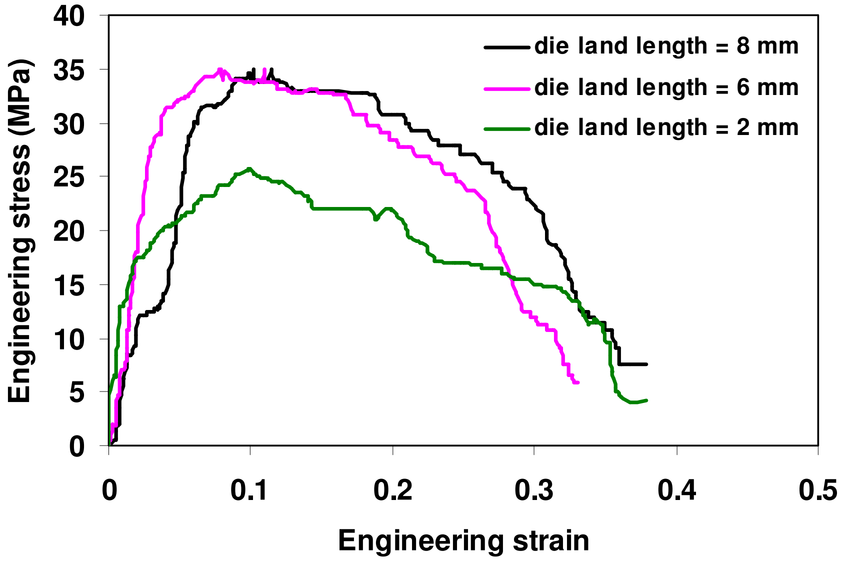


Figure 7.22. Engineering stress-strain curves for extruded products from centre hole

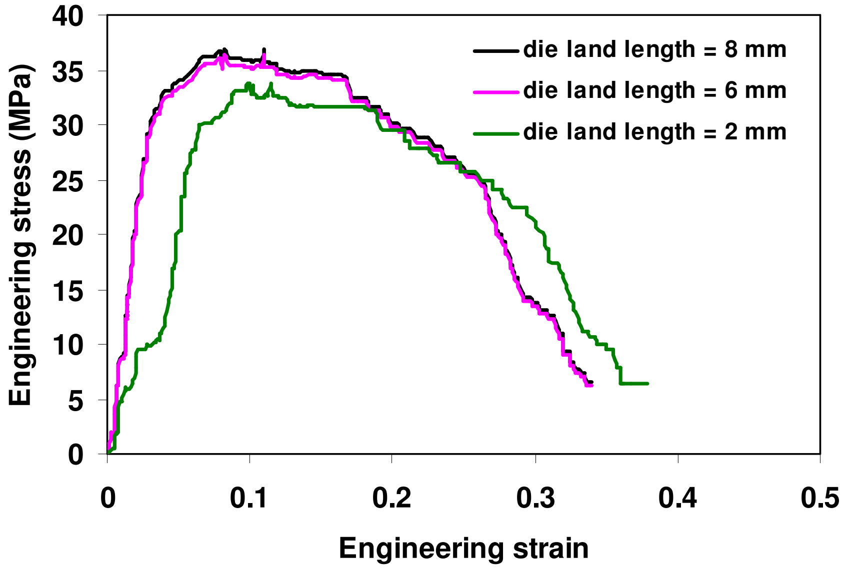


Figure 7.23. Engineering stress-strain curves for extruded products from peripheral hole

It is noted that in the micro hardness test, greater hardness value is obtained with the smaller product length from peripheral holes. From the observations of micro hardness test and micro tensile test it is found that products from peripheral holes have higher tensile strength and hardness compared to the products of centre hole due to more work hardening experienced by the products of peripheral holes. This is in contrast to observations made in Chapter 4 for meso extrusion

7.4 Conclusion

In the present work, multi-hole microextrusion is carried out and set up is developed. A 5-hole die with average hole diameter of 350 micron is produced. The extrusion of wax and lead alloy is carried out. The following conclusions are drawn:

- Wax material of different billet length is extruded at different ram speeds. Greater extrusion load is observed with higher ram speed. With reduced die land length, the extrusion load decreases. In lead alloy extrusion, lesser extrusion load is also observed for smaller die land length.
- In wax extrusion, the length of the extruded products obtained from centre and peripheral holes are found to be almost same. A significant variation in extruded product length of lead alloy is observed. The extruded products length from centre hole is higher than that of peripheral holes and this trend is different in meso extrusion. These variations are due to the high friction factor at the container-billet contact region and die land length.
- In microhardness tests, along radial directions, high hardness value is observed at the locations away from the centre and this is due to more work hardening on the surface of the extruded products. Along the axial direction a slight decrease in average hardness value is observed.
- Higher tensile strength is also observed for the products coming out from the peripheral holes as compared to the centre hole products. Extruded products with less tensile strength are obtained from the die having small die land length (2 mm).
- The present work demonstrates the feasibility of multi-hole micro extrusion process. The difficulties come across the die and extrusions set up fabrication and during experiments are explained for future development.

Chapter 8

Conclusions and Scope for Future Work

8.1 Conclusions

In this thesis, experiments and simulations have been carried out on the multi-hole extrusion process. The effects of different process parameters on extrusion load and quality of the extruded products are studied. The parameters considered are extrusion ratio, lubrication, die land length, die pockets and vibration. A series of experiments have been carried out with different types of dies to observe extrusion load and product quality. For product quality, bending, hardness, tensile strength and surface finish of the extruded products are studied. It is observed that the die land length and lubrication influence the extrusion load, bending of the extruded products and mechanical properties as well as surface finish of the extruded products. A good qualitative agreement of experimental results with the finite element simulations using DEFORM 3D® is observed. A constrained multi-hole extrusion process is proposed, set up is developed and its performance is compared with the free multi-hole extrusion process. The constrained multi-hole extrusion process is found to produce straight and equal length extrudates. The developed process is suitable for small-length components. The major drawback of constrained extrusion process is that it consumes more power than the free extrusion process. However, when a multi-hole constrained extrusion process is compared with a single-hole free extrusion process, this fact gets undermined.

Multi-hole microextrusion process has been proposed and set up has been developed. Wax and lead alloy were extruded and products with average diameter of 350 μm have been produced. Billet length and ram speed influence the extrusion load. The die pockets are also found to be effective parameter in multi-hole microextrusion. The hardness and tensile strength of the extruded lead products are also studied.

The conclusions of the thesis can be summarized as follows:

- In multi-hole extrusion process, ram force depends on different parameters such as the number of holes, die land length and lubrication. Ram force decreases with increase in number of holes. The smaller die land length and lubrication reduce the ram force in multi-hole extrusion. Ram force increases with the increase in ram speed. The decrease in billet length also reduces the ram force as the friction at the billet-container interface decreases.
- Imposed vibration helps in reducing friction during extrusion process. Much difference in ram force was not observed in extrusion with lubricated dies as compared to unlubricated dies with imposed vibrations. Hence, the imposed vibrations can substitute lubrication and thus help in green manufacturing.
- The extrusion loads obtained from finite element simulations are found to be in good agreement with the extrusion loads obtained from the experiments. Simulations indicated about 15% reduction in ram force for dies having no die land length as compared to the dies with 10 mm die land length.
- From experiments and finite element simulations, it was observed that dies with larger die land length produce less curved products. Peripheral holes produce less curved products than the centre hole. Less curved products were obtained from the unlubricated dies than the lubricated ones.
- Extruded products obtained from the dies having larger die land lengths have better strength compared to the products obtained from the dies of smaller die land lengths. Higher extrusion ratio and die land length help to improve the mechanical properties of the extruded products. The ironing effect at the die land region helps in improving the mechanical properties of the extruded products.

Effect of extrusion ratio is less significant on hardness of the extruded products obtained from smaller die land length (3 mm) as compared to the products from larger die land length (10 mm).

- For both lead and aluminum extrusion, extrusion ratio, die land length and lubrication are found to be significant factors for surface finish of the extruded products. Low extrusion ratio and lubrication help in reducing the surface roughness of the extruded products.
- Die pockets in multi-hole extrusion help in balancing material flow and thus more uniform extruded product lengths are obtained. For a particular die design, the optimum die pocket depth exists for obtaining the least extrusion load. Simulations indicate that the effective strains are the maximum at the entry of the die land region and decrease with increase in pocket depth. The radii of curvature of the extruded products were found to decrease with increase in pocket depths.
- The constrained multi-hole extrusion proposed in this work produces equal lengths of the extruded products. The extruded products of constrained multi-hole extrusion have better mechanical properties than those obtained from the free extrusion. The increase in mechanical properties is due to more work hardening of the extruded products. The average ultimate tensile strength of the extruded products from constrained extrusion was about 14% greater than that of the products from free extrusion for 5-hole dies. In case of 9-hole dies, the average ultimate tensile strength of the extruded products from constrained extrusion was about 22% greater than that of the products from free extrusion. The constrained multi-hole extrusion consumes more power than the free extrusion. Still the improvement in geometric accuracy and mechanical property of the extruded products makes a strong case for the use of this process.
- In this thesis, the multi-hole microextrusion set up is developed. The average hole diameter of 350 µm are produced on 5-hole die. During

experiments with microextrusion set up, the difficulties encountered were considered in modifying the set up. It was observed that just scaling down of the set up is not enough for carrying out extrusion at micro level successfully. Wax and lead alloy were extruded. The increase in extrusion load was found with increase in ram speed. The reduced die land length produces low extrusion load.

- Significant differences in extruded product lengths of lead were observed. The friction factor at billet-container interface and at die land region was found to be most influencing factor. The extruded products length from centre hole is higher than that of peripheral holes. This is in contrast with macro extrusion.
- In multi-hole microextrusion, higher hardness value is observed with the peripheral products as compared to the products from centre hole in contrast to macro extrusion. The die land length also affects the hardness distribution in extruded products along radial and axial directions. Higher tensile strength is also observed with the products coming out from the peripheral holes as compared to the centre hole products.
- Removal of extruded products from the die land region was found to be a difficult task. Heating of the die was carried out to remove the lead metal from the die land region. This method is time consuming and the die quality deteriorates due to repeated heating. There is a need to develop a better method.

8.2 Scope for Future Work

- In the present work, study of the effect of different process parameters was carried out for extrusion load and bending of the extruded products in multi-hole extrusion. The work can be extended to other materials and with different process parameters combinations. The optimum relationships can be formulated for minimum extrusion load and bending of the extruded products. The experimental data can be used to develop empirical relations.

- It was noticed that certain parameters have more influence on the surface finish and mechanical properties of the extruded products. In the present work, extrusion ratio, die land length and lubrication have great influence on the surface roughness. However, high extrusion ratio and die land length help in improving the mechanical properties. Future work can be directed towards optimizing the process for various conflicting goals.
- During the multi-hole extrusion with imposed vibrations, it was observed that vibrations help in reducing the extrusion load (by reducing friction factor) and obtain the better quality products. Future study may be carried out on developing an integrated vibration assisted multi-hole extrusion set up to eliminate the lubrication.
- Flat die profiles have been used in the present study on multi-hole extrusion process. Other types of die profiles can be used and the effects of process parameters can be studied. The strategies for the number of holes on the multi-hole die, extrusion load, billet size and die strength can be developed to make the multi-hole extrusion process more productive.
- In the present work, the constrained multi-hole extrusion has been proposed and experiments have been carried out to produce equal extruded product length with improved strength. Finite element analysis may be carried out for studying the process.
- In the present work, the multi-hole micro die with average diameter of 350 μm has been produced. Further experiments may be carried out using multi-hole micro die of smaller diameter than the present case.
- The three dimensional finite element simulations of multi-hole micro extrusion, could not produce satisfactory results due to high mesh distortion in the deformation zone. A detailed FEM analysis of this process is left as future work.

References

- Aggarwal, K., Gupta, R. and Yaramshetti, V., (2007), A study of multi-hole extrusion process, B. Tech Project Report, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India.
- Ajiboye, J.S. and Adeyemi, M.B., (2006a), Effect of die land on cold extrusion of lead alloy, Journal of Material Processing Technology, **171**, pp. 428–436.
- Ajiboye, J.S. and Adeyemi, M.B., (2006b), Upper bound analysis of die land length in cold extrusion, Journal of Material Processing Technology, **177**, pp. 608–611.
- Ajiboye, J.S. and Adeyemi, M.B., (2007), Upper bound analysis for extrusion at various die land lengths and shaped profiles, International Journal of Mechanical Sciences, **49**, pp. 335–351.
- Akbari Mousavi, S.A. A., Feizi, H. and Madoliat, R., (2007), Investigations on the effects of ultrasonic vibrations in the extrusion process, Journal of Materials Processing Technology, **187-188**, pp. 657–661.
- Alexandrov, S., Mishuris, G., Miszuris, W. and Sliwa, R.E., (2001), On the dead-zone formation and limit analysis in axially symmetric extrusion, International Journal of Mechanical Sciences, **43**, pp. 367–379.
- Altan, T., Ngaile, G. and Shen, G., (2005),Cold and hot forging fundamentals and applications, American Society of Metals, The materials Information Society, Materials Park, Ohio.

- Altan, S.B., Antar, N. and Gultekin, E., (1992), A comparison of some deformation model in axisymmetric extrusion, Journal of Materials Processing Technology, **33**, pp.263–272.

- Alting. L., Kimura, F., Hansen, H.N. and Bissaccoo, G., (2003), Micro Engineering, CIRP Annals–Manufacturing Technology, **52**, pp. 635–657.

- Altinbalik, T. and Can, Y., (2006), An experimental study of lateral extrusion of splines, Materials and Design, **27**, pp.727–734.

- Altinbalik ,T. and Ayer, O., (2008), A theoretical and experimental study for forward extrusion of clover sections, Materials and Design, **29**, pp. 1182–1189.

- Bae, W.B. and Yang, D.Y., (1992), An upper-bound analysis of the backward extrusion of internally elliptic-shaped tubes from round billets, Journal of Materials Processing Technology, **33**, pp.13–30.

- Bae, W.B. and Yang, D.Y. (1993a), An upper-bound analysis of the backward extrusion of tubes of complicated internal shapes from round billets, Journal of Materials Processing Technology, **36**, pp.157–173.

- Bae, W.B. and Yang, D.Y. (1993b), An analysis of backward extrusion of internally circular-shaped tubes from arbitrarily-shaped billets by the upper-bound method, Journal of Materials Processing Technology, **36**, pp.175–185.

- Bakhshi-Jooybari, M., (2002), A theoretical and experimental study on friction in metal forming by the use of forward extrusion process, Journal of Materials Processing thechnology, **125–126**, pp. 369–374.

- Bakhshi-Jooybari, M., Saboori, M., Noorani-Azad, M. and Hosseinipour, S.J., (2007), Combined upper bound and slab method, finite element and experimental study of optimal die profile in extrusion, Materials and Design, 28, pp. 1812–1818.

- Balaji, P.A., Sundarrajan, T. and Lal, G.K., (1991), Viscoplastic deformation analysis and extrusion die design by FEM, ASME Journal of Applied Mechanics, 58, 644–650.
- Barbier, C., Thibaud, S., Richard, F. and Picart, P., (2009), Size effects on material behavior in microforming, International Journal of Material Forming, **2**, pp. 625–628.
- Bianchi, J.H. and Sheppard, T., (1987), A comparison of a viscoplastic finite element model with slip line method and upper bound solution for non-hardening material subjected to plane strain and axisymmetric extrusion, International Journal of Mechanical Sciences, 29, pp. 61–81.
- Biswas, S.K and Rao, K.M., (1984), Flow of metal in constrained plane-strain extrusion forging: Part I, Journal of Mechanical Working Technology, **11**, pp. 161–179.
- Biswas, S.K and Vidyasagar, A., (1985), Flow of metal in constrained plane-strain extrusion forging: Part II, Journal of Mechanical Working Technology, **11**, pp. 139–149.
- Bjork, T., Bergstrom, J. and Hogmark, S., (1999), Tribological simulation of aluminum hot extrusion, Wear, **224**, pp. 216–225.
- Bjork, T., Berger, M., Westergard, R., Hogmark, S. and Bergstorm, J., (2001), New physical vapour deposition coatings applied to extrusion dies, Surface and Coating Technology, **146-147,** pp. 33–41.
- Cao, J., Krishnan, N., Wang, Z., Liu, W. and Swanson, A., (2004), Microforming: Experimental investigation of the extrusion process for micropins and its numerical Simulation using RKEM, Journal of Manufacturing Science and Engineering, **126**, pp. 642–652.

- Chan, W.L., Fu, M.W. and Lu, J., (2011), The size effect on micro deformation behavior in micro-scale plastic deformation, Materials and Design, **32,** pp. 198–206.
- Chan, W.L., Fu, M.W. and Yang, B., (2011), Study of size effect in micro-extrusion process of pure copper, Materials and Design, **32,** pp. 3772–3782.
- Celik, K.F. and Chitkara, N.R., (2000), Application of an upper bound method to off-centric extrusion of square sections, analysis and experiments, International Journal of Mechanical Sciences, **42**, pp.321–345.
- Chen, C.T. and Ling, F.F., (1968), Upper bound solution to axisymmetric extrusion problems, International Journal of Mechanical Sciences, **10**, pp.863–879.
- Chen, C.T., (1970), Upper bound solutions to plane strain extrusion problems, ASME Journal of Engineering for Industry, **92**, pp. 158–164.
- Chen, F. K. and Tsai J. W., (2006), A study of size effects in micro-forming with micro-hardness tests, Journal of Materials Processing Technology, Vol. 177, pp. 146–149.
- Chen, F.K., Chuang, W.C. and Torng, S., (2008), Finite element analysis of multi-hole extrusion of aluminum- alloy tubes. Journal of Materials Processing Technology, **201**, pp. 150–155.
- Chenot, J.L., Felgeres, L., Avarenne, B.L. and Salencon, J., (1978) A numerical application of the slip line field method to extrusion through conical dies, International Journal of Engineering Science, **16**, pp. 263–273.
- Chitkara, N.R and Aleem, A., (2001), Extrusion of axi-symmetric tube from hollow and solid circular billet: a generalised slab method of analysis and some experiments, International Journal of Mechanical Sciences, **43**, pp. 1661–1684.
- Choi, H. J., Choi, J. H. and Hwang, B. B., (2001), The forming characteristics of radial- backward extrusion, Journal of Materials Processing Technology, **113**, pp.141-147

- Conning, S.W., Farmer, L.E. and Oxley, P.L.B., (1982a), Strain-hardening extrusion-I. Construction of slip line fields from experimental flow patterns, Journal of Mechanics and Physics of Solids, **30**, pp. 225–247.
- Conning, S.W., Farmer, L.E. and Oxley, P.L.B., (1982b), Strain-hardening extrusion-II. Analysis of slip line fields based on experimental flow patterns, Journal of Mechanics and Physics of Solids, **30**, pp. 249–263.
- Dieter, G.E., (1988), Mechanical Metallurgy, Mc. Graw-Hill Book Company.
- Dixit, P.M and Dixit, U.S., (2008), Modeling of metal forming and machining processes: By finite element and soft computing methods, Springer-Verlag, London.
- Dodeja, L.C. and Johnson, W., (1957), On the multiple hole extrusion of sheets of equal thickness, Journal of the Mechanics and Physics of Solids**, 5**, pp. 267–280.
- Dodeja, L. C. and Johnson, W., (1957), The cold extrusion of circular rods through square multiple hole dies, Journal of the Mechanics and Physics of Solids, **5,** pp. 281–295.
- Donati, L. and Tomesani, L., (2005), The effect of die design on the production and seam weld quality of extruded aluminum profiles, Journal of Materials Processing Technology, **164-165**, pp.1025-1031.
- Donati, L., Tomesani, L. and Shikorra, M., (2009), The effect of pocket shape in extrusion dies, International Journal of Materials Forming, **2**, pp. 97–100.
- Ebrahimi R., Reihanian, M. and Moshksar M.M., (2008)An analytical approach for radial-forward extrusion process, Materials and Design, **29**, 1694–1700

- Engel, U. and Eckstein, R., (2002), Microforming– from basic research to its realization, Journal of Materials Processing Technology, **125-126**, pp. 35–44.

- Eaves, A.E., Smith, A.W., Waterhouse, W.J. and Sansome, D.H., (1975), Review of the application of ultrasonic vibrations to deforming metals, Ultrasonics, **13**, pp.162–170.

- Fenton, R.G. and Durai Swamy, B., (1975), Slip line field solution of strain rate sensitive materials, International Journal of Machine Tools. Design and Research, **55,** pp. 105–115.
- Fang, G., Zhou, J. and Duszczyk, J., (2009), FEM simulation of aluminum extrusion through two-hole multi-step pocket dies, Journal of Materials Processing Technology. **209,** pp. 1981–1900.
- Fard, R. and Akhlaghi, F., (2007), Effect of extrusion temperature on the microstructure and porosity of A356-SiC$_p$ composites, Journal of Materials Processing Technology, **187-188**, pp.433–436
- Farmer, L.E. and Oxley, P.L.B., (1971), A slip line field for plane strain extrusion of an strain-hardening material, Journal of Mechanics and Physics of Solids, **19**, pp. 369–388.
- Farmer, L.E. and Oxley, P.L.B. (1990), An extrusion process for uniformly working metals, Annals of the CIRP, **2**, pp. 147–150.
- Fenton, R.G. and Durai Swamy, B., (1975), Slip-line field solution of extrusion of strain rate sensitive materials, International Journal of Machine Tool Design and Research, **15**, pp. 105–115.
- Geiger, M., Geibdorfer S. and Engel, U., (2007), Mesoscopic model: advanced simulation of microforming process, Production Engineering Research and Development, **1**, pp.79–84.

- Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N. and Engel, U., (2001), Microforming, CIRP Annals-Manufacturing Technology, **50**, pp. 445–462.

- Gordon, W.A., Van Tyne, C.J. and Moon, Y.H., (2007), Overview of adaptable die design for extrusions, Journal of Materials Processing Technology, **187-188**, pp.662–667.

- Green, A.P., (1955), On unsymmetrical extrusion in plane strain, Journal of the Mechanics and Physics of Solids, **3**, pp. 189−196.
- Gunasekera, J.S., Hoshino, S. and Brown, R.H., (1980), Extrusion of Non-circular sections through shaped dies, Annals of the CIRP, **29**, pp. 141−145.
- Gunasekera, J.S., Hoshino, S., (1982), Analysis of extrusion or drawing of polygonal sections through straightly converging dies, ASME Journal of Engineering for Industry, **104**, 38–45.
- Gunasekera, J.S., Gegal, H.L., Malas, J.C., Doraivelu, S.M. and Morgan, J.T., (1982), Computer aided process modelling of hot forging and extrusion of aluminum alloys, Annals of CIRP, Manufacturing Technology, **31**, pp. 131−135.

- Gunasekera, J.S., Gegel, H.L., Doraivelu, S.M. and Malas J.C., (1984), Computer aided design of "Multi-holed" streamlined dies, Annals of the CIRP, **33**, pp. 129−131.
- Gunasekera, J.S., Hoshino, S., (1985), Analysis of extrusion of polygonal sections through streamlined dies, ASME Journal of Engineering for Industry, **107**, 229–233.
- Hayashi, M., Jin, M., Thipprakmas, S., Murakawa, M., Hung, J-Chung., Tsai, Chung, Y. and Hung, C-Hua., (2003), Simulation of ultrasonic-vibration drawing using the finite element method (FEM), Journal of Material Processing Technology, **140**, pp. 30–35.
- Hirota, K., (2007), Fabrication of micro-billet by sheet extrusion, Journal of Materials Processing Technology, **191,** pp. 283–287.
- Hwang, B.C., Lee, H.I. and Bae, W.B., (2003), An UBET analysis of the non- axisymmetric combined extrusion process, Journal of Materials Processing Technology, **139**, pp.547−552.

- Huang, Guo-Ming., Wang, Jang-Ping., Lee, Hsien-Der. and Chang, Cheng-Sung., (2009), Rigid-plastic boundaries approach to the analysis of arbitrary profile dies in axisymmetric extrusion, Journal of Materials Processing Technology, **209**, pp.4351–4359.
- Huang, Z., Lucas, M. and Adams, M.J., (2002), Influence of ultrasonics on upsetting of a model paste, Ultrasonics, **40**, pp. 43–48.
- Ishikawa, T., Sano, H., Yoshida, Y., Yukawa, N., Sakamoto, J. and Tozawa, Y. (2006), Effect of extrusion conditions on metal flow and microstructures of aluminum alloys, Annals of the CIRP, **55**, pp. 275–278.
- Iwata, K., Osakada, K. And Fujino, S., (1972), Analysis of hydrostatic extrusion by finite element method, ASME Journal of Engineering for Industry, 94, pp. 697–703.
- Jeswiet, J., Geiger, M., Engel, U., Kleiner, M., Duflou, J., Neugebauer, R., Bariani, P., and Bruschi, S., (2008), Metalforming progress since 2000, CIRP Journal of Manufacturing Science and Technology, **1**, pp. 2–17.
- Jo, H.H, Lee, S.K., Ko, D.C and Kim, B.M., (2001), A study on the optimal tool shape design in hot forming process, Journal of Materials Processing Technology, **111**, pp. 127–131.
- Johnson, W., Mellor, P.B. and Woo, D.M., (1958), Extrusion through single hole staggered and unequal multi-hole dies, Journal of the Mechanics and Physics of Solids, **6**, pp. 203–222.
- Johnson, W., (1958), Experiments in the cold extrusion of rods of non circular sections, Journal of the Mechanics and Physics of Solids, **7** , pp. 37–44.
- Johnson, W., (1956), Experiments in plane-strain extrusion, Journal of the Mechanics and Physics of Solids, **4**, pp. 269–282.
- Joun, M.S. and Hwang, S.M., (1993), Optimal process design in steady state metal forming by finite element method-II: Application to die profile design in extrusion, International Journal of Machine Tools and Manufacture, **33**, 63–70.

- Juneja, B.L. and Prakash, R., (1975), An analysis for drawing and extrusion of polygonal sections, International Journal of Machine Tool Design and Research, **15**, pp. 1–30.
- Keife, H., (1993), Extrusion through two die openings: A 2D upper-bound analysis checked by plasticine experiments, Journal of Materials Processing Technology, **37**, pp. 189–202.
- Kim, Y. T. and Ikeda, K., (2000), Flow behavior of the billet surface layer in porthole die extrusion of aluminum, Metallurgical and Materials Transactions A, **31A**, pp. 1635-1643.
- Kiuchi, M., (1988), Computer aided simulation of unsteady metal flow in non-axisymmetric extrusion, CIRP Annals-Manufacturing Technology, **37,** pp. 251–254.
- Kobayashi, R. and Thomesn, E.G., (1965), Upper bound and lower bound solution to axisymmetric compression and extrusion problems, International Journal of Mechanical Sciences, **7**, pp.127–143.
- Krishnan, N. Cao, J. and Dohda, K., (2007), Study of the size effect on friction conditions in microextrusion—Part I: Microextrusion experiments and analysis, Journal of Manufacturing Science and Engineering, **129**, pp. 669–676.
- Kumar, S. and Vijay, P., (2007), Die design and experiments for shaped extrusion under cold and hot condition, Journal of Materials Processing Technology, **190**, pp. 375–381.
- Laue, K. and Stenger, H., (1981), Extrusion: Processes, Machinery, Tooling, American Society for Metals.
- Lee, C.H., Iwasaki, H. and Kobayashi, S., (1973), Calculation of residual stresses in plastic deformation processes, ASME Journal of Engineering for Industry, 95, pp. 283–291.

- Lee, E.H., Mallet, R.L. and Yang, W.H., (1977), Stress and deformation analysis of the metal extrusion process, Computer Methods in Applied Mechanics and Engineering, **10**, pp. 339–353.
- Lepadatu, D., Hamblen, R., Kobi, A. and Barreau, A., (2006), Statistical investigation of die wear in metal extrusion process, International Journal of Advanced Manufacturing Technology, **28**, pp.272–278.
- Lesniak, D. and Libura, W., (2007), Extrusion of sections with varying thickness through pocket dies, Journal of Materials Processing Technology, **194**, pp. 38–45.
- Li, F. Chu, G.N. and Feng, S.L., (2010), Effect of die aperture offset on flow behavior in an extrusion process with aluminum alloy, Proceedings of the Institution of Mechanical Engineers, Journal of Engineering Manufacture, **224**, pp. 1425–1430.
- Li, Q., Smith, C.J., Harris, C. and Jolly, M.R., (2003a), Finite element investigations upon the influence of pocket die designs on metal flow in aluminum extrusion Part I. Effect of pocket angle and volume on metal flow, Journal of Materials Processing Technology, **135**, pp. 189–196.
- Li, Q., Smith, C.J., Harris, C. and Jolly, M.R., (2003b), Finite element modeling investigations upon the influence of pocket die designs on metal flow in aluminum extrusion Part II. Effect of pocket geometry configurations on metal flow, Journal of Materials Processing Technology, **135**, pp. 197–203.
- Lin, C. and Ransing, R.S., (2009), An innovative extrusion die layout design approach for single-hole dies, Journal of Materials Processing Technology, **209**, pp. 3416–3425.
- Luri, R., Luis Perez, C.J., Salcedo, D., Puertas, I., Leon, J., Perez, I. and Fuertes, J.P., (2011), Evolution of damage in AA-5083 processed by equal

channel angular extrusion using different die geometries, Journal of Materials Processing Technology, **211**, pp. 48–56.

- Mahadevan, P., (2006), Numerical and Experimental study of axisymmetric cold forging process, M. Tech Thesis, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India.
- Mahayotsanun, N., Lee, H.C. and Cheng, T.J., (2009), Development of high-speed micro-extrusion machine to investigate size, stain rate and tribological effects, International Conference on Micro Manufacturing (ICOMM), 4M/ICOMM, pp. 383–386.
- Malapani, M. and Kumar, S., (2007), A feature based analysis of tube extrusion, Journal of Materials Processing Technology, **190**, pp. 363–374.
- Medarno, R.E., Hinesley, C.P., Gillis, P.P and Conard, H., (1978), Visioplasticity analysis of 2024 aluminum alloy extrusion, International Journal of Mechanical Sciences, 15, pp. 955–965.
- Milind, T.R. and Date, P.P., (2008), Micro-extrusion–Challenges and Developments, Metalworld, pp. 20–23.
- Misiolek, W.Z., (1996), Material physical response in the extrusion process, Journal of Materials Processing Technology, **60**, pp.117–124.
- Mori, L.F., Krishnan, N., Cao, J. and Espinosa, H.D., (2007), Study of the size effects and friction conditions in microextrusion–Part II: Size effect in dynamic friction for brass-steel pairs, Journal of Manufacturing Science and Engineering, 129, pp. 677–689.
- Muammer, K and Tugurl, O., (2011), Fundamentals of Micro-manufacturing, Micro-manufacturing: Design and Manufacturing of Micro-products, John Wiley & Sons.
- Muller, K. B., (2006), Bending of extruded profiles during extrusion process, International Journal of Machine Tools and Manufacture, **46**, pp. 1238–1242.

- Murakawa, M. and Jin, M., (2001), The utility of radially and ultrasonically vibrated dies in the wire drawing process, Journal of Materials Processing Technology, **113**, pp. 81–86.
- Narayanasamy, R., Ponalagusamy, R., Venkatesan, R. and Srinivasan, P., (2006), An upper bound solution to extrusion of circular billet to circular shape through cosine dies, Materials and Design, **27**, pp. 411–415.
- Noorani-Azad, M., Bakhshi-Jooybari, M., Hosseinipour, S.J. and Gorji, A., (2005), Experimental and numerical study of optimal die profile in cold forward extrusion of aluminum, Journal of Materials Processing Technology, **164-165**, 1572–1577.
- Oh, Hunk-K. and Phark, Joung-W., (1987), A study of the axisymmetric forward extrusion of porous metal through a square die, Journal of Mechanical Working Technology, **15**, pp. 119–130.
- Olejnik, L., Presz, W. and Rosochowski, A., (2009), Backward extrusion using micro-blanked aluminum sheet, International Journal of Materials Forming, **2**, pp. 617–620.
- Onuh, S.O., Ekoja, M. and Adeyemi, M.B., (2003), Effect of die geometry and extrusion speed on the cold extrusion of aluminum and lead alloys, Journal of Materials Processing Technology, **132**, pp.274-285.
- Osakada, K. and Niimi, Y., (1975), A study on radial flow field for extrusion through conical dies, International Journal of Mechanical Sciences, **17**, pp. 241–254.
- Parasiz, S.A., Kinsey, B.L., Mahayatsanun, N. and Cao, J., (2011), Effect of specimen size and grain size on deformation in micro extrusion, Journal of Manufacturing Processes, **13**, 153–159.
- Parasiz, S.A., Krishnan, N., Cao, J. and Li, M., (2007), Investigation of deformation size effects during microextrusion, Transactions of the ASME, Journal pf Manufacturing Science and Engineering, **129,** pp. 690–697.

- Peng, Z. and Sheppard, T., (2004), Simulation of multi-hole die extrusion, Materials Science and Engineering A, **367**, pp. 329–342.
- Peng, Z. and Sheppard, T., (2005), Effect of die pockets on multi-hole die extrusion, Materials Science and Engineering A, **407**, pp. 89–97.
- Plancak, M., Bramley, A. and Osman, F., (1992), Non-conventional cold extrusion, Journal of Materials Processing Technology, **34**, pp. 465–472.
- Pohlman, P. and Lehfeldt, E., (1966), Influence of ultrasonic vibration on metallic friction, Ultrasonics, **4**, pp. 178–185.
- Qin, Yi., (2006), Micro-forming and miniature manufacturing systems-development needs and perspectives, Journal of Materials Processing Technology, **177**, pp. 8–18.
- Qin, Yi., Brockeett A., Ma, Y., Razali, A., Zhao, J., Harrison, C., Pan, W., Dai, X. and Loziak, D., (2010), Micro–manufacturing: research, technology outcomes and development issues, International Journal of Advanced Manufacturing Technology ,**47**, pp. 821–837.
- Reddy, N.V., Dixit, P.M. and Lal, G.K., (1995), Die design for axisymmetric extrusion, Journal of Materials Processing Technology, **55**, pp.331–339
- Reddy, N.V., Sethuraman, R. and Lal, G.K., (1996), Upper bound and finite element analysis of axisymmetric hot extrusion, Journal of Materials Processing Technology, **57**, pp.14–22.
- Saotome, Y. and Iwazaki, H., (2001), Superplastic backward microextrusion of microparts for micro-electro-mechanical systems. Journal of Materials Processing Technology. **119**, pp. 307–311.
- Shah, S.N and Kobayashi, S., (1977), A theory on metal flow in axisymmetric piercing and extrusion, Journal of Production Engineering, 1, pp.73.
- Shahzad, M. and Wagner, l., (2009), Microstructure development during extrusion in wrought Mg-Zn-Zr alloy, Scripta Materialia, **60**, pp. 536–538.

- Sheppard, T., (1999), Extrusion of aluminum alloys, Kluwer Academic Publishers, The Netherlands.
- Schikorra, M., Donati, L., Tomesani, L. and Kleiner, M., (2007), The role of friction in the extrusion of AA6060 aluminum alloy process analysis and monitoring, Journal of Materials Processing Technology, **191**, pp. 288–292.
- Schikorra, M., Donati, L., Tomesani, L. and Tekkaya, A.E. (2008), Microstructure analysis of aluminum extrusion: Prediction of microstructure on AA6060 alloy, Journal of Materials Processing Technology, **201**, pp. 156-162.
- Shiraishi, M., Nikawa, M. and Goto, Y., (2003), An investigation of the curvature of bars and tubes extruded through inclined dies, International Journal of machine Tools and Manufacture, **43**, pp. 1571–1578.
- Siegert, K and Ulmer, J., (2001), Superimposing ultrasonic waves on the dies in tube and wire drawing, Journal of Engineering Materials and Technology, **123,** pp. 517–523.
- Sinha, M.K., (2008), Modeling and experimental investigation of multi-hole extrusion process, M. Tech thesis, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India.
- Sinha, M.K., Deb, S. and Dixit, U.S., (2009a), Design of a multi-hole extrusion process, Materials and Design, **30**, pp. 330–334.
- Sinha, M.K., Deb, S., Das, R. and Dixit, U.S. (2009b), Theoretical and experimental investigations on multi-hole extrusion process, Materials and Design, **30**, pp. 2386–2392.
- Solomon, N. and Solomon, I., (2010), Effect of die shape on the metal flow pattern during direct extrusion process, Revista De Metalurgia, **46**, pp.396–404.

- Sortais, H.C. and Kobayashi, S., (1968), An optimum die profile for axisymmetric extrusion, International Journal of Machine Tool Design and Research, **8**, pp. 61–72.
- Srinivasan, R., Gunasekera, J.S., Gegel, H.L. and Doraivelu, S.M., (1990), Extrusion through controlled strain rate dies, Journal of Material Shaping Technology, **8**, pp. 133–141.
- Talbert, S.H and Avitzur, B., (1996), Elementary mechanics of plastic flow in metal forming, John Wiely & Sons, England.
- Talebanpour, B., Ebrahimi, R. and Janghorban, K., (2009), Microstructural and mechanical properties of commercially pure aluminum subjected to dual equal channel lateral extrusion, Materials Science and Engineering A, **527**, pp. 141–145.
- Tayal, A.K. and Natrajan, R., (1981), Extrusion of rate sensitive materials using a viscoplastic constitutive equation and the finite element method, International Journal of Mechanical Sciences, 23, pp. 89–98.
- Thomsen, E.G., Yang, C.T. and Bierbower, J.B., (1954), An experimental investigation of the mechanics of plastic deformation of metals, University of California Press, Berkeley, **5**, pp. 89–114.
- Tiernan, P., Hillery, M.T., Draganescu, B. and Gheorghe, M., (2005), Modeling of cold extrusion with experimental verification, Journal of Materials Processing Technology, **168**, pp.360–366.
- Uematsu, Y., Tokaji, K., Kamakura, M., Uchida, K., Shibata, H. and Bekku, N., (2006), Effect of extrusion condition on grain refinement and fatigue behavior in magnesium alloy, Materials Science and Engineering A, **434**, pp. 131–140.
- Ulysse, P. and Johnson, R. E., (1998), A study of the effect of the process variables in unsymmetrical single-hole and multi-hole extrusion processes, Journal of Materials Processing technology, **73**, pp. 213–225.

- Verma, A.K., (2008), Experimental study and simulation of cold extrusion process, M. Tech Thesis, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India
- Vollertsen, F., (2008), Categories of size effects, Production Engineering Research and Development, **2**, pp. 377−383.
- Wagener, H. W. and Wolf, J., (1994), Coefficient of friction in cold extrusion, Journal of Materials Processing Technology, **44**, pp. 283−291.
- Waldo, A Yack and Sczepanski, Floyd H., (1955), Extrusion of Metals, United States patent Office, Patent no-2,720,310.
- Wang, J.P., (1997), A slip line approach to visioplasticity in plane strain extrusion by the finite flow line region techniques, Journal of Materials Processing Technology, **70**, pp.77−82.
- Wang, J.P., (1998), A new approach to visioplasticity in plane-strain extrusion, Journal of Materials Processing Technology, **79**, pp.144−154.
- Wifi, A.S., Shatla, M.N. and Abdel-Hamid, A., (1998), An optimum-curved die profile for the hot forward rod extrusion, Journal of Materials processing Technology, **73**, pp. 97−107.
- Wu, X., Li, J. J., Zheng, Z. Z., Liu, L. and Li, Y., (2010) Micro Back Extrusion of Bulk Metallic Glass, Scripta Materialia, **63**, Issue 5, pp. 469–472.
- Yang, D.Y. and Lange, K., (1984), Analysis of hydrofilm extrusion of 3D shapes from round billet, International Journal of Mechanical Sciences, **26**, pp. 1−19.
- Yang, D.Y., Han, C.H. and Lee, B.C., (1985), The use of generalized extrusion boundaries for the analysis of axisymmetric extrusion through curved dies, International Journal of Mechanical Sciences, **27**, pp. 653−663.
- Yang, D.Y., Kim, Y.G. and Lee, C.M., (1991), An upper bound solution for axisymmetric extrusion of composite rods through curved dies, International Journal of Machine Tools and Manufacture, **31**, pp. 565−575.

- Yang, D.Y. and Han, C.H., (1987), A new formulation of generalised velocity field for axisymmetric forward extrusion through arbitrarily curved died, ASME Journal of Engineering for Industry, **109**, pp. 161−168.
- Yang, D.Y. and Kang, Y.S., (1996), Analysis and design of industrial hot extrusion process through square dies for manufacturing complicated Al alloy profiles, Annals of the CIRP, **45**, pp. 239–243.
- Yeh, J-wei., Yuan, S-Ying. and Peng, C-Hung., (1997), Microstructures and tensile properties of an A1-12 Wt Pct Si alloy produced by reciprocating extrusion, Metallurgical and Materials Transactions A, **30A**, pp. 2503–2512.
- You-feng, HE., Shui-sheng, XIE., Lei, C., Guo-jie, H. and Yao, FU., (2010), FEM simulation of aluminum extrusion process in porthole die with pockets, Transactions of Nonferrous Metals Society of China, **20**, pp. 1067–1071.
- Yu, S., Hu-ping, Y. and Xue-yu, R. (2006), Discussion and prediction on decreasing flow stress scale effect, Transactions of Nonferrous Metals Society of China, **16**, pp. 132–136.
- Zienkiewicz, O.C., Jain, P.C. and Onate, E., (1978), Flow of solids during forming and extrusion; some aspects of numerical solutions, International Journal of Solid Suructures, **14**, pp. 15-
- Zimerman, Z. and Avitzur, B., (1970), Metal flow through conical converging dies-A lower bound approach using generalized boundaries of the plastic zone, ASME Journal of Engineering for Industry, **92**, pp. 119−129.

Appendix

Appendix A

Specifications of the Different Machines Used for Carrying Out Experiments

1. Universal Testing Machine

Model:	UTE 20
Capacity:	200 kN
Load resolution:	10 N
Load range with accuracy of measurement:	4–200 kN (±1.0%)
Stroke:	200 mm
Resolution of piston movement (Displacement)	0.1 mm
Straining/piston speed (no load)	0–150 mm/min
Clearance for compression test at fully descended working piston	0–700 mm
Clearance for tensile test at fully descended working piston	50–700 mm
Manufactured by:	Fuel Instrument and Engineers Pvt. Ltd Block No-1, Industrial Estate, Ichalkaranji, 416115, Maharastra, India.

Note: This machine has been used to carry out the extrusion with different multi-hole dies

2. Universal Testing Machine (INSTRON) Servo hydraulic dynamic testing machine

Model: 8801

Capacity: 100 kN

Actuator stroke: ±75 mm (±3 in)

Load cell height: 97 mm (3.8 in)

Actuator fully retracted: 63 mm (2.5 in)

Maximum daylight: 1480 mm (58.3 in)

Column spacing: 652 mm (22.1 in)

Column diameter: 70 mm (2.1 in)

Table height: 890 mm (35 in)

Overall width: 920 mm (36.2 in)

Overall depth: 546 (21.5 in)

Overall height (maximum): 2778 mm (109.4 in)

Weight: 625 kg (1375 lb)

Manufactured by: Instron Corporation
825 University Ave
Norwood, MA 02062-2643 USA

Note: This machine has been used for constrained multi-hole extrusion and multi-hole microextrusion due to its precision.

3. Hydraulic Press

Model: LM-17

Capacity: 2000 kN

Least Count: 2 kN

Stroke: 150 mm

Control: Manually operated speed regulator

Manufactured by: Lawrence & Mayo, New Delhi

Note: This machine has been used for constrained multi-hole extrusion due to it high load capacity.

4. Micro Tensile Tester

Model:	MICROTEST
Maximum load:	5 kN
Motor speed:	0.1–2.0 mm/min
Data sample time:	100 ms–5 sec
Maximum travel:	10 mm
Manufactured by:	DEBEN UK Ltd
	Sheepcote Hall, Stowupland
	Stowmarket, Suffolk 1P145 BS, UK.

Note: This machine has been used for measurement of micro tensile strength due to its suitability for smaller dimension products and accuracy.

5.Micro-hardness Tester

Model:	MICROMET 2101
Load range:	1–2000 gf
Calibration range:	0.1–2.0 mm/min
Data sample time:	0.5 micron
Dwell time:	5–99 sec (10–15 sec recommended)
Manufactured by:	Buehler Ltd
	41, Waukegan road
	Lake Bluff, Illinois 60044.

Note: This machine has been used to measure the micro hardness of the extruded products.

6. Polishing Machine (Variable speed polisher)

Model:	ECOMET –6
Speed range:	10–350 rpm (step increment of 10 rpm)
Applied force range	0–60 lbs
Manufactured by:	Buehler Ltd
	41, Waukegan road
	Lake Bluff, Illinois 60044.

Note: This machine has been used for polishing of the micro hardness of the specimen samples.

7. Surface Roughness Tester

Model:	Pocket Surf (EMD-1500-321)
Make:	Mahr
Measurement range:	R_a → 0.03 μm to 6.35 μm R_y → 0.2 μm to 25.3 μm R_{max} → 0.2 μm to 25.3 μm
Accuracy:	±0.01 μm
Evaluation length:	2.4 mm
Cut off length:	0.8 mm
Traverse speed:	5.08 mm per second
Probe type:	Piezoelectric
Maximum stylus force:	15.0 mN

Note: This machine has been used for surface roughness measurement of the extruded products.

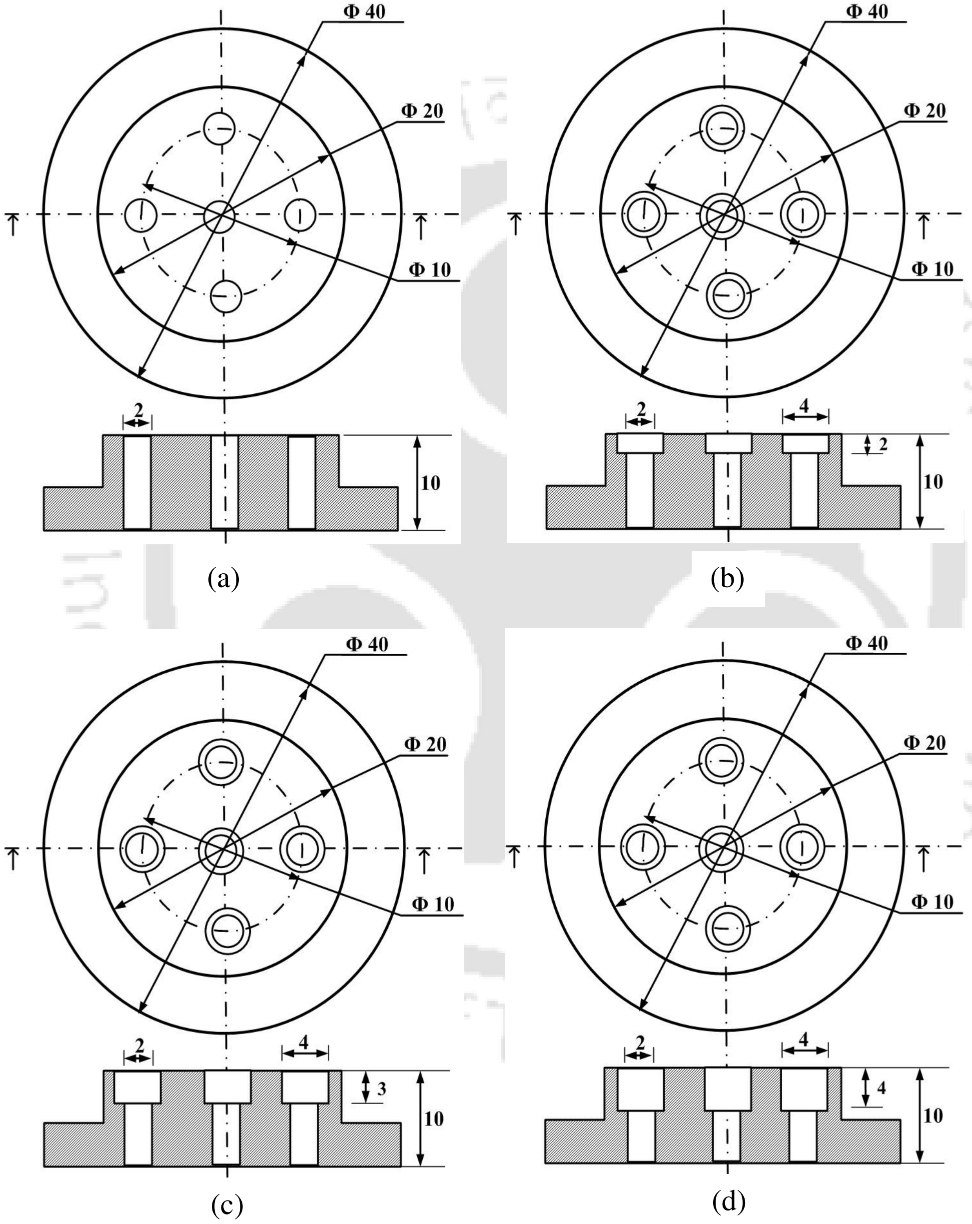
8. Scanning Electron Microscope

Model:	1430 VP
Resolution:	3.5 nm @30 kV (tungsten)
Magnification range:	15 X to 300 KX
Accelerating voltage:	200 V to 30 kV
Manufacturer:	Leo

Note: The machine has been used to find out the composition of the aluminum and lead billet materials.

Appendix B

Schematics of the Multi-hole Dies with Pockets



(a)

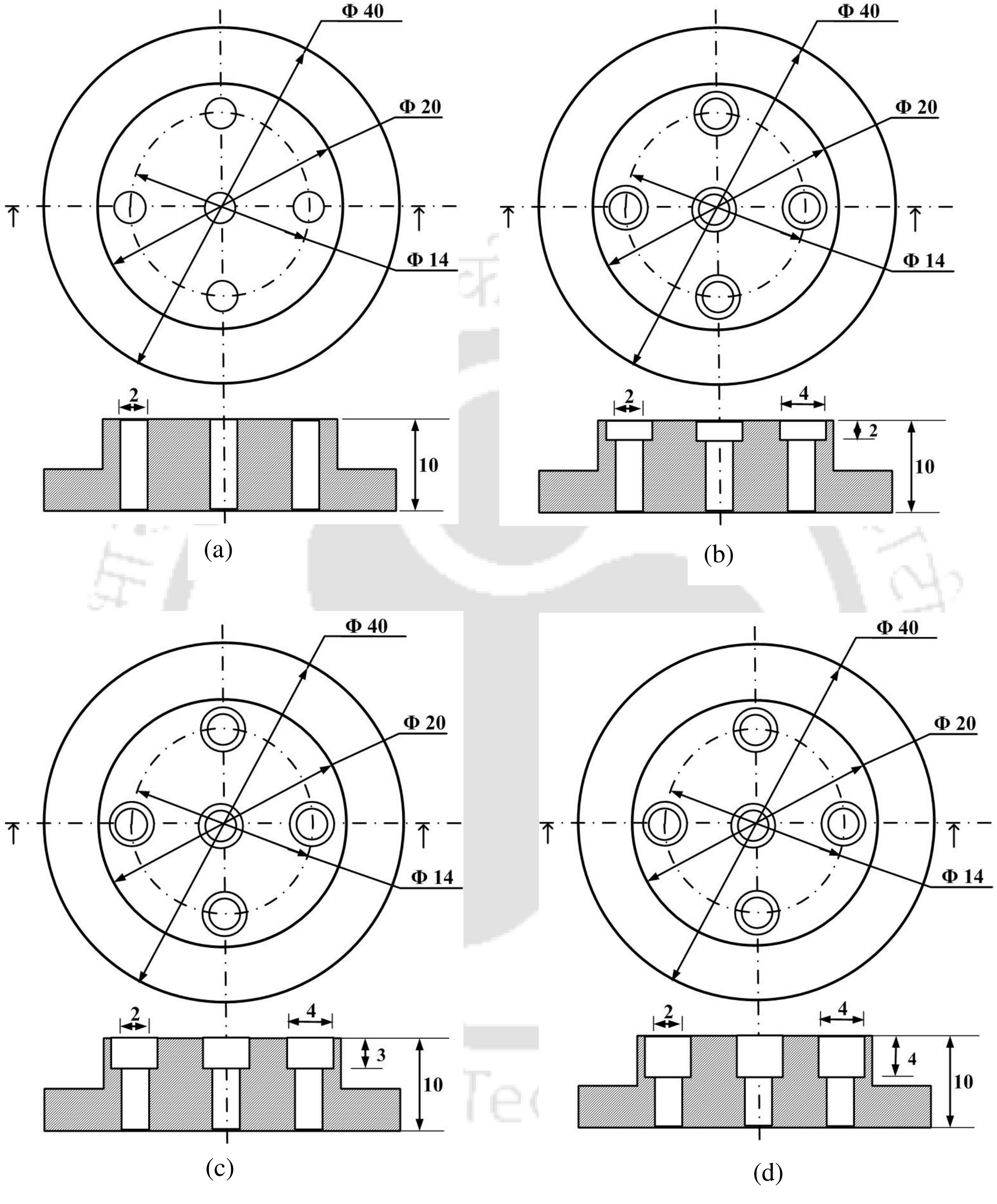
(b)

(c)

(d)

(All dimensions are in mm; drawing not to scale)

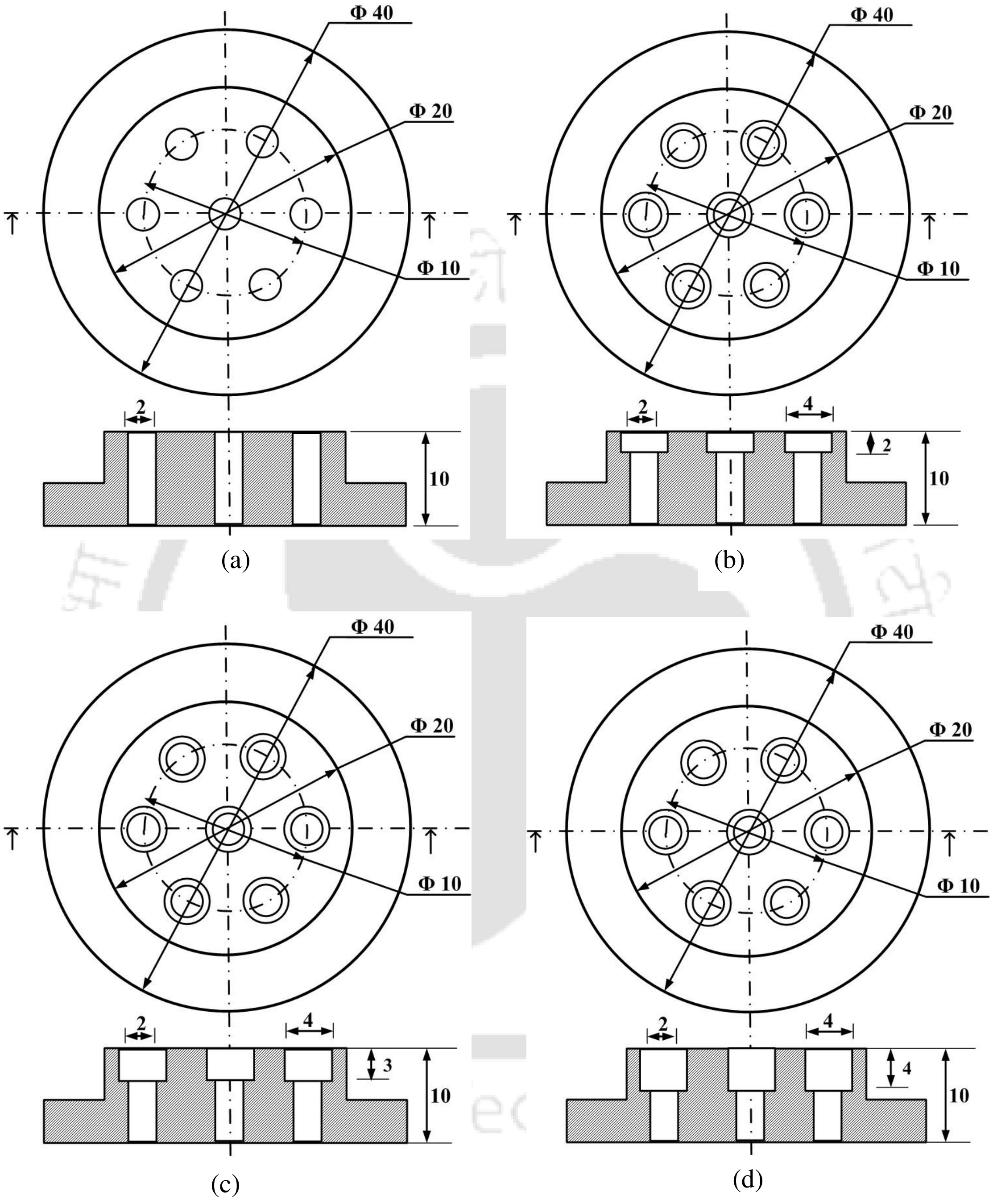
Figure B.1. Schematic of Die IV (a) no die pocket (b) pocket depth 2 mm (c) pocket depth 3 mm (d) pocket depth 4 mm.



(a) (b) (c) (d)

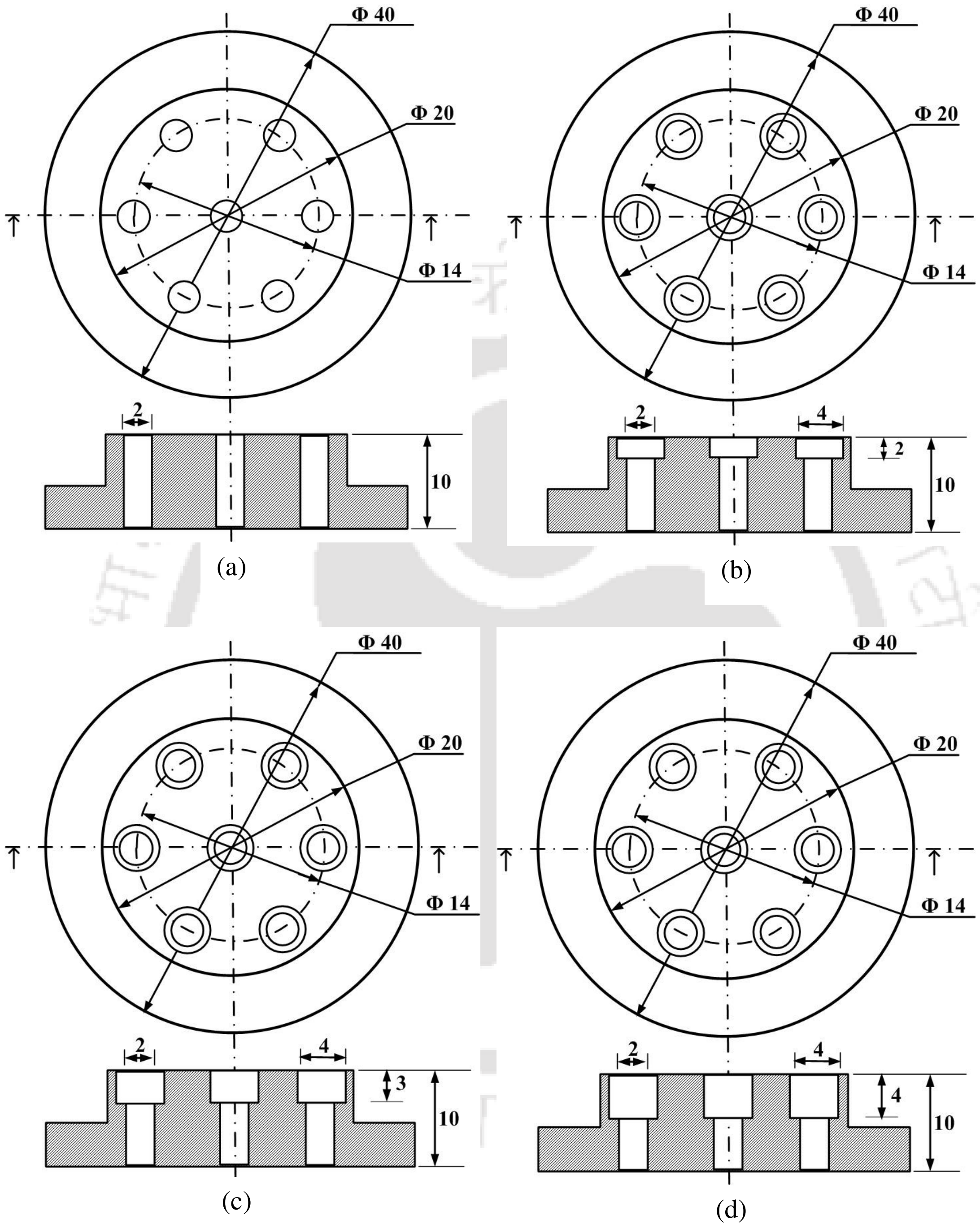
(All dimensions are in mm; drawing not to scale)

Figure B.2. Schematic of Die V (a) no die pocket (b) pocket depth 2 mm (c) pocket depth 3 mm (d) pocket depth 4 mm.



(All dimensions are in mm; drawing not to scale)

Figure B.3. Schematic of Die VI (a) no die pocket (b) pocket depth 2 mm (c) pocket depth 3 mm (d) pocket depth 4 mm.



(All dimensions are in mm; drawing not to scale)

Figure B.4. Schematic of Die VII (a) no die pocket (b) pocket depth 2 mm (c) pocket depth 3 mm (d) pocket depth 4 mm.

Appendix C

Hypothesis Testing using Student's *t*-test

1. Hypothesis test for micro hardness of lead products

When the test sample size is small, then the test of significance is carried out based on Student's *t*-test. The test of significance of two means of two small samples is carried out when it is necessary to ascertain that samples come from the populations having the same mean.

For measurement of micro hardness of the extrudates, three replicates were carried out. The hardness values were measured in 4-5 places. In the measurement of micro hardness of the extruded lead products, it is hypothesized that the means of the different sample do not differ significantly.

The null hypothesis is given by

H_0: $\overline{x}$ and $\overline{y}$ do not differ significantly. (C.1)

The t-statistic for the test of significance is

$$t = \frac{\overline{x} - \overline{y}}{s\sqrt{1/n_1 + 1/n_2}}, \tag{C.2}$$

$$s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}, \tag{C.3}$$

where $\overline{x}$ is the mean of a sample size of n_1 and $\overline{y}$ is the mean of a sample size of n_2 and *s* is the standard deviation. The degree of freedom is $n_1 + n_2 - 2$.

The micro hardness test was carried out for the extruded lead products obtained from the 5-hole, 9-hole and 13-hole dies. The dies with 10 and 3 mm die land lengths are used with and without lubrication conditions. As an example, the micro hardness of the products obtained from centre hole die are considered and discussed here. Tables C-1, C-2, C-3 and C-4 show the sample means, standard deviations and t-test values for the extrusion at different conditions.

The sample size $n_1 = n_2 = 5$. Two tailed critical *t*-value for the degree of freedom of 8 is 2.31 at 95% confidence level.

Sample calculation:

$\overline{x} = 10.88, \overline{y} = 10.64,$

$n_1 = n_2 = 5,\ s_1 = 0.601, s_2 = 0.336$

$$s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2},$$

Putting all given values, $s = 0.486$

$$t = \frac{\overline{x} - \overline{y}}{s\sqrt{1/n_1 + 1/n_2}}$$

$$t = \frac{10.88 - 10.64}{0.486\sqrt{1/5 + 1/5}} = 0.78$$

Table C-1. The t-test data for the hardness values of the extruded products from centre hole of 5-hole die (10 mm die land length, unlubricated condition)

Experiment 1		Experiment 2		Experiment 3	
Mean hardness value ($\overline{x}$) (VHN)	Standard deviation (s_1) VHN	Mean hardness value($\overline{y}$) (VHN)	Standard deviation (s_2) VHN	Mean hardness value($\overline{z}$) (VHN)	Standard deviation (s_3) VHN
10.88	0.601	10.64	0.336	10.42	0.248
t-test values					
Experiment 1 & 2		Experiment 2 & 3		Experiment 1 & 3	
0.78		1.192		1.583	

Table C-2. The t-test data for the hardness values of the extruded products from centre hole of 5-hole die (10 mm die land length, lubricated condition)

Experiment 1		Experiment 2		Experiment 3	
Mean hardness value ($\overline{x}$) (VHN)	Standard deviation (s_1) VHN	Mean hardness value ($\overline{y}$) (VHN)	Standard deviation (s_2) VHN	Mean hardness value ($\overline{z}$) (VHN)	Standard deviation (s_3) VHN
10.76	0.512	10.72	0.192	10.84	0.288
t-test values					
Experiment 1 & 2		Experiment 2 & 3		Experiment 1 & 3	
0.163		-0.775		-0.304	

Table C-3. The t-test data for the hardness values of the extruded products from centre hole of 5-hole die (3 mm die land length, unlubricated condition)

Experiment 1		Experiment 2		Experiment 3	
Mean hardness value ($\overline{x}$) (VHN)	Standard deviation (s_1) VHN	Mean hardness value ($\overline{y}$) (VHN)	Standard deviation (s_2) VHN	Mean hardness value ($\overline{z}$) (VHN)	Standard deviation (s_3) VHN
10.4	0.187	10.36	0.23	10.5	0.158
t-test values					
Experiment 1 & 2		Experiment 2 & 3		Experiment 1 & 3	
0.301		-1.122		-0.914	

Table C-4. The t-test data for the hardness values of the extruded products from centre hole of 5-hole die (3 mm die land length, lubricated condition)

Experiment 1		Experiment 2		Experiment 3	
Mean hardness value ($\overline{x}$) (VHN)	Standard deviation (s_1) VHN	Mean hardness value ($\overline{y}$) (VHN)	Standard deviation (s_2) VHN	Mean hardness value ($\overline{z}$) (VHN)	Standard deviation (s_3) VHN
10.28	0.13	10.28	0.13	10.36	0.092
t-test values					
Experiment 1 and 2		Experiment 2 and 3		Experiment 1 and 3	
0.0		-1.124		-1.124	

From the above tables it is observed that in all cases *t*-values are less than critical value of 2.31. Hence at 95% confidence level, the variation in the average hardness among the replicates is insignificant. Similar calculations for other observations have been carried out.

2. Hypothesis test for micro hardness of aluminum products

Hypothesis tests are carried out for the micro hardness value of the extruded aluminum products from 9-hole die with 15 and 10 mm die land lengths in lubrication condition. The hypothesis test carried out for the products obtained from 9-hole die with 15 mm die land length is discussed here. Table C-5 shows the sample means, standard deviations. Table C-6 shows the *t*-test values. In this case, the sample size is 4.

The t-statistic is calculated using Eq. (C.2).

Table C-5. The average hardness values and standard deviations of the aluminum extruded products from 9-hole die (15 mm die land length, lubricated condition)

Hole number	Experiment 1		Experiment 2		Experiment 3	
	Sample mean($\overline{x}$) VHN	Standard deviation (s_1) VHN	Sample mean($\overline{y}$) VHN	Standard deviation (s_2) VHN	Sample mean($\overline{z}$) VHN	Standard deviation (s_3) VHN
1	40.3	1.02	40.6	1.04	40.6	1.41
2	45.05	2.63	45.17	2.56	45.02	2.89
3	39.1	1.10	39.05	0.78	39.22	0.86
4	41.27	2.63	41.3	2.68	41.15	2.77
5	41.95	2	41.52	1.83	41.52	1.88
6	41.95	1.81	41.65	1.61	41.62	1.88
7	41.22	2.10	41.42	2.2	41.37	2.26
8	40.57	1.16	40.82	0.98	41.15	1.62
9 (centre)	41.82	2.4	41.6	1.9	41.55	2.09

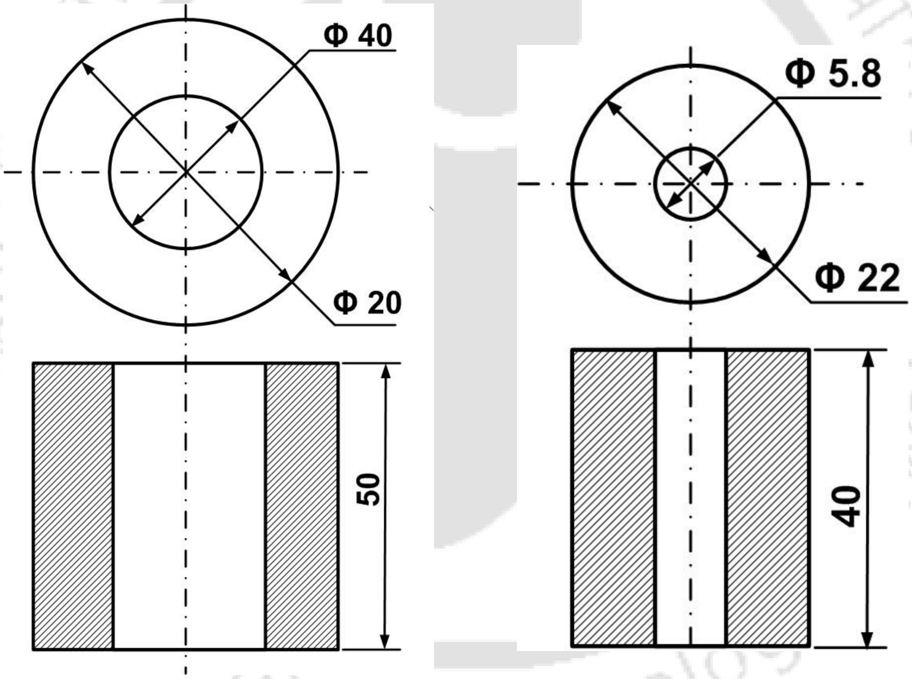
Table C-6. The t-test data for the hardness values of the aluminum extruded products from 9-hole die (15 mm die land length, lubricated condition)

Hole number	*t*-test value for experiment 1 and 2	*t*-test value for experiment 2 and 3	*t*-test value for experiment1 and 3
1	-0.412	-0.548	-0.466
2	-0.0653	-0.284	-0.04
3	0.074	1.18	1.136
4	-0.0159	0.138	-0.245
5	0.3172	0.214	-0.087
6	0.2476	0.342	0.869
7	0.1315	0.306	0.782
8	-0.3292	0.258	0.901
9 (centre)	0.1437	0.545	0.379

Two tailed critical value for the degree of freedom of 6 is 2.45 at 95% confidence level. The *t*-test values obtained from calculation are less than 2.45. Hence at 95% confidence level, the variation in the average hardness among the replicates is insignificant. Similar calculations have been carried out for the replicates of the experiments carried out with 10 mm die land length.

Appendix D

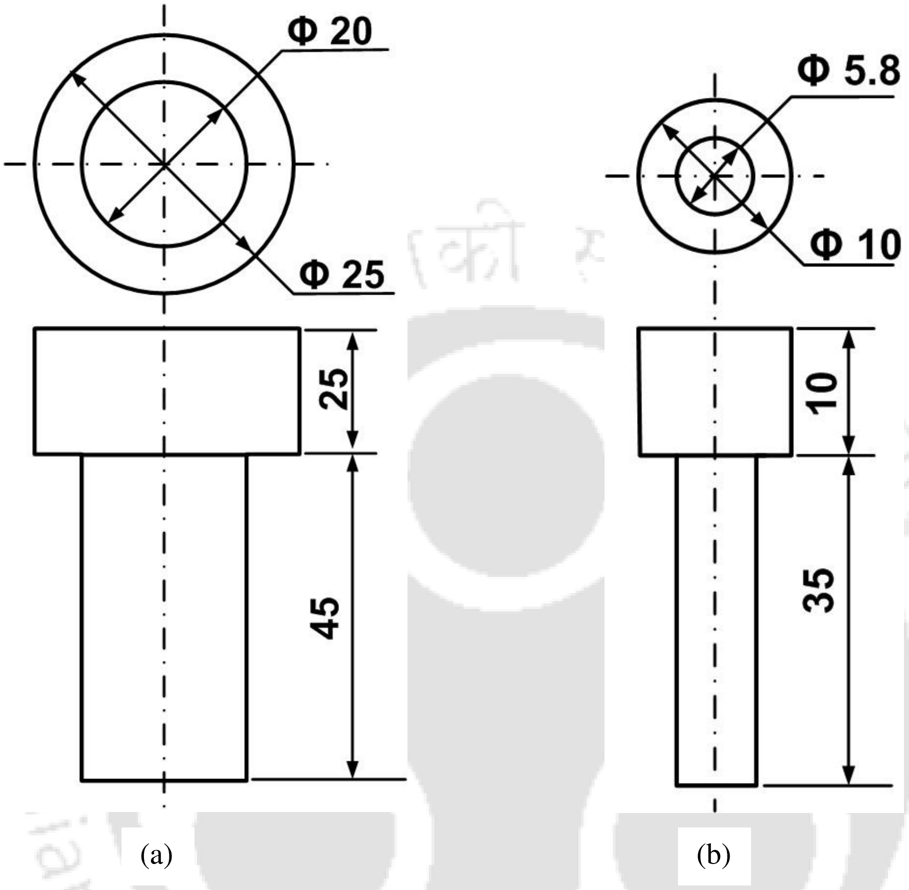
Drawings of Multi-hole Microextrusion Set up Components



(a) (b)

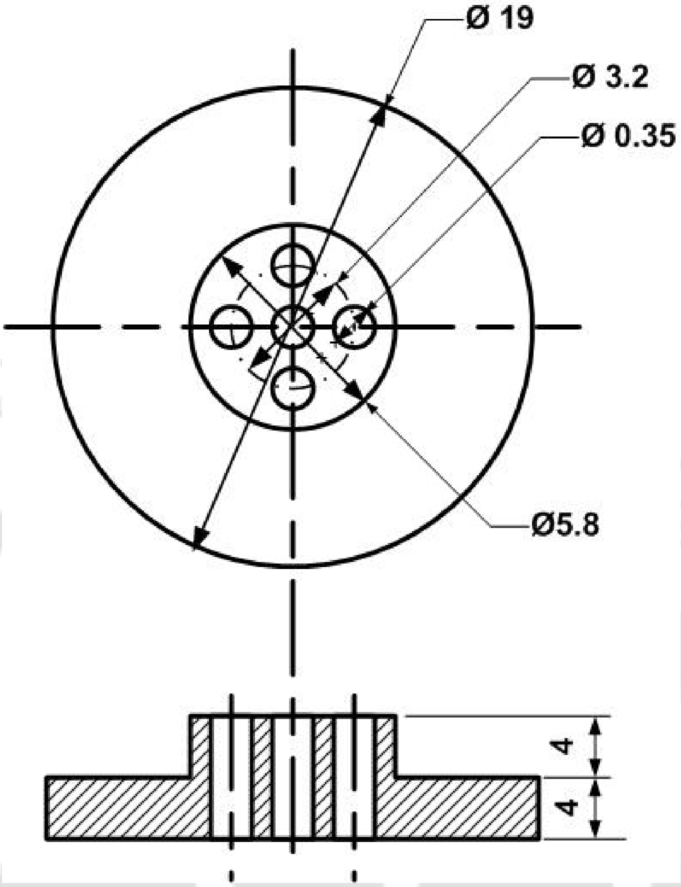
(All dimensions are in mm, drawing not to scale)

Figure D.1. Drawings of containers used for (a) meso extrusion (b) microextrusion (Old design)



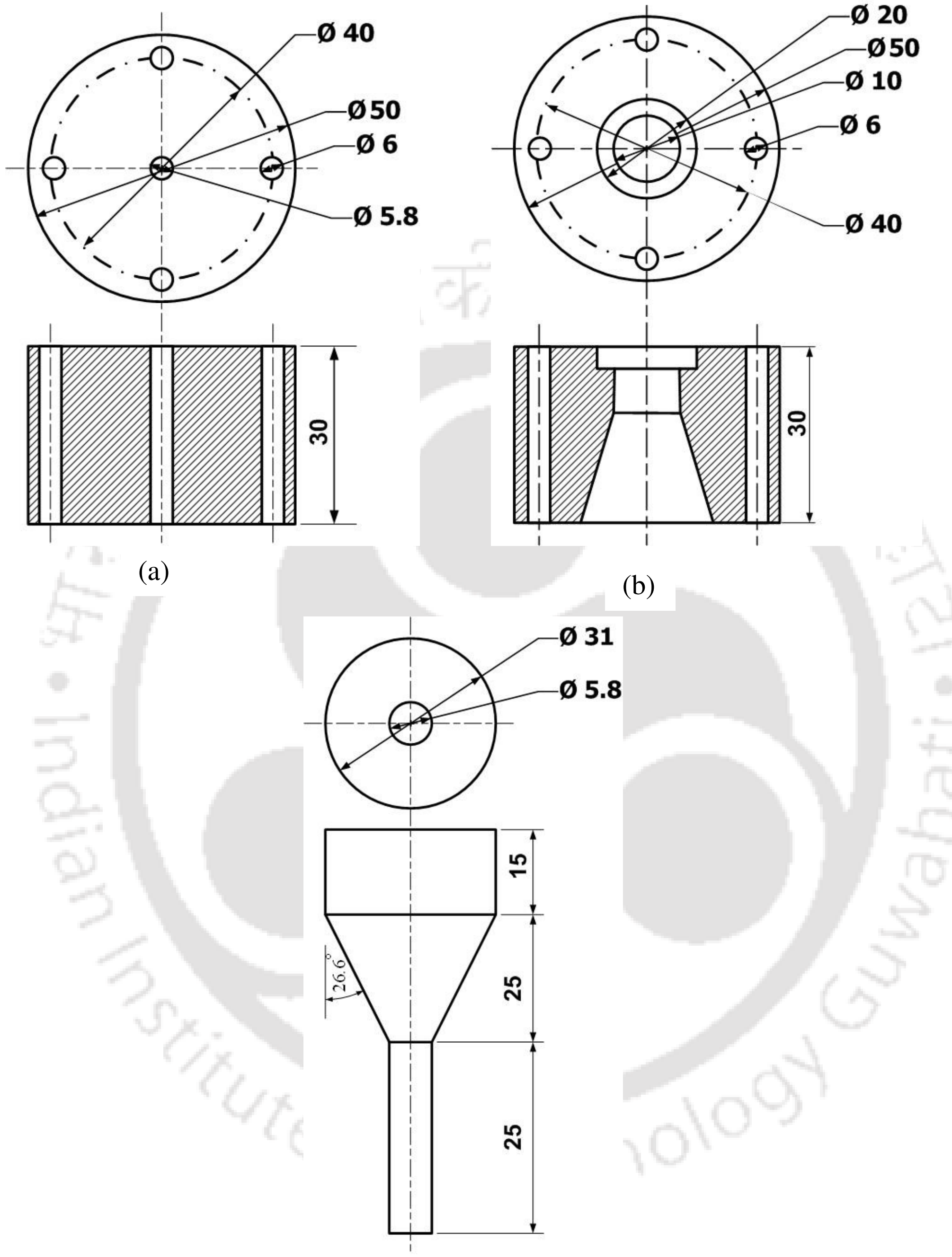
(All dimensions are in mm, drawing not to scale)

Figure D.2. Drawings of punch used for (a) meso extrusion (b) microextrusion (Old design)



(All dimensions are in mm, drawing not to scale)

Figure D.3. Drawing of micro multi-hole die



(a)

(b)

(c)

(All dimensions are in mm, drawing not to scale)

Figure D.4. Drawing of microextrusion set up (a) container (b) die holding block (c) punch (New design)

Publications from this research work

International Journals

1. R. Das, U. S. Dixit and S. Deb, Effect of die land length and lubrication on the mechanical properties of the extruded products in a multi-hole extrusion process: An experimental study, International Journal of Manufacturing Technology and Industrial Engineering (IJMITE), 1(2), pp. 175–179, 2010.
2. R. Das, U. S. Dixit and S. Deb, An experimental study on constrained multi-hole extrusion process, Journal of Machining and Forming Technologies, Vol.4, issue 1/2, 2012.
3. R. Das, U. S. Dixit and S. Deb, An experimental study on the effect of lubrication, die land length and vibration in multi-hole extrusion process, International Journal of Applied Industrial Engineering, in press
4. Ratnakar Das, U. S. Dixit and S. Deb, Effect of Extrusion Ratio, Die Land Length and Lubrication on Hardness and Surface Roughness in Multi-Hole Extrusion, International Journal of Manufacturing Technology Research (IJMTR), Vol.4, Issue 1/2, 2012.

International Conferences

1. R. Das, U. S. Dixit and S. Deb, Effect of die land length and lubrication on the mechanical properties of the extruded products in a multi-hole extrusion process: An experimental study, Proceedings of the 4th International Conference on Advances in Mechanical Engineering (ICAME), pp.418–422, S. V. National Institute of Technology, Surat-395007, Gujarat, India, September 23–25, 2010. [This paper has been published as International Journal paper number #1]
2. R. Das, U. S. Dixit and S. Deb, An experimental study on the effect of lubrication, die land length and vibration in multi-hole extrusion process, Proceedings of the 2nd International Conference on Production and Industrial Engineering (CPIE-2010), pp. 84–90, NIT Jalandhar, India, December 3–5, 2010. [This paper has been accepted for publication as International Journal paper number #3]

3. Ratnakar Das, U. S. Dixit and Sankha Deb, Effect of extrusion ratio, die land length and lubrication on hardness and surface roughness in multi-hole extrusion, Proceedings of the 3rd International and 24th AIMTDR Conference, pp. 971–976, Andhra University, Vishakapatnam, India, December 13–15, 2010. [This paper has been accepted for publication as International Journal paper number #4]
4. Ratnakar Das and U. S. Dixit, Effect of Die Pockets in Multi-Hole Extrusion Process, Proceedings of the International Conference on Computational Methods in Manufacturing (ICCMM2011), pp. 107–114, Indian Institute of Technology Guwahati, Guwahati, India, December 15–16, 2011.