# S & T INTERVENTION IN BELL METAL PRODUCT MANUFACTURING: PROCESS IMPROVISATION, PRODUCT DIVERSIFICATION AND DRUDGERY FREE WORKSTATION DESIGN

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**DOCTOR OF PHILOSOPHY**

by

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*Dedicated to all my respected Teachers*

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# CERTIFICATE

It is certified that the work contained in the thesis entitled **“S & T INTERVENTION IN BELL METAL PRODUCT MANUFACTURING: PROCESS IMPROVISATION, PRODUCT DIVERSIFICATION AND DRUDGERY FREE WORKSTATION DESIGN”** submitted by **Mr. PRANAY KUMAR SARKAR** 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 **School of Agro and Rural Technology**. This work has not been submitted elsewhere for the award of any other degree or diploma.

This thesis, in my opinion, has reached the standard fulfilling the requirements for the award of the degree of Doctor of Philosophy in accordance with the regulations of the institute.

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# SELF DECLARATION

I declare that,

a. The work contained in this thesis is original and has been carried out by me under the supervision of **Prof. Sashindra Kumar Kakoty**.

b. To the best of my knowledge, the work has not been submitted to any other institute for any degree or diploma.

c. I have followed all the guidelines provided by the institute in preparing the thesis.

d. Whenever I have used any materials (data, theoretical analysis, figures) from any other sources, due credit has been given to all of them by properly citing the documents.

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# ABSTRACT

*Small Scale Industries, like the **bell metal** (also known as high tin bronze/ β bronze/ kanah/ kansha) industry, plays significant roles in the economic activity of industrialized countries by creating new job opportunities on a large scale in the shortest period of time. In India, the bell metal (a copper-tin alloy having 75-80 percent copper and 20-25 percent tin on weight basis) industry provides employment to nearly 1 million people. The bell metal is extensively used for manufacturing of different industrial products viz., bearing, bushing, gears, valve, pump impeller etc. and domestic products viz., utensil, musical instruments, decorative items etc. due to its specific excellent properties viz., reverberating, resistance to corrosion and wear, high hardness and strength etc.*

*Though the bell metal industry worldwide enjoys heritage estates, field survey and literature review shows the industry is presently encompassed with several difficulties, such as age-old traditional production techniques, limited range of products, lack of modernization in terms of workstation, tools and equipments design, etc. The average annual transactions of the Sarthebari bell metal cluster have decreased from ₹11 million in 2017–18 to ₹7.5 million in 2019–20 and hence the workers are experiencing a very tough time. Moreover, the young artisans have started to leave the occupations due to the presence of a very high level of drudgeries with the current production units and hence, the bell metal industry is facing the manpower scarcity problem.*

*To encourage the young entrepreneurs, this Ph.D. thesis devotes towards the drudgery reduction from the bell metal products manufacturing industries through S&T interventions. Firstly, the thesis addressed the **mechanical properties** of bell metal processed in different conditions for improvisation of the present production process. Thereby, oil quenching has been evaluated to be superior for products that required finishing work at room temperature against the present practice of the water quenching process. Another aspect of this study is creating a database on the mechanical properties of bell metal processed in different conditions to help the engineers on selecting the exact processing conditions for the specific applications. Thereafter, this thesis invented that the bell metal can be joined through **TIG welding** process and then different sets of TIG welding parameter has been proposed based on **Pareto optimal solutions** for various applications. The outcome of this study will open new markets for the industry by allowing the production of diversified welded bell metal products. Further, the thesis advocated for statistically determining the level of **drudgeries** associated with the present bell metal production process. The level of drudgeries experienced by bell metal workers has also been confirmed through the digital human modelling. Eventually, a user-centric ergonomically correct workstation has been proposed along with the dimensions of few regularly used tools and equipments to reduce the level of drudgeries experienced by the bell metal artisans. Finally, the amount of **copper leached** in the drinking water from the bell metal utensils has been measured to prove the existing perceptions of the health benefits of using the bell metal utensils. Overall from the thesis work, it has been expected that due to reduced drudgery and increased efficiency of the **designed workstation**, on implementation, the young artisans who began to leave the trade will start to return to the occupation and hence the manpower scarcity problem will be resolved. Moreover, due to the opening of new markets and improved production process, the income level of artisans will increase and hence, the standard of living of millions of people engaged with the industry will improve.*

**Keywords:** *Bell metal, Mechanical properties, TIG welding, Pareto optimal solution, Drudgery, Workstation design, Copper leaching.*

# CONTENTS

# LIST OF NOMENCLATURE

| | |
|---|---|
| $\alpha, \beta, \gamma, \delta, \eta$ | Different microstructural phases |
| A, B, C | Different microstructural zones |
| P, Q, R, S | Phase transition temperatures |
| Y | Output welding quality |
| I | Welding current |
| V | Welding voltage |
| S | Welding speed |
| d | Stand-off distance |
| $R_{max\_c}$ | Maximum compressive stress |
| $R_{max\_t}$ | Maximum tensile stress |
| E | Modulus of elasticity |
| n, N | Number of respondents |
| $\varphi$ | Confidence level |

# LIST OF ACRONYMS

| | |
|---|---|
| AAS | Atomic Absorption Spectroscopy |
| ANOVA | Analysis of Variance |
| ASTM | American Society for Testing and Materials |
| BCC | Body Centered Cubic |
| BMI | Body Mass Index |
| BSA | Body Surface Area |
| CATIA | Computer Aided Three-Dimensional Interactive Application |
| CDA | Copper Development Authority |
| CV | Coefficient of Variation |
| DC | Direct Current |
| DOF | Degree of Freedom |
| DSC | Differential Scanning Calorimetry |
| DTA | Differential Thermal Analysis |
| EDX | Energy Dispersive X-ray spectrometer |
| FCC | Face Centered Cubic |
| FESEM | Field Emission Scanning Electron Microscope |
| FSSAI | Food Safety and Standards Authority of India |
| FZ | Fussion zone |
| HAZ | Heat-Affected Zone |
| HV | Hardness Value |
| MSD | Musculoskeletal Disorders |
| MSLP | Modified Systematic Layout Planning |
| RSM | Response Surface Method |
| RULA | Rapid Upper Limb Assessment |
| SC | Simple Cubic |
| SD | Standard Deviation |
| SEM | Standard Error of the Mean |
| SLP | Systematic Layout Planning |
| SRD | Space Relationship Diagram |
| SSI | Small Scale Industry |
| SSIs | Small Scale Industries |
| S&T | Science and Technology |
| TEW | Tools, Equipment and Workstations |
| TIG | Tungsten Inert Gas |
| UTM | Universal Testing Machine |
| UTS | Ultimate Tensile Strength |
| WEDM | Wire Electric Discharge Machine |
| WHO | World Health Organization |
| XRD | X-ray Diffraction |

# LIST OF FIGURES

# LIST OF TABLES

# Chapter 1 INTRODUCTION, LITERATURE REVIEW, OBJECTIVES

## 1.0 Introduction

The Small Scale Industries (SSIs), like the bell metal (also known as high tin bronze/ β bronze/ kanah/ kansha) industry, have been found to be most valued vehicles for economic growth of industrialized nations. This chapter gives an outline of the present scenario of the bell metal industry (field study report), motivations of the present study, summary of literature review and possible scope of S&T interventions for further development of the industry.

## 1.1 Background

SSIs play significant roles in the economic activity of advanced industrialized nations such as Germany, Japan, the United Kingdom and the United States of America etc. by creating new job opportunities on a large scale in the shortest period of time [1–4]. During the severe economic meltdown in America and Europe, both developed and developing nations have realized that the Small Scale Industry (SSI) sector is one of the most valued vehicles for economic growth. The capacity of SSIs to create jobs in Japan has been found to be the greatest in the world. Today in Japan, the SSIs account for more than 50% of the total exports and employ approximately 80% of private-sector industrial workers and hence, play a significant role in the country's industrial structure [2].

Prof. K.T. Shah was the first Indian economist to recognize and highlighted the importance of SSIs in India. He defined SSI as "An enterprise or series of operations carried on by a workman skilled in the craft on his responsibility, the finished product of which he markets himself." Later, M.K. Gandhi and Rabindranath Tagore play crucial roles to strongly motivate the people of India to understand the silent features of the SSIs in the economic regeneration of the country. In 1955, the Karve committee recommended several programmes on SSIs as an eliminator of rural poverty and as an agency for rural development activities [5].

Today, the SSIs constitute a very important segment of the Indian economy and significantly contributes to the socio-economic objectives of growth in the generation of employment, expansion of the export markets, dispersal of industries, decentralization of the economic power and promotion of entrepreneurship. Currently, in India, the total number of working SSIs is 44,45,868 (registered SSIs 9,01,291), accounts for around 95% of the total industrial units, out of which 39.69% are engaged with manufacturing activities and 55.21% are located in rural areas providing direct employment to 2,49,32,763 persons (61,63,479 employees in registered SSIs). The gross output of SSIs is ₹2,82,26,99.8 million [6].

In India, the small scale metallic craft industries have been recognized as one of the most important SSIs. The history of the small scale metallic craft industry in India dates back to the Vedic period (about the 15th century B.C.) [7]. According to local folklore, progenitor of the *Panchala* tribe (in Telegu *Kamsalas* and in Tamil *Kammalaras*) has five sons, namely *Manu, Maya, Twastra, Silpi* and *Visvajana,* known for their individual expertise in iron, wood, copper and copper alloys, stone and gold & silver respectively [7]. Numbers of papers written by British administrators show that prior to British colonization, there was a worldwide glory of Indian metallic crafts [7–10]. However, during colonization, Indian artisans have begun to produce only ornamental products to meet the European market demands and hence started to lose their skills of producing diversified metallic crafts [9–11]. After independence, the nonferrous industries have started to regrow at full-fledged and as a result, produced 2950 tons (worth ₹63.75 million according to 1952) of non-ferrous alloy products [12, 13]. Latter, copper and its alloy industries have slowly ousted the aluminium industries due to high scrap value and attractive lustres [12, 14]. Moreover, lurking suspicion of aluminium toxicity has favoured the conditions for more expansion of copper and its alloy industries [12]. Currently, Bidri (Karnataka) works on copper and silver; Jharkhand, Madhya Pradesh and Himachal Pradesh work on leaded copper by *Dhokra* techniques; Assam, Kerala, Manipur, Odisha and West Bengals works on Bell metal; Punjab works on copper; Gujrat, Rajasthan and Uttar Pradesh work on brass metal are few of the famous metal craftworks present in India drawing worldwide attention due to its unique products [3, 15–18]. Out of all of the copper and copper alloys, brass and bell metal products are extensively and alternatively used in India [17, 19, 20]. Technically, the bell metal processing for the production of different items is more difficult, compared to brass and other copper alloys, due to its brittle nature [21, 22].

Despite of processing difficulties, bell metal products are largely used in India and have a very extraordinary demand due to its specific properties, religious conventions, the existing belief of health benefits and higher average lifespan of 15 years (10 years for brass products) in regular daily use [12, 23, 24]. India is the largest producer of bell metal items [3, 19]. Bhutan, Nepal, Sri Lanka and Bangladesh are the major exporter of bell metal items manufactured in India [15, 16]. Bell metal industry shares nearly 3% of total India SSI economy and provides direct and indirect employment to nearly 1 million people [25, 26].

## 1.2 Bell metal

Bell metal is a binary copper-tin alloy containing 20 – 25 percent tin (Sn) and 75–80 percent copper (Cu) on the weight basis along with less than 1% other minor alloying elements being Mn, P, Fe and Si [27]. Bell metal is the hard form of bronze. The name "**bell metal**" is derived from its application in the manufacturing of the **bell** [20]. Bell metal is also known as *kanh/ kansha* in India and *high tin bronze/ β-bronze* in the archaeo-metallurgical world [22, 28]. The next section discusses few common uses and properties of bell metal.

## 1.3 Properties and applications of bell metal

In industry, bell metal is used for the manufacturing of bearing, bushing, gears, bells, valve, pump impeller, etc. [29, 30]. In various mechanical and electronic engineering applications, bell metal is extensively used due to its excellent resistance to wear, high hardness, thermal conductivity and moderately high strength [31, 32]. Bell metal also started drawing attention in some specialized industries because of its shape memory effects and super plasticity at elevated temperatures [33, 34]. Srinivasan (1994) [22] reports that bell metal products are preferred in industries due to its non-toxic nature and excellent corrosion resistance properties. Few other unique properties viz., long-lasting golden lustre, reverberating qualities etc., also help to maintain extraordinary industrial demand for bell metal [35–37]. The bell metal is also extensively used in the surface treatment industry, especially for decoration purposes, because of its excellent flow properties inside the mould and lower melting points [38]. Different bell metal products viz., cannon, measuring instruments, utensils, oil lamps, ornaments, decorative items, etc., are in regular use from prehistoric times, which represents a high level of technical maturity and rich cultural heritages [36, 39, 40]. Moreover, in India, especially in places like Assam, Kerala, Tamilnadu, Manipur, West Bengal, Gujrat, Karnataka, Rajasthan, Uttar Pradesh etc. bell metal utensils is exhaustively used due to traditional perceptions of different health benefits, which help to maintain the high market demand [15, 24]. Figure 1.1 shows few commonly used bell metal utensils. The next section discusses an overview of the bell metal industry, specifically describing the origin of the bell metal industry.

**Figure 1.1 Bell metal utensils**

## 1.4 Overview of bell metal industry

The bell metal industries are present all over the world. The bell metal industry has widely spread in Europe from the 6th century onwards for the casting of church bells [41]. In Germany, bell manufacturing industries were established between the 8th - 9th centuries (in Byzantium empire) [41]. The '*Marinelli Pontificia Fonderia di Campane'* established in 1339 is Italy's oldest bell metal industry [42]. Few famous works from this industry are 600kg bell of *Leaning tower of Pisa*, '*Jubilee bell'* of *St. peter Square,* etc. The *Church bell foundry*, established in 1570, is the oldest bell metal industry in the United Kingdom [43, 44]. This industry is renowned for the manufacturing of '*Liberty bell'*. The *Grassmayr bell foundry* is the largest and oldest bell metal industry in Austria [45, 46]. The industry was established in 1599 and is known for the manufacturing of '*Mösern Friedensglocke'* (peace bell) of weight 10 tons. The '*Motron Family'* of Moscow, Russia, is known for the manufacturing of the world's largest bell namely the '*Tsar Bell'* of weight 202 tons [47]. This bell was installed in the year 1735 but cracked at a very early stage because of the casting fault and is presently not in working condition [48]. However, Gnesin (2015) [41] claimed that the *Tsar bell* cracked due to induced thermal stress during the fire of 1737. Whereas, the '*Great Bell of Dhammazedi'* (also known as the *lost bell*), having a weight of 327.5 tons, is believed to be the largest bell of world history and it was manufactured in Myanmar [49].

In India, the bell metal industries are present through its length and breadth, particularly in Assam, Kerala, Karnataka, Manipur, Madhya Pradesh, Odisha, Tamil Nadu, Uttar Pradesh and West Bengal [15, 20]. However, the aesthetics peculiarity and items manufactured in various industries are found to differ from place to place [15]. It is considered under the green category industry in India, i.e., the pollution index is below 30 [50]. In Assam, this industry was introduced in different places by Ahom King *Chu Chengpha* (also known as *Burha Roja* or *Pratap Singha*) between 1611 to 1649 A.D. [9]. However, few ancient documents, especially the letters written by *Kumar Bhaskar Barman*, king of *Barman dynasty* to *Harshavardhana*, king of *Kannouj* show that the Sarthebari bell metal industry was present prior to of 7th century A.D. [16]. Presently, about 40% of the people who live in the Sarthebari area are engaged in bell metal works that consist of 280 manufacturing units employing almost 5000 workers [51]. In the year 2011–12, the Sarthebari bell metal industry produced 4,16,38,820kg of finished goods [52]. In Manipur, the bell metal industries are present in Imphal. According to *Cheitharol Kumbaba*, the ancient Meitei chronicle of Manipur, the bell metal industries were established by the Meitei king, *Charairongba,* during the 17th century for productions of roofing [53]. In Himachal Pradesh, the bell metal industries are present in Chamba and Palampur, famous for manufacturing hand bells [15]. Mannar is known as the '*Bell Metal Town of Kerala*', famous for manufacturing big church bells [54]. The bell metal industries are also present in Thiruvananthapuram of Kerala and famous for manufacturing deities. In Tamil Nadu, the bell metal industries are present in Kumbakonam and the Nachiarkoil town of Thanjavur district and known for manufacturing of excellent musical instruments. The origin of bell metal product manufacturing clusters in Kerala and Tamil Nadu has not been discovered yet, but written documents and archaeological evidence show that the industry was at its zenith during the Chola Period i.e. in 3rd century A.D. [55, 56]. Similarly, the Kantilo and Balasore in Odisha are known for their ritualistic bell metal handicraft industries [17]. The bell metal industry in Odisha was at its height of perfection during the rule of Ganga kings in the 11th Century A.D. [57]. In Uttar Pradesh, the bell metal industries are present in Mushirdabad and Varanashi. In West Bengal, the bell metal industries are present in the Bankura and Murshidabad. The bell metal industry of West Bengal was at its peak during the Malla dynasty in the 8th century A.D. [58]. It is estimated that around 2.5% of the total population (approximately 90,000 people) of Bankura districts are presently involved with the bell metal industry [19].

In spite of worldwide heritage estate, the bell metal industries are presently encompassed with several difficulties, such as the use of traditional age-old laborious production techniques, scarcity of manpower due to low wages and high drudgeries, and many more [19, 20, 58–60]. Therefore, urgent research for the development of the industry is in high demand to maintain its heritage status. The next section discusses the motivation of the present study.

## 1.5 Motivation to this study

Worldwide, appreciable interest in enhancing the small scale industries, especially the industries that have high heritage value like the bell metal industry, has been observed in the last few decades to meet the demand of ever-increasing job scarcity. The bell metal industry is available in different parts of the World, especially throughout the length and breadth of India, known for its unique items from ancient times and shares a significant amount in India SSI economy. The bell metal is also extensively used as engineering materials in different other industries for the production of several items. A small effort towards the improvement of the industry will have an impact on the millions of lives directly or indirectly engaged with the bell metal industry throughout the world. An attempt for the development of the industry will also help to mitigate the ever-present global problem of unemployment.

In view of the above mentioned motivations, the research was started by carrying out field surveys. Field survey provides the base to understand and monitor the present scenario of the industry. Field survey also helps to collect primary data which are not available in published documents. The research then forwards with literature review and is followed by defining the objectives according to the research gaps. The research has finished with a list of recommendations drawn from the exhaustive amount of works carried out in this thesis to fulfill the objectives. The next section discusses the field survey report on the bell metal industry.

## 1.6 Field survey

Field survey is one of the most common methods used by researchers to start a new investigation from scratch. In the current study, numerous field surveys were carried out in order to collect different types of data. The field survey started with the selection of study locations for the present study, followed by data collection and reporting. The next section discusses the selection of study locations.

### 1.6.1 Selection of study location

A bell metal products manufacturing industry located in Sarthebari (26.35ºN, 91.22ºE), Assam, India, is selected as a study area to carry out the field study because this place is the largest producer in North-East India and being the nearest bell metal manufacturing cluster to the institute. The Sarthebari bell metal industry is the second largest SSI of the North East after the Bamboo industry [51, 52, 61]. Sarthebari bell metal articrafts are world famous because of their 260 varieties of products, which are regularly used in day-to-day life as a representation of socio-economic conditions and the cultural milieu of Assamese people [62]. The next section discusses the types of data collected during the field surveys.

### 1.6.2 Data collection

The field surveys are carried out to gather the information's on the present source of raw material, types of raw material, the quantity of raw material processed per day, types of products manufactured, production times, types of activities performed per day, amount of waste generated per day, the number of total artisans involved, numbers of working clusters, working environment, physio-psychological conditions of artisans, level of drudgeries while performing the activities, infrastructure facility, annual turnover etc. The data during the field survey were collected through videos, still photos, questionnaires and personal interviews. Interactions with the artisans and customers were also carried out to find any other difficulties. The next section discusses observation reports from the field surveys.

### 1.6.3 Report from the field survey

In Sarthebari, old scrap material collected from the local market is used as raw material for the production of the next batch of items. The bell metal items which got defected during service due to various reasons are the source of the old scraps. The collected old bell metal scraps are first washed in water to avoid any unwanted contamination during production time. Then the scraps are broken into small pieces to fit in the melting crucibles. Earthen crucibles and charcoal-fired open furnaces are regularly used in Sarthebari for melting and heating purpose. The melting temperature is maintained between 1100ºC and 1200ºC. During melting, the crucible is covered with charcoal to avoid any high-temperature oxidation of raw material and hence the formation of slag. The molten metal is then poured into the open clay moulds and allows to cool in the air up to room temperature. Sometimes, the moulds are polished with crude oil or burnt Mobil. In each unit of the cluster, two artisans generally do casting between

6 am to 10 am daily. At this time, the artisans produce 10–12kg cast ingots of different sizes (each ingot weighs 500gm to 2kg) depending on the final products. The casted material is either a semi-finished product or an ingot. The cast ingots are then heated in the charcoal-fired open furnace to carry out the high-temperature beating process (technically termed as hot forging process). The heating and subsequent beating/hot forging is a repetitive process and continues till the final shape of the desired product is obtained. During forging, the temperature of the cast ingot is not allowed to fall below 550ºC. It is observed that, after a few initial repetitive cycles of heating and forging, the ingots are stacked and then the cycle continues. The forging process is carried out simultaneously by 3–4 artisans between 10 am to 12 pm. This process is the major source of waste generation in the production line. The failed products are again re-casted and followed the series of the manufacturing process to produce the products. According to artisans, the item fails in the production line due to non-uniform heating of the material during processing. Artisans informed that in each cluster, 30–35kg per month (i.e., nearly 1kg per day) of waste generates in each unit because of improper heating.

Then the forged items are again heated to a temperature up to 800ºC and then dipped into the water bath from that high temperature to cool up to the room temperature called the quenching process. Then cleaning is done to remove the black oxide layer formed on the surface of the water quenched and semi-finished cast products. This process is another source of waste generation in the production line. It is observed that nearly 0.5kg of waste per day in each unit is generated as oxides, which cannot be further used as raw material. Further, few products failed due to the use of improper tools. Figure 1.2 shows a bell metal product that failed during cleaning. These failed products are also re-casted and followed the same series of the manufacturing process to produce the products.

After cleaning, few artworks are also made on the surface of the water quenched products. No artworks are made on the casted products. Cleaning and art working of each item are done by individual artisans between 1.30 pm to 6.30 pm. The surface cleaning and art working are time-consuming operations and require the large attention of the workers. These two operations sometimes do not complete on the same day because of the above-mentioned reasons. Moreover, from interactions with the artisans, it was found that few customers (mostly from Bhutan and Bangladesh) preferred non-art worked products. They prefer to do artwork by themselves to represent their own cultures. The finished products are then packed and sold to the market. The bell metal products manufactured in Sarthebari are marketed in Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura. Figure 1.3 shows the different stages of the present manufacturing process of bell metal products.

**Figure 1.2 Failed bell metal products during cleaning**

In particular, to artisans working posture, it can be easily observed from Fig. 1.3 that workers have to adopt awkward postures during performing the tasks. Further, it is observed that during forging and surface cleaning activities, the workers need to move their body forcefully for a repeated number of times, which is typically considered as a potential source of drudgery. Moreover, from the photos of Fig. 1.3, it can be observed that the condition of the workplace in the bell metal production units is very poor as the workers are exposed to direct heat radiating from the charcoal-fired open furnaces during casting, heating, forging and quenching activities. These factors are creating several difficulties for the workers to perform the tasks at the workplace and clearly indicate the existence of task-related drudgeries.

It is also observed that in Sarthebari, the bell metal products are generally manufactured as a single piece, except few products like xorai, bota etc. The products which are manufactured in parts are joined by riveting, as shown in Fig. 1.4. However, the customer does not very likely prefer the riveted bell metal products because of leakage from the joints and cleaning difficulties. On inquiry, it has been found that the user gets numbers of palm cuts during cleaning of the riveted portion of the joined bell metal products and hence do not preferred. Again, a group of customers reported that the parts joined by riveting often separate from each other after a period of time during service. Further, the artisans said that during drilling, the hole size could not be maintained to insert the rivet and hence there is a possibility of leakage and loose fit.

Figure 1.3 Photograph of bell metal production center in Sarthebari, Assam

In an interaction with artisans, it was found that the market demand for bell metal products has decreased over a period of time. The average transactions of the Sarthebari bell metal cluster have significantly decreased from ₹11 million in 2017–18 to ₹7.5 million in 2019–20 (source: *Industry and Commerce Department, Govt. of Assam*). Another interaction with customers, it has also been found that limited range and high cost of products are the major barrier in day to day use of bell metal products. The next section discusses the summary of the field survey.

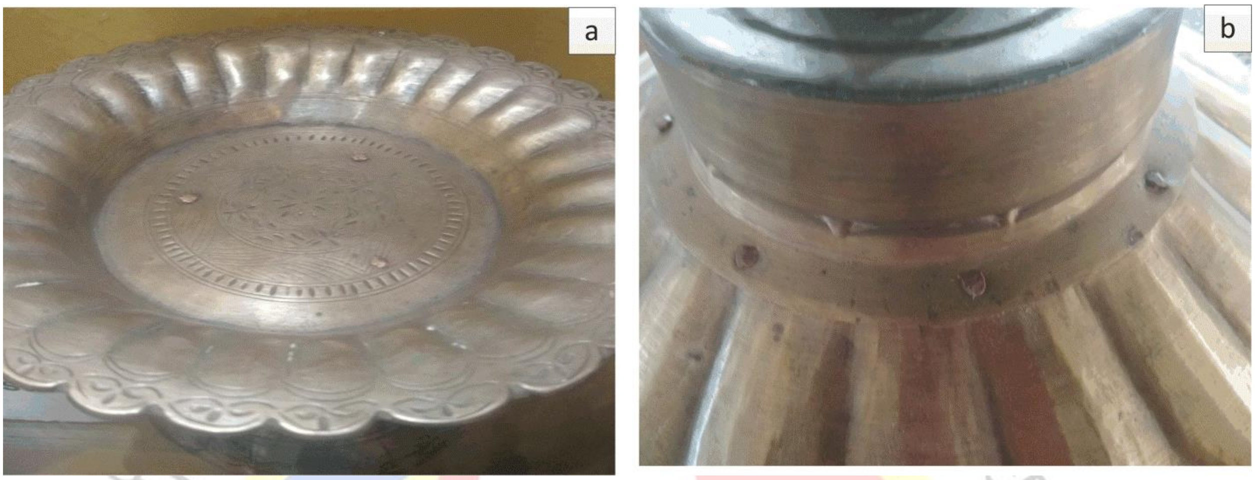

**Figure 1.4 Riveted bell metal products: a) Bota, b) Xorai**

### 1.6.4 Summary of the field survey

From the field survey, it was observed that in one unit, daily 10kg of bell metal products is manufactured in batch by following the casting, forging, water quenching, surface cleaning and art working process in sequence. It was observed that a high amount of waste generates (nearly 1kg per day) in the production centers due to the use of improper material processing techniques. The failed products were then again re-casted and followed the same series of the manufacturing process in sequence to produce the new products, which is a time consuming and expensive process. Therefore, a revisit to the manufacturing techniques is essential to reduce the amount of waste generates per day. Further, it was found that 0.5kg of waste generates as oxide scraps, which are not used in the future. So, a study to reduce the oxide scrap will be beneficial. It was also observed that different improper/ poorly designed tools/ equipments are used by the artisans for the production of bell metal items. And consequently, Sarthebari bell metal workers have to adopt awkward postures during performing the tasks near the open furnaces, which commonly indicates the presence of ergonomic-related drudgeries in the cluster. Therefore, an effort to posture rectification will improve the health condition of workers and hence will reduce the drudgery from the workstation. Further, a study on designing tools/ equipments will reduce the products failure rate in the production centers. It was also found that few of the bell metal products are manufactured in parts and joined by riveting. But the riveted joining method is not very well accepted by the end-users because of handling difficulties, leakage from the joins and loose fittings. Moreover, technological difficulties are also there in the riveting process. Therefore, a suitable joining process of bell metal parts will definitely be helpful for the industry. It is expected that besides reducing the handling difficulties, a suitable bell metal joining technique may also open up avenues for manufacturing new and diversified products for different use in industry as well as for domestic purposes.

In view of the above summary, it has been observed that there are many windows for future research to develop the bell metal items production centers. However, the present field survey report has several limitations, such as a) it does not provide information about the manufacturing process practiced in other clusters for the production of bell metal items, b) it does not provide any light on the scientific/ technological advancements already has been carried out by researchers from different parts of the world but not implemented in the Sarthebari bell metal cluster, c) it cannot describe the scientific or technological links between the cause and effects of the bell metal processing techniques, it only provides the experience of artisans, etc. In order to overcome these limitations, the study forwards by reviewing the published literature related to bell metal and its production industries. The next section discusses the review of available published literature.

## 1.7 Literature review

The metallographic and mechanical properties of any material help to understand the behaviour of the material and hence the performance of the product during service. A general idea of the metallographic and mechanical properties of any material is also helpful for its industrial applications [63]. Therefore, the first area selected for the literature survey is the metallographic and mechanical properties of bell metal.

### 1.7.1 Metallographic and mechanical properties of bell metal

The bell metal products can be divided into two groups from a metallographic point of view [38]. The first group of bell metal products is cast bell metal products. The highly used cast bell metal products are the different musical instruments viz., bell, gong, cymbal etc. Ninety percent of total bell metal products are cast bell metal products [38]. The secondary processed bell metal products are the second group of bell metal products. The secondary process includes high temperature forging and water quenching from that elevated temperature. The secondary processed bell metal products include different types of utensils used in day-to-day life.

### 1.7.1.a Cast bell metal

In this section, mechanical properties, namely microstructure, hardness, the fracture strength of cast bell metals, have been overviewed.

***Microstructure***

The microstructure of cast bell metal is mainly composed of two zones [64]. The first zone is the dendritic zone having the α phase. The second zone is the inter-dendritic zone having an δ phase [64]. The dendritic zone covers most of the area. A similar microstructure has also been reported by Audy and Audy (2008) [65] and Nadolski (2017) [66]. Few studies show the presence of a third fringe zone (β phase) in the interface of the dendritic and inter-dendritic zone [21]. The presence of the δ phase makes the cast bell metal brittle in nature and hence limits its regular use for the production of domestic items [22]. However, because of the excellent viscosity and high strength of cast bell metal, it is extensively used for manufacturing heavy load bushing, valves, piston rings and bearings [30].

Many authors reported that the α phase has FCC (face-centered cubic) structure and the β phase has BCC (body-centered cubic) structure [37, 67–69].

Saunders and Miodownik (1990) [70] have reported that the δ phase has an SC (simple cubic) structure and is responsible for the brittle nature of cast ingots.

***Hardness***

Audy and Audy (2008) [65] have reported an average Vickers hardness value of 180 in α phase and 369 in the δ phase from the investigation of casted church bells manufactured in different eras.

Nadolski (2017) [66] has observed that the Brinell hardness value of cast bell metal increases from 198 to 308, with an increase in the percentage of Sn content from 20% to 24% in the alloy composition.

***Fracture strength***

Nadolski (2017) [66] has reported that fracture strength under a tensile load of cast bell metal product varies from 238.12MPa to 163.33MPa on increasing the Sn content in the alloy from 20% to 24%.

### 1.7.1.b Secondary processed bell metal

In this section, mechanical properties, namely microstructure, hardness, the fracture strength of both secondary processed bell metals, have been overviewed.

### *Microstructure*

Several authors have reported the microstructure from the study of secondary processed bell metal products recovered from different archaeological sites. The microstructures of secondary processed bell metal products consist of two different types of zones as a) α phase island zones and b) β phase needle-like martensitic zones, along with annealing twins in island zones [22, 71–73].

Park and Jung (2007) [71] and Srinivasan (1994) [22] has reported that the martensitic structure formed in the microstructure because of the water quenching process and the annealing twins are formed due to the recrystallization process during high temperature forging.

Pandey et al. (1991) [69] have studied the detailed martensitic transformation process for a wide range of Cu-Sn alloys and reported that the martensitic structure is formed due to the transformation of the BCC structured β phase into the basal plane by lattice deformation shear followed by a lattice invariant shear.

Huang et al. (2016) [74] have reported that the annealing twins formed only in the FCC structured α island phase due to its lower stack fault energy.

Mahajan et al. (1997) [75] have reported that the annealing twins formed in secondary processed bell metal are of type II.

### *Hardness*

Srinivasan (1998) [14], from a study on ancient jug unearthed during the excavation of archaeological sites of Nilgiri hills, Tamil Nadu, India, has reported that the Vickers hardness value of secondary processed bell metal products varies between 290–300HV.

Y. Li et al. (2013) [72], from a study on an ancient vessel discovered in the archaeological site Hubei Province, China, has reported that the Vickers hardness value of secondary processed bell metal products lies between 495.3–535HV.

Park et al. (2009) [38] have reported that the Rockwell hardness (B scale) value increases from 78 to 103.5 as the percentage of Sn increases from 17% to 22% in the water quenched Cu-Sn alloy (quenching temperature is 750ºC). Again, for Cu-Sn alloy containing 20% Sn, the Rockwell hardness (B scale) value increases from 90.8 to 97.5 on increasing the quenching temperature from 610ºC to 750ºC.

***Fracture strength***

No published literature has been found reporting fracture strength of secondary processed bell metal.

Fracture strength, which depends on the microstructure of any material, determines the maximum load that can be applied to the material without failure. Therefore, the fracture strength value of any material is essential for its engineering applications. It is quite surprising to find that no authors have reported or studied the fracture strength of secondary processed bell metal. Again, in general, the fracture strength and hardness value of materials are proportional to each other in a ratio of 2 to 3. However, Nadolski's (2017) [66] results on cast bell metal contradict this general convention. Therefore, a revisit on the mechanical properties of cast bell metal is essential to clarify the facts.

Further, to overcome the limitations of the field survey report discussed in section 1.6, the manufacturing process practiced in the other clusters has been reviewed and reported in the next section.

### 1.7.2 Bell metal products manufacturing process

The bell metal products manufacturing process has survived for ages, yet there seems to be a very little transition in the production process of bell metal items [60]. Numbers of papers on the bell metal products manufacturing process have been published from India [20, 22, 28, 35, 76, 77], China [72, 73] and Korea [71, 78].

Gnesin (2015) [41] have studied the manufacturing process of bell metal products (mostly bells) and reported the manufacturing process as a) melting the raw material at 1000ºC, b) pouring the molten metal into dried and fired clay mould under gravitational pressure, c) solidification of molten metal at a high cooling rate to prevent phase separation and uneven tin distribution and d) finishing to remove the moulding material and uneven surfaces. This study further described that bell metal having 20% tin and 80% copper ensure the perfect sound of the bell with high strength and toughness. On decreasing tin content to 17%, the reverberating properties of the bell reduce; whereas on increasing tin content above 22%, the sound quality improves but the brittleness increases and hence not preferred. Again, the study says on adding small amounts of zinc, lead, and iron to the alloy, the casting properties slightly improve, but it affects the bell sound.

Park and Jung (2007) [71] have studied the bell metal products manufacturing process practiced in Korea. From the microstructure of the artifacts unearthed Boonhwang temple site at Kyongju has reported the manufacturing process as a) casting an exact shape of the items, b) quenching the cast items in water and c) surface cleaning. This study has further reported that the products having a composition of more than 22% Sn are produced by the water quenching process and others are made by only casting process.

Y. Li et al. (2013) [72] have studied the techniques employed in making ancient thin-walled bell metal vessels unearthed in the Hubei Province of China. This study has reported the possible fabricating processes from the microstructural study of the vessels as a) alloying the high-tin bronze, b) casting an approximate shape of the vessels, c) repeatedly forging the vessel in the $\beta$-phase temperature range of 586–798ºC, d) wiping tinning on the inside and outside surfaces of the vessel at high temperature immediately after hot forging for several minutes to form a tin-rich layer, e) quenching the vessels in water to room temperature and f) at last grinding and polishing the surface of the vessels.

Park and Shinde (2013) [76] have studied the manufacturing process of bell metal products practiced in Nagpur, India, from the microstructure of different ancient bronze items unearthed from megalithic sites. This study reported the manufacturing process as a) casting high-tin bronze ingots, b) repeatedly forging the ingots either in the $\gamma$-phase temperature range of 520–586ºC or in the $\beta$-phase at the temperature range of 586–798ºC, c) quenching in water to room temperature and d) removing of the oxide layer to uncover the golden glazing surface.

Srinivasan (2016a, 2015, 1994) [22, 79, 81] and Srinivasan and Glover (1998) [37] have extensively studied the bell metal industry of Kerala & Tamil Nadu and reported the manufacturing process in detail. These studies report the manufacturing process as a) casting high-tin bronze ingots, b) repeatedly forging the ingots in the $\beta$-phase at the temperature range of 586–798ºC, c) quenching the hot forged products in water to cool up to the room temperature and d) polishing to reveal the golden luster. These studies also indicated that the manufacturing process has not changed from the 1st mid BCE to modern time from the comparative analysis of microstructure of various products manufactured in present time and unearthed from different locations of Kerala & Tamil Nadu.

Naher and Chattopadhyay (1995) [82] have studied the bell metal items production techniques practiced in Bengal, Jharkhand and Odisha. This study reported that a similar production technique as a) casting, b) soaking in temperature 700ºC, c) thermo-mechanical controlled processing, i.e., forging at elevated temperature, d) quenching and tempering and

e) surface cleaning is followed in all the above locations.

Pillai et al. (2002, 1994) [35, 36] have reported a different manufacturing process, namely lost wax casting methods for the production of bell metal products presently practiced in few parts of India. In this method, firstly, a wax pattern (bee wax: resin: groundnut oil in the ratio of 4:4:1) is prepared and then a clay layer of 3mm is put on the wax pattern (the clay layer work as mould) and subsequently heated in a furnace to melt to drained out the wax. Then the molten bell metal is poured inside the pattern to produce the items. During casting, iron wire is also used as chaplets to initiate the formation of dendritic structures [20]. Finally, burnishing is done to smoothen the sharp edges and to remove the dark layer on the surface. This method is mostly used to manufacture metal images [20]. In the Southern part of India, both hollow and solid metal images are manufactured by using this method.

Therefore, from the above literature, it can be said that the bell metal product manufacturing process varies from cluster to cluster. However, the basic manufacturing process like casting, forging, quenching and surface cleaning process is followed in all the clusters. Further, from the field survey (see section 1.6), it has been observed that a high amount of waste is generated (nearly 1kg per day) in the production centers due to adopting faulty processing techniques. The failed products are then again re-casted and followed the series of the manufacturing process to produce the new products, which is a time consuming and expensive process. Again, 0.5kg of waste generates as oxide scraps, which are further not used. In order to address these issues, the technical aspects of each basic manufacturing stage have been reviewed and reported in the next section.

### 1.7.3 Technical aspects of each manufacturing stage

In this section, development in each stage of the production process has been reviewed and reported.

#### 1.7.3.a Casting process

The casting process is the backbone and foundation block of the bell metal items production process. The casting process is described as the melting of the raw materials at a predetermined temperature, called the casting temperature, and then pouring the molten metal in a mould to cool it from the casting temperature to the room temperature in a controlled cooling rate called the solidification rate. The casting process depends on the nature of the raw material, casting temperature, melting environment and the solidification rate.

### Raw materials

Both old scrap and new virgin materials are used as raw materials for bell metal casting [82]. Srinivasan (1994) [22], from a study on the Kerala bell metal cluster, has reported that sometimes a small quantity of virgin tin (Sn) is added with old scrap materials during the melting process to compensate for the losses that occurred during use. Further, this study has reported that, in the case of virgin material, the exact amount of raw materials is measured and then melted in the crucible.

### Casting temperature and melting environment

Casting temperature is the summation of melting temperature and degree of superheat, which is the temperature above the melting temperature. The melting temperature of bell metal having 22% and 25% tin is 883ºC and 797ºC respectively [83]. *Copper Development Authority* (CDA) recommended 250ºC to 300ºC degrees of superheating and an oxidizing environment of melting for the quality casting of bell metal [27]. Whereas, Naher and Chattopadhyay (1995) [82] from a study on bell metal items production techniques practiced in Bengal, Jharkhand and Odisha from India have reported that the molten metals are covered with straw in the mould during the casting process to reduce the oxidation process. Again, during the field survey also it was observed that the crucibles were covered with charcoal to minimize the high temperature oxidation process and hence the formation of slags.

Bartocha and Baron (2016) [84] have said that superheating temperature during melting and pouring temperature influence the density and hardness of bell metal which further affects the bell's tone. This study has reported that with the increase in pouring temperature, the density decreases from two case studies. In the first case, 99.99% pure copper and 99.99% pure tin in the ratio of 80:20 at 1200ºC is melt and poured from 1200ºC, 1150ºC, 1100ºC, 1050ºC and 1000ºC. And in the second case, the metal is melted at 1000ºC first and then each sample is cast by increasing the melting temperature by 50ºC up to 1200ºC.

Slamet et al. (2019) [85] from the microstructural studies have concluded that with an increase in pouring temperature, the hardness increases due to the increased amount of $\alpha + \delta$ eutectoid phase from the study on lost wax investment casting of bell metal.

### Solidification process

Kohler et al. (2008) [86] have studied the solidification process of bell metal to understand the casting process in a single pan thermal analyzer. This study has reported that the molten metal solidifies by series of phase transformation processes. The phase transformations process and temperatures are as follows i) nucleation of the α phase from the molten metal in between the temperature 836 – 861ºC, ii) peritectic reaction between the α phase and Sn rich liquids for the formation of β phase in the temperature range of 796 – 787.7ºC, iii) ordering reaction to transform the β phase to the γ phase at temperature 579.2ºC and iv) eutectoid reaction to transform the γ phase to the δ phase at temperature 512ºC.

Song et al. (2011) [87] have described the solidification process of bell metal from differential thermal analysis (DTA) curves as follows i) formation of the α phase and Sn rich liquid at a temperature around 850ºC, ii) formation of β phase in the mushy zones from the reaction between the α phase and Sn rich liquids at a temperature near 800ºC, iii) the β phase transforms to γ phase at 580ºC and iv) at 510ºC the γ phase transform to higher Sn content δ phase by absorbing the excess Sn present in the solution and by this time the initially formed α phase makes dendritic structures and finally solidified as α phase dendritic structures and Sn rich δ phase solution in the inter-dendritic zone at room temperature.

Acharya and Mukunda (1988) [64] and Acharya (2001) [88] have studied the reverse solidification process, i.e., the melting process of bell metal to develop the phase diagram and reported that the liquidification reactions as a) α + δ → α + γ at 520ºC; b) α + γ → α + β at 586ºC; c) β → α along with decompositions of the β phase to the liquid phase at 799ºC and d) melting of the α phase i.e., liquefaction of bell metal at 850ºC.

Fürtauer et al. (2013) [89] have also studied the melting process of bell metal and reported four-phase transformation reactions as a) α + δ → α + γ at 518ºC; b) α + γ → α + β at 566ºC; c) β → α along with decompositions of the β phase to the liquid phase at 798ºC and d) melting of the α phase at 850ºC. This study also calculated the lattice parameters of different Cu-Sn alloys processed in different conditions.

Further, D. Li et al. (2013) [90] and Saunders and Miodownik (1990) [70] have studied the Cu-Sn melting process of bell metal via thermodynamic modelling and reported the phase changing temperatures as 520ºC, 586ºC, 798ºC and 850ºC.

Konečná and Fintová (2012) [91] have said that the wide freezing range (50–60ºC) of bell metal makes the solidification process complex. This study reported that the formation of mushy zones during solidification in permanent mould casting results in 1 to 2% of porosity in cast bell metal ingots due to inter-dendritic shrinkages or micro-shrinkages. This study concluded that the micro-shrinking effect might be overcome by proper designing of the riser and using chills.

***Solidification rate***

Sugita and Priambadi (2015) [92] studies have emphasized the solidification rate over the influence of casting and pouring temperature. This study reported that solidification rate is the main controlling parameter of the hardness and damping capacity of bell metal. This report was made based on the investigations of the influence of different solidification rates (13.112ºC/s, 10.206ºC/s and 7.722ºC/s) and casting temperatures (1000ºC, 1100ºC and 1200ºC) on the hardness and damping capacity of bell metal.

### 1.7.3.b Forging process

The forging process includes heating the cast ingots up to the temperature of 650–700ºC and then beating the ingots at elevated temperature or in red hot condition to provide the shape of the product to be manufactured [35, 36]. The forging process is the most crucial process in the bell metal production line as it directly controls the thickness of the final product [71, 72]. Non-uniform thickness throughout the products may lead to failure during service [35, 36].

Srinivasan (1994) [22], from a study on the bell metal industry located in Kerala, has reported that forging is done by 3–4 men with the hammer at elevated temperature till the material is shaped in the form of the final product. This study also published photographs of the actual forging process practiced in Kerala. From the pictures, it can be easily found that the forging process is very cumbersome, laborious and full of drudgeries. There is a very high possibility of life risk. A similar result of the present field survey report.

Literature has also been searched in the line of understanding the forging process, i.e., the amount of force required to provide the shape, material behaviour during forging, the influence of forging die parameter etc. But no published literature has been found in these directions.

### 1.7.3.c Quenching process

The quenching process includes reheating the forged material up to the temperature range of 550 – 700ºC and then dipping it into a water bath from that high temperature to cool up to room temperature [14, 38, 93–95]. Park et al. (2009) [38], from a study on the mechanical properties of water quenched bell metal, have reported that the quenching process, i.e., the quenching temperature and quenching medium, controls the final quality of products.

No published literature has been found in the direction of explaining the fundamentals of the bell metal quenching process, i.e., clarifying the facts of selecting the water as a quenching medium. Moreover, studies related to bell metal processed in other quenching media like oil have not been found.

### 1.7.3.d Surface cleaning and art working

Surface cleaning, the second most important (after the casting process) and most time consuming process among all manufacturing stages are done for removing the black oxide layer formed during the previous processing to uncover the golden luster of bell metal products [14, 79]. The pictures published by Srinivasan (1994) [22] show artisans from Kerala use hand made tools to carry out the cleaning and artworking activities. The cleaning and artworking activities are carried out manually.

No published literature has been found in the direction of explaining and eliminating the bell metal oxidation process to reduce the oxide scraps and hence, the production time. Further, no published literature has been found on electro-chemical machining of bell metal to reduce the artwork time and hence, to reduce the production time and drudgery.

In view of the ongoing observation, it can be said that although sufficient amounts of studies have been carried out to understand the casting process, there are certain unclearity or need more rigorous investigations in the relation between casting parameters and the properties of casted products. Again, a very limited amount of work has been carried out to understand the other stages of the manufacturing process viz., forging, quenching, etc., used to produce the bell metal items, apart from reporting the common practices used in the industry. Therefore, the problems of intermediate waste generation in the production line still exhibits in the industry. Further, due to the lack of S&T interventions, the industry still uses age-old manufacturing process. So, studies related to understanding and standardizing each stage of the manufacturing process will be useful for the industry to reduce intermediate waste generated in the production line and hence to reduce the production time.

Again, from the field survey (see section 1.6), it has been observed that the workers use different improper/ poorly designed tools/ equipments, which leads the artisans to adopt different awkward postures while performing the tasks in hot environments. In order to find the progress on tools and equipments developed for the bell metal industry, published papers have been reviewed and reported in the next section.

## 1.7.4 Current scenario of other production centers

Ganguly et al. (2016) [19], Mukherjee (2018) [60], Pillai et al. (2002, 1994) [35, 36] and Srinivasan (2016b, 1998, 1997) [14, 39, 81] have published few photos from the workstation/ workplace of bell metal items production centers. The tools/ equipments used in other clusters, as observed from the published photos, have been described in the next section.

### 1.7.4.a Tools

The bell metal industry uses several hand-operated tools to perform different activities. For example,

***Hammer***

Different types and sizes of hammers are used in the bell metal industry to carry out forging and art working activities. Hammers are also used to break the initial old scrap materials before using them as raw material for the next batch.

***Tong***

Different sizes of tongs are used in the bell metal industry to carry out holding of the crucible during melting and holding materials during heating, forging, quenching, art working activities.

***Anvil***

Different sizes of anvils are used in the bell metal industry to carry out forging activities.

***Other tools***

The bell metal workers also use some other basic wooden/ bamboo tools to perform artwork and surface cleaning activities.

### 1.7.4.b Equipments

The bell metal industry uses a few hand-operated types of equipment to perform different activities. For example,

***Lathe***

The bell metal industry uses a manually operated wooden lathe to carry out finishing and art working activities. The quenched material is fixed to the chuck of the lathe by a molten resin or hot incense [22].

***Grinder***

Photos published by Pillai et al. (2002, 1994) [35, 36] show the use of grinders to remove the sharp edges formed during casting.

### 1.7.4.c Furnace

The bell metal industry uses furnaces for melting the raw material and heating the cast ingots before the forging and quenching process. From the published photos of industry, it has been observed that all the bell metal cluster uses charcoal based open flame furnaces for performing the activities. In the recent past, Biswas and Choudhury (2016) [96] and Choudhury et al.

(2016) [97] have started to investigate on design and development of furnaces for the bell metal industry. However, no report of implementation has been found.

In view of the above literature, it has been found that all the bell metal cluster uses age-old traditional handmade tools. Again, it has been observed that apart from reporting the tools and equipments used in the industry, no attention has been paid by the scientific community to advance the design/ modify the tools and equipments related to the bell metal industry. Therefore, studies related to the design of tools and equipment will be beneficial for the industry to upgrade the present production system or in other words, to modernize the industry and hence to reduce the drudgeries.

Further, from the field survey report, it was observed that the end-users do not well accept the riveted products (see section 1.6) and hence there was a demand for alternate joining techniques. Therefore, the next section discusses the published literature on the bell metal joining techniques.

### 1.7.5 Bell metal joining techniques

In this section, published literature on the joining method of bell metal products has been reviewed.

Lucien (1993) [98] first tried to join the bell metal bells by pouring a calculated amount of molten bell metal into the fracture slit to form the join between the parts. This method can be successfully used to join bell metal parts but requires highly skilled workers and is not efficient when the cavity size is larger; hence not well accepted [99].

Ernesto and Vega (2014) [99] have proposed powder metallurgy to join bell metal pieces. In this process, powder of the same compositions is filled in the crack cavity and then the powder is melt with a torch flame to join the pieces.

Schwartz (2014) [100] has reported that bell metal can be joined by brazing with preheating. However, the brazed product has weaker joint strength and there is the possibility of mixing filler material in brazed products [101]. Moreover, tin segregation on the joining surface during preheating complexes the brazing process [102].

Brown (1994) [103] has reported that few copper-based alloys can be joined by the welding process to obtain leak-proof joints with smooth surface finish and high strength. But, the weldability of bell metal has not been reported in this study. Therefore, a revisit on the welding process to join bell metal parts may have the potential to solve the joining issue of the industry.

Again, from the field survey report, it has been observed that the workers adopt awkward postures during performing the tasks in high-temperature environments with improper/ poorly designed tools, i.e., there is an existence of drudgery in the cluster. In connection to this, the literature reporting presence of drudgeries in the bell metal clusters has been reviewed and reported in the next section.

### 1.7.6 Drudgeries in the bell metal industry

Ganguly et al. (2016) [19], Mukherjee (2018) [60], Pillai et al. (2002, 1994) [35, 36] and Srinivasan (2016b, 1998, 1997) [14, 39, 81] have published few photos from the workstation/ workplace of bell metal items production centers. From the published photos, it can be clearly observed that in every cluster, the workers adopt awkward postures during performing the tasks in high-temperature environments with improper/ poorly designed tools, i.e., there is an existence of drudgery in each cluster. In general, working at high temperatures enhanced the risk of musculoskeletal disorders (MSDs) and adversely affected workers efficiency, hence the plants productivity [104, 105]. Roy (2014) [52] and Sahay (2015) [51], separately from two different studies, have reported that many workers engaged with the bell metal industry have started to migrate to less physically demanding production jobs. Consequently, the bell metal industry is facing a scarcity of human resources and thus, the net share of the bell metal industry in the Indian economy is decreasing day by day [19, 20, 59, 61]. Roy (2014) [52] reported that different occupational health hazards are possessed in the bell metal industry as most of the artisans were found to be sufferings from various health diseases. Ganguly et al. (2016) [19] reported the presence of nutritional deficiency among the bell metal workers due to the rigorous workload and underdeveloped socio-economic conditions. No published paper has been found reporting the level of drudgeries, i.e., statistical data related to the amount of drudgeries present in the bell metal industry.

In order to understand the drudgery condition of other SSIs, literature has been reviewed and reported in the next section.

### 1.7.7 Drudgeries in other SSIs

Generally, the SSIs enjoys certain inherent strength such as exploitation of local resources and skills, capacity to execute indigenous small orders, high employment to capital investment ratio, better use of scarce factors of production, higher heritage values with past glory, flexibility in production, informality in labour relations, the talent of dispersal to offer customized services and many more [1]. However, its major problems like inadequate infrastructure facilities, low output per unit due to traditional and outdated tools, equipment, workstations (TEWs) etc. are still inhibiting the SSIs, which results in the presence of a high level of drudgeries [1, 106]. [107, 108][107, 108][107,108][107,108][107,108]Li et al. (2020) [107] and Hani et al. (2021) [108], separately from two different study have reported that nearly 30% of nonfatal injuries and illnesses that occur in the manufacturing sectors are due to different work-related drudgeries experienced by the workers and it results in days away from work.

Many authors have repeatedly reported the presence of drudgery in India. For example,

Qureshi and Solomon (2021) [109], from a study on 105 workers performing different activities in the foundry industry of India, has reported that 44.76% of the total population are performing tasks at very high risk due to adopting awkward postures and poorly designed tools. No attention has been paid in this study to reduce the drudgery apart from suggesting that to avoid the awkward postures of workers grinding machines and manual moulding machine has to be redesigned based on anthropometric principles.

Singh (2010) [110] has carried out a drudgery analysis of 130 workers related to performing different tasks in a forging industry located in Punjab, India, reported 44.72% of the total population are working at a high-risk level. Another study on 100 workers engaged in the casting industry of Punjab, India, Singh (2012) [111] has reported that 67.82% of people are working at a high-risk level because of the incorrect working posture of the body and higher working temperature at the workplace. This study also laid down the conclusions as high working temperatures enhance the risk of MSDs among the workers. Both the studies have not made any design modification of the tools to reduce the drudgery apart from the recommendation of the dire need for ergonomic intervention.

Sanjog et al. (2019) [112] have carried out the drudgery analysis of 46 workers working in a plastic chair manufacturing unit located in Assam, India and the survey reported that 56.5% of workers suffer from shoulder pain, 82.6% of workers suffer from lower back pain, 52.2% workers suffer from wrist pain and 34.8% workers suffer from knee pain. This study has developed few adjustable tools and stands to reduce the drudgery based digital human modelling.

Singh et al. (2013, 2012) [113, 114] have carried out the drudgery analysis of 102 workers working in small-scale forging industry present in Ludhiana and Jalandhar of Punjab, India. They have reported that 44.6% of workers are working at high-risk levels due to adopting the wrong posture while performing various tasks viz., blanking, cutting, shearing, hammering, punching, trimming, grinding, drilling, broaching, heat treatment, welding, etc. in the industry. Both the studies have only made the recommendations of the awareness training programmes.

Ansari and Sheikh (2014) [115] have carried out a drudgery analysis of 15 workers working in different manufacturing industries under Mumbai Industrial Development Corporation located in Wardha, India and reported that 53% of workers are performing tasks at a high-risk level. This study has also recommended for the awareness training programme.

Joshi and Lal (2014) [116] have studied the posture of 200 workers engaged in different casting industries located in Punjab, India and reported that 79.5% of workers performing tasks at very high-risk factors because of higher working temperature at the workplace and improper tools design, which forced the worker to adopt wrong working posture while performing the task.

Dewangan and Singh (2015) [117] have done a drudgery analysis of 7 operators doing pulpit operation in a steel plant and reported that 60% of workers suffer from neck pain, 80% of workers suffer from shoulder pain, 50% of workers suffer from back pain and 80% workers suffer from lower back pain because of wrong working posture and poor tool design. This study has also designed a workstation layout to reduce the drudgeries from the industry.

Kushwaha and Kane (2016) [118] have carried out the drudgery analysis of 27 shipping crane operator working in a steel manufacturing industry present in India and found that 62.9% operator suffers from neck pain, 44.4% operator suffered from shoulders pain, 33.3% operator suffers from elbow pain, 29.6% operator suffers from wrist/hand pain, 66.6% operator suffers from upper back pain, 51.8% operator suffers from lower back pain, 66.6% operator suffers from hip/thigh pain, 59.25% operator suffers from knee pain and 22.2% operator suffers from ankle/feet pain. This study reported the cause of drudgeries as adopting awkward postures during the task, performing work with repetitive forceful body movements, prolonged working periods, lack of adequate rests during the task, improper working tools and bad workstation design. This study has designed a shipping crane cabin by digital human modelling.

Few authors also reported the presence of ergonomic-related discomforts in SSIs from other parts of the world. For example, Abdullah and Dawal (2020) [120] reported that in 2017, 61.6% of the total occupational disease among the Malaysian workers engaged in the manufacturing industries was due to ergonomic related hazards viz., MSDs, pains in different body parts etc. Nur et al. (2019) [121], from a study on workers engaged in the Malaysian aerospace industry, has reported the presence of ergonomics related discomforts. Iranzo et al. (2020) [122], from a study on workers engaged in automotive assembly plants of Spain, has also reported the presence of ergonomic related discomforts. Tendai and Jerie (2017) [123] have studied the drudgery level of 200 employees working in the steel industry of Zimbabwe and reported that 69.4% of employees suffer from ergonomic related drudgeries because of awkward working posture, excess manual weight lifting, forceful movement of the body, vibration of tools and higher temperature at the working environment.

Many authors have claimed that physio-psychological factors affect the level of drudgeries experienced by the workers while performing different tasks in the workplace. For example, Roffey et al. (2010) [124] have reported that the nature of the job is the critical parameter enhancing ergonomic-related drudgeries among the workers in metallic industries. Yu et al. (2012) [125] reported that age is an important factor influencing the drudgery of workers. This study has observed that older workers have a higher risk of pain in the wrists and lower back. Lanfranchi and Duveau (2008) [126] indicated that job satisfaction is the critical factor influencing the level of drudgeries experienced by the workers. Fedorowich et al. (2013) [127] have reported work fatigue as the factor that significantly influences the body's drudgery level. Colombini and Occhipinti (2006) [128] have shown that sufficient break rest per hour plays the most vital role in workers drudgery levels.

From the above discussions, it has been observed that the use of age-old TEWs and adopting awkward working postures at the workplace are very common in all SSIs; which results in different ergonomic related drudgeries viz., musculoskeletal disorders (MSDs), pain in different body parts, discomforts/ irritations, etc. among the workers. Figure 1.5 shows few natural and awkward postures of different body parts. The next section discusses the benefits of drudgery removal from SSIs.

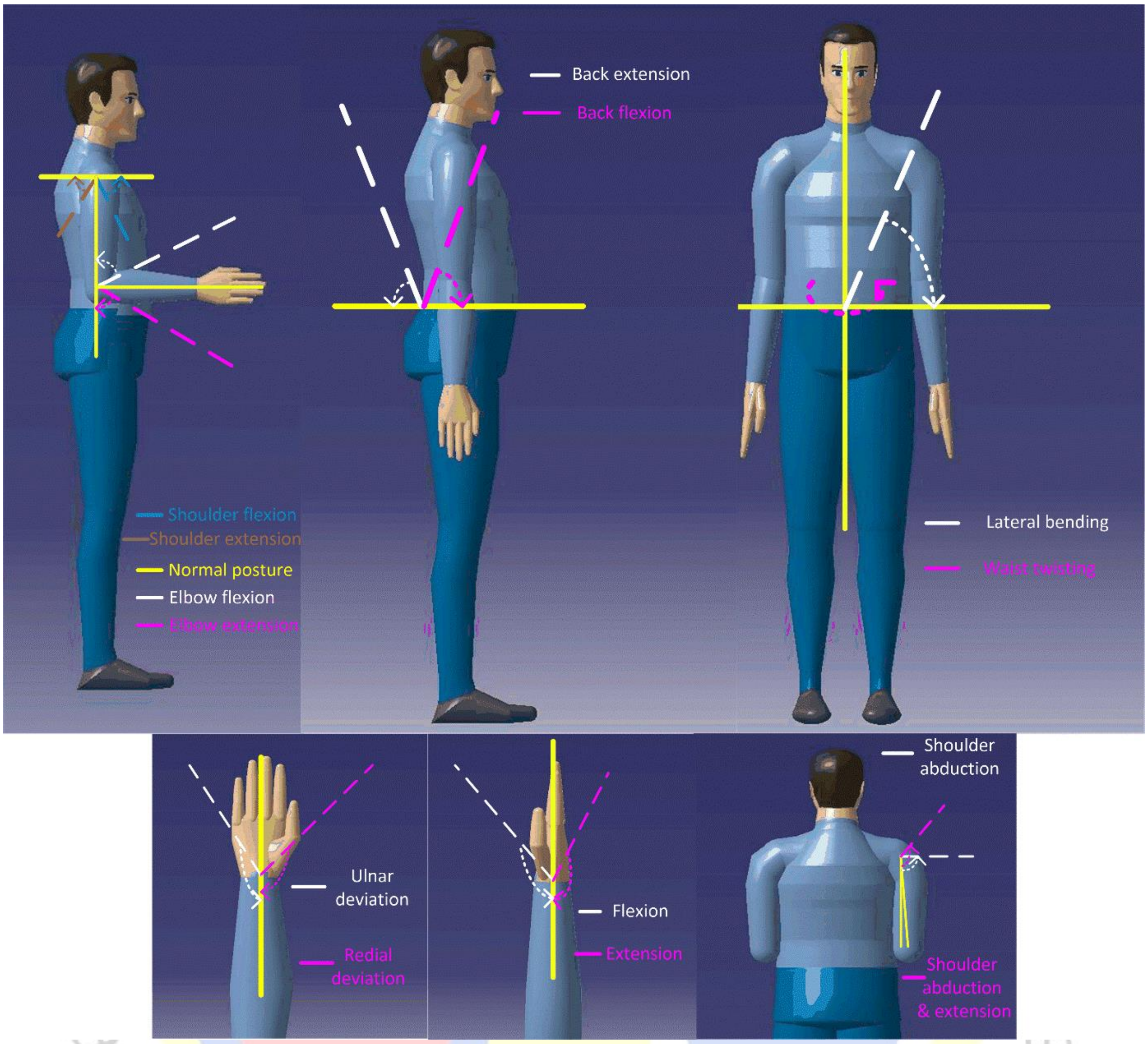

**Figure 1.5 Natural and Awkward posture [129]**

### 1.7.8 Benefits of drudgery removal

Drudgery removal is essential from all industries as it directly affects the employees physical health and hence productivity of the plant [104, 105, 109]. Mohan et al. (2008) [130] have reported an improvement of the health score of the grinding machine operator from 30% to 100% after drudgery removal by modifying the machine. Kushwaha and Kane (2016) [118] have also shown an improved health score of the crane operator after the modification of the crane cabin. Govindaraju et al. (2001) [131] have studied a circuit board manufacturing company and reported a 23% increment in operators productivity and 19% reduction in injuries of workers due to drudgery removal. Yeow and Sen (2006) [132] have studied a printed circuit assembly factory and reported an improvement of 50.1% in labour productivity 59.8% increment in the total revenue after drudgery removal. Mukhopadhyay and Ghosal

(2008) [133] have studied an incense stick manufacturing industry located in Gujarat, India and reported a 15% increase in plant productivity after drudgery removal.

Some authors reported that drudgery removal is also helpful to increase the benefit-to-cost ratio. For example, Guimarães et al. (2014) [134] have studied a footwear company located in Brazil and reported that after drudgery removal, the productivity increased by 3% and rework reduced by 85%. The cost of the intervention is 70,132$, while the annual savings are 503,479$. Lahiri et al. (2005) [135] have studied the wood processing industry and found that after drudgery removal, productivity increased by 50% and the benefit-to-cost ratio to 84.9. Tompa et al. (2013) [136] have studied a cloth manufacturing industry located in South-western Ontario, Canada and found that the benefit-to-cost ratio has increased to 5.5 from 3 due to drudgery reduction.

From the above literature, it has been observed that drudgery removal not only increases the health score of artisans but also improves the operator efficiency and hence plants productivity. Thus the benefit-to-cost ratio of the plant increases. Therefore, it is very much possible that on the removal of the drudgeries present in the bell metal industry will improve the benefit-to-cost ratio and health score of the workers engaged in the industry. And hence the scarcity of artisans due to low income and different drudgeries will also resolve. However, before carrying out any study to remove drudgeries, proper assessment of drudgery data associate with the bell metal industry will be helpful. So, the different drudgery assessment tools have been reviewed and reported in the next section.

### 1.7.9 Drudgery assessment tools

Drudgery assessment is done to identify the potential risk factors, whose consequences are fatal, like permanent disability and death [118, 137]. The drudgery level varies among the workers depending on the abilities of a worker to perform a specific task [138].

Several authorities have developed numbers of drudgery assessment tools viz., Ovako working posture analysis system (OWAS), rapid entire body assessment (REBA) posture analysis, rapid upper limb assessment (RULA) posture analysis, push-pull analysis, Washington Industrial Safety and Health Act (WISHA) lifting calculator, National Institute for Occupational Safety and Health (NIOSH) lifting equation, liberty mutual manual material handling tables (Snook tables), hand-arm vibration calculator (HAV), muscle fatigue assessment (MFA) etc. for assessment of different tasks [139]. These tools are developed based on ergonomic risk factors viz., awkward posture, force, repetition of work, vibration, static load etc. [140].

RULA and REBA methods use scoring techniques to categorize the postures and exertion force of the worker with different risk levels by considering the parameters like gender, age, height, weight, working experience etc. [139]. Good working posture means a low score in RULA and REBA scoring methods [137]. OWAS analysis use time motion to measure the frequency of repetition of a particular posture [141]. A push-pull analysis is carried out to assess the awkward posture that occurred during the push-pull activities [140]. NIOSH and WISHA methods use biomechanical equations to measure musculoskeletal stress. MFA analysis uses the scoring method of a person's body parts before assigning a particular task for a short duration [140].

From the above literature, it has been observed that several activity/ tasks oriented assessment tools have been developed to measure the level of drudgeries associate with the industries. Therefore, the selection of the assessment tool will be crucial to assess the level of drudgery associate with the industry. The next section discusses the drudgery removal methods commonly practiced by researchers/ industrialists.

### 1.7.10 Methods of drudgery removal

Several methods of drudgery removal from SSIs have been proposed by researchers viz., replacing the present production process with a more efficient process, reducing the waste, modifying the tools, equipments and workstation/ workplace (TEWs), etc. [142]. Many authors reported that modifying the design of TEWs is the easiest and most beneficial way of reducing the level of drudgeries involved among the workers [143–145]. In 2015, 2.9 million nonfatal occupational injuries and occupational diseases had been observed in the United States, which is approximately 3 per 100 employees due to working in poorly designed TEWs [146]. Hosseini-Nasab et al. (2018) [147] reported that incorrect designs of TEWs in the metallic industry could reduce the production efficiency by more than 35%. Heidarimoghadam et al. (2020) [148] said that modification of TEWs improves the human machine's interactions and hence reduces nonfatal injuries. Numerous studies reported that modifying the dimensions of TEWs based on operators body dimensions reduces the drudgery of the workers by several times [143, 144, 149, 150]. Modification of TEWs design is a scientific art and it is specific to a particular industry [151].

From the above discussions, it has been found that TEWs modification allows to remove the drudgeries from the SSIs. Further, from the field survey (section 1.6) and discussion on section 1.7.4, it has been observed that the bell metal industry uses different poorly designed tools and equipments, which may be one of the main reasons for drudgeries. Therefore, a study to modify the TEWs will be essential to reduce the drudgery from the bell metal industry. The next sections discuss methods of TEWs modification/ design procedure for removing the drudgeries present in the SSIs.

### 1.7.10.a Tools and equipment design/ modification

Most of the authors viz., Bhattacharjya and Kakoty (2020) [151], Dewangan et al. (2010) [152], Feyzi et al. (2019) [153], Hermawati et al. (2014) [154], Jung and Jung (2008) [155], Unnikrishnan et al. (2015) [156], Victor et al. (2002) [157] etc. have emphasized and recommended on the application of anthropometric data in design/ modification of tools and equipments to reduce the work-related drudgeries from the SSIs. Although serious attention has been paid by researchers in respect to designing tools/equipments with consideration of anthropometric data to reduce the drudgeries from the industries, but the researcher has not received a significant response from the end users of SSIs due to lack of required capital to made the changes [106, 142, 154]. Therefore, an integrated design focus i.e., low cost design based on anthropometric data, will be necessary to reduce drudgery from the SSIs.

### 1.7.10.b Workstation design/ modification

Workstation modification allows to rectify the working posture most significantly and hence removes the most potential ergonomic-related drudgeries [143, 144]. A properly designed workstation reduces the workers physical and psychological pressure due to minimum movement of materials and hence, improves the health of workers by minimizing the stress/ drudgery [158]. Workstation design/modification is a scientific art that depends upon several factors viz., design of products to be manufactured, production techniques, required machines, production rate, available area, etc. [147]. Workstation redesign/modification means rescheduling the space allocation for man, machine and material movement in the production line, starting from the entry of raw materials to the production of the finished goods. Appropriate placement of machines in the production line reduces the cost of the product by optimal use of available space and effectively utilizing the resources, i.e., man, machine and materials [159]. A well designed workstation is safe and flexible for future changes. A noble workstation also increases the industrial profit by decreasing the production cost and time due to decreased delay between intermediate activities [147, 160, 161].

In literature, workstation designs have been divided into four basic groups based on the layout, namely, a) product layout, b) process layout, c) fixed position layout and d) cellular layout. The layout divisions are made based on the production capacity, range of products manufactured in the plane and productivity of the plant [147, 160–162]. These workstations are designed by using a tool called SLP (systematic layout planning). In SLP, the workstation design starts with collecting information on the manufacturing process and flow of materials inside the production units. Then a relationship diagram between the manufacturing process and flow of materials is developed. The relationship diagram is the spatial arrangement of the departments present in the industry showing the interrelation between the departments. Few alphabetical characters are used in the relationship diagram to represent the relationship between different departments and levels of importance between the departments. For example, the letter "A" is used to represents the relation between two absolutely necessary departments, "E" is used to represents the especially important relations, "I" is used to represents the important relations, "O" used to represent the okay relations, "U" is used to represents the unimportant relations and "X" is used to represents the undesirable relations [163]. Then the required machines are either selected from the market or designed for the workstation. Then calculations are made to measure the required and avail space for the man, machines and material flow. Then finally, the workstation is designed. If any practical constrains are exist in the industry, like special customs, dress codes, etc., present in the location, then the workstation is further modified before executing the final design for production [163].

Again, a modified systematic layout planning (MSLP) has been recommended by authors to develop/ modify the workstation for the removal of drudgery present in the SSIs [143, 144, 150, 164]. The MSLP differs from the SLP in terms of consideration of anthropometry data or body dimensions of the artisans in designing a workstation. Figure 1.6 shows the flow chart of MSLP. From Fig 1.6, it has been observed that after the development of the relationship diagram, anthropometry data of the targeted group is used to modify or select the machines that need to be used in the industry. It is the most crucial step in terms of drudgery removal [148, 165, 166]. Wrong anthropometric data can lead to a mismatch in the dimensions between machines/tools and operators and hence may further increase the drudgeries [151, 167]. The consideration of anthropometric data of the persons who will be working in that industry is essential to correct the working posture causing ergonomics-related medical disorders in workstations [164, 168, 169]. Moreover, as a result of anthropometry data interventions, workstation efficiency further improves [148, 165, 166].

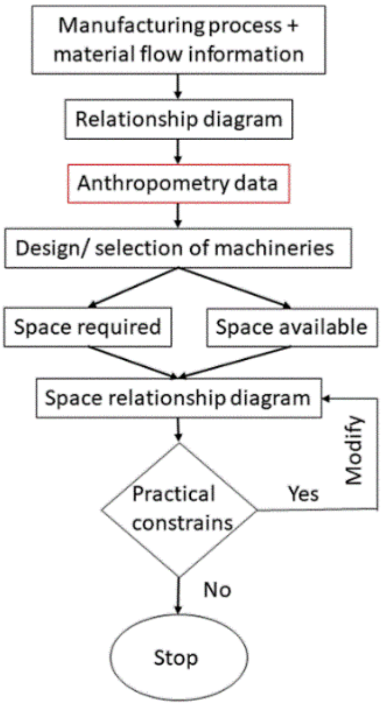

**Figure 1.6 Flow chart of MSLP**

From the ongoing discussions, it has been observed that workstation modification to reduce the drudgeries present in SSIs also requires anthropometric data of the artisans. The next section discusses available anthropometric data of artisans.

### 1.7.10.c Anthropometric data

Several authors have collected the anthropometric data (body dimensions) of operators and utilized it to design/ modify the TEWs. For example, Lavender et al. (2002) [149] has collected 21 anthropometry data of 87 female workers of the 16-40 years age group working in an electric motor manufacturing facility located at Reynosa, Mexico, to modify the workstations. Wibneh et al. (2020) [170] have collected 31 anthropometry data of 250 male army persons of 18–52 years age group lived in Ethiopia to design defence equipments. Ray et al. (1990) [171] have collected 82 anthropometry data of 147 female housewives of the 21–56 years age group who lived in Bombay, India, to modify the design of kitchens and cooking equipments. Taifa and Desai (2017) [172] have collected 12 anthropometry data of 2223 students of the 17–37 years age group studied in Gujrat states of India to redesign the school's desks. Arunachalam et al. (2020) [173] have collected 23 anthropometry data of 120 male bike riders of the 19–44 years age group who lived in 20 states of India. Dewangan et al. (2005) [174] has collected 33 anthropometry data of 280 male farmers of the 20–30 years age group who lived in Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland and Tripura states of India. Bhattacharjya and Kakoty (2020) [151] have collected 70 anthropometry data of 265 male and 188 female workers engaged in the pottery industry of 18–60 years age group lived in different districts of Assam, India.

Many authors also collected body dimensions of farmers to design farm tools, equipment's or machinery. For example, Gite and Yadav (1989) [175] have collected 50 anthropometry data of 39 male farmworkers of the 15–60 years age group working in Bhopal, India, to design farm tools. Majumder (2014) [176] has collected 25 anthropometry data of 147 male farmworkers of the 18–65 years age group working in Odisha, India, to design farm machinery. Victor et al. (2002) [157] have collected 9 anthropometry data of 300 male farmers of the 21–48 years age group who lived in Chhattisgarh states of India to design farm hand tools. Luthra (2018) [177] has collected 32 anthropometry data of 120 people of the 8–80 years age group who lived in the Madhya Pradesh state of India. Kharb et al. (2020) [179] has collected 16 anthropometry data of 200 male farmers of the 20–30 years age group who lived in Haryana, India.

From the published anthropometric data, it has been observed that the data varies from one place to another place. Bhattacharjya and Kakoty (2020) [151] further reported that the anthropometric data varies among the working groups of the same locations. Therefore, the consideration of anthropometric data of the persons who will be working in that industry is essential to correct the working posture causing ergonomics-related medical disorders in workstations [151, 164, 168, 169]. However, no anthropometric data for the artisans working in the bell metal Industry has been found in literature, which is the most essential parameter for workstation modification in order to reduce the drudgeries. Therefore, an anthropometric data collection drive for the artisans engaged in the bell metal industry will be indeed for the development of the workstation for the industry. This data may be helpful for other industries also who are engaged in designing tools and equipements for the bell metal industry.

Again, in India, bell metal is extensively used for the manufacturing of household and ritualistic utensils and the industry enjoys high market demand because of the existing traditional perceptions of different health benefits. Therefore, the next section discusses the published literature on the health benefits of using bell metal utensils.

### 1.7.11 Health benefits of using bell metal utensils

'*Kansyam Buddhivardhanam*', a popular verge written in the Sanskrit language, means using bell metal improves intellectual property. Fine powder of bell metal is very commonly used as an ingredient in the ancient Indian medicine system *Ayurveda* for the treatment of various diseases [180]. Again, as per the *Ayurveda*, serving of water is considered to be healthy in bell metal utensils, which might be due to the copper leaching property of bell metal [180]. At present, it is well known that a limited amount of copper, which must be accumulated externally through food or water, is essential in the body for the maturation and improvement of the nervous systems and bones [181]. Copper in the body also helps in protecting the cardiovascular systems by stimulating the proliferation and migration of endothelial cells, which further promotes the formation of new blood vessels [181, 182]. Many isomers of fibroblast growth factor (FGF) connecting tissue cells require the participation of copper present in the body [183].

Feng et al. (2009) [184] have reported that copper in the body activates and promotes hypoxia-inducible factor-1 (HIF-1), which is a regulatory factor of angiogenesis under hypoxia.

Wapnir (1998) [185] has reported that in an adult body, 50–150 mg of copper improves the performance of enzymes involved in the metabolism of glucose, amino acids, and cholesterol.

Sudha et al. (2012) [186] from a study reported that copper in drinking water kills the diarrhoeagenic bacteria like *Vibrio cholerae* O1, *Shigella flexneri* 2a, enterotoxigenic *Escherichia coli*, enteropathogenic *E. coli*, *Salmonella enterica Typhi*, and *Salmonella Paratyphi;* provided the copper concentration retained in water is within the World Health Organization (WHO) recommended limits. WHO has provided the regulated or guideline limit for copper in drinking water is 1.5 mg/L and a per day range of 0.05 – 3 mg/L, based on data from 104 counties [187]. Nevertheless, there has also been discussion to acknowledge copper from drinking water can be an important source for individuals consuming a copper-deficient diet [188]. The leaching copper from bell metal utensils can be an important source of copper in drinking water to mitigate copper-deficient diseases. Therefore, a study in this line is definitely a potential gap of research. The next section discusses a summary of the published literature.

### 1.7.12 Summary of published literature

The published literature can be summarized as follows a) the bell metal is extensively used in numbers of industries due to its different specific properties; however, the mechanical properties of the bell metal processed in different conditions has merely been reported in literature, b) the bell metal items manufacturing process varies among the clusters; however, the basic fundamental process like casting, forging, surface cleaning and art-working process, etc. are same in all the clusters, c) each stage of bell metal manufacturing process is critical; yet, a very limited amount of work has been carried out to understand the stages of manufacturing process used to produce the bell metal items, so forth its consequences related to intermediate waste generation process, d) recently, few authors tried to join bell metals in order to repair the faulty products; but none of the process has received industrial efficiency, e) in all the bell metal cluster artisans still use hundreds of years age-old traditional handmade tools and equipments, which are mainly responsible for the drudgery of artisans; however, no significance study has been found related to design and development of tools and equipments for the bell metal industry, f) very high-level drudgeries are present in almost all the SSIs due to using poorly designed tools/ equipments and adopting awkward postures; hence the SSIs are facing a lack of human resources, g) anthropometric data of the targeted group is essential to rectify the postures and hence to reduce the ergonomic related hazards; but, the anthropometric data of the bell metal artisans has not been reported in literature, h) bell metal utensils is extensively used in India due to the existing perception of health benefits; yet, no studies have been carried out to prove the perceptions.

From the ongoing discussions, it has been observed that there is an urgent need for detailed and in depth multi-disciplinary study for the development of the bell metal industry and hence to solve the ever increasing global problem of unemployment. The next section discusses a few of the available research gaps.

## 1.8 Research gaps

A number of gaps have been identified from the literature review and the field survey report to carry forward the research. For example, study related to the mechanical properties of the bell metal processed in different conditions; understanding the different stages of the manufacturing process viz., forging, quenching, etc. and its consequences in waste generation process; developing a suitable joining process for the bell metal; material behaviour during forging and quenching process; study related to design and development of tools and equipments for the bell metal industry to reduce production time and drudgeries; assessment of drudgery data of the bell metal industry; interventions of ergonomics to reduce the drudgeries of the workers engaged in the bell metal industry; study on health benefits of using bell metal utensils and many more. Each of the gaps required urgent and special attention from the research community. However, based on the available research facility and time, the area of present thesis work has been restricted to study only a few of the unfilled gaps. The next section discusses the scope of the present thesis work and objectives selected for the present work.

## 1.9 Scope of the present work and objectives

In this thesis, several important aspects of the bell metal production process have been studied to modernize the industry. The primary aim of the present thesis is to study the insights of the bell metal products manufacturing industry to reduce the drudgeries of the worker and hence to increase the income level of artisans to redraw the attention of new generations to solve the manpower scarcity problem. Another aim of the study is to enhance the industrial use of bell metal products by increasing the range of products for the development of the bell metal industry.

This thesis focused on understanding the present bell metal products production techniques and finding the effects of the different processes on the mechanical properties of bell metal products. Further, the present work concentred on removing the riveted products to decrease the handling difficulties by exploring the different joining techniques. Improving the present working conditions to reduce the drudgeries of artisans engaged in the bell metal industry is another area of this study. Finally, the thesis puts some light on the existing belief of the health benefits of using the bell metal utensils.

In view of the above, the following objectives are drawn for this thesis works:

1. To investigate the mechanical properties of bell metal processed in different conditions and hence to create a database on mechanical properties of bell metal.
2. To explore the possible joining process and hence to find a suitable technique for joining the bell metal parts.
3. To assess the level of drudgeries associated with the bell metal industry.

4. To design an ergonomically correct workstation for drudgery reduction of the workers engaged in the bell metal industry.
5. To investigate the copper leaching property of bell metal utensils.

## 1.10 Organization of this thesis

Chapter 1, i.e., this chapter starts with a brief introduction of small scale industry and its significance on the Indian economy. Subsequently, general properties and applications of the bell metal have been discussed. The state of the manufacturing industry and the art of the production process have also been highlighted in this chapter. The research works of other authors on the SSIs especially focusing on the bell metal item production process, have also been presented in this chapter. The literature review and field surveys were carried out to formulate the objectives of this thesis. The motivation of the present study, along with the research objectives, has also been highlighted in this chapter.

Chapter 2 will showcase the materials and methods used in this study, which includes the selection and preparation of materials, experimental techniques used to achieve the objectives and testing methods used to obtain the results. Chapter 3 presents the detailed mechanical properties of bell metal products manufactured in Sarthebari. Chapter 4 deals with a detailed investigation report on the effects of processing parameters on the mechanical properties, namely hardness and fracture strength of bell metal.

Chapter 5 represents details of the experimental studies performed to join the bell metal. Finally, sets of TIG welding parameters to obtain the best bell metal weldments have been brought out in this chapter. Chapter 6 shows the statistical analysis of ergonomic risks associated with the workers engaged in the bell metal industry and details of designing a drudgery-free workstation to remove the awkward postures adopted by the artisans while working in the bell metal industry. Chapter 7 demonstrates the copper leaching properties of bell metal utensils in drinking water.

Chapter 8 contains an overview and key contributions from the present thesis work. Few recommendations to reduce the drudgery based on the findings of the present thesis work have also been discussed in chapter 8, along with the concluding remarks. In this chapter, few scopes for future study have also been demonstrated. Following that, the novelties of the current thesis work have been highlighted. Further, on the last page, a list of publications from the present thesis work has been attached.

# Chapter 2 MATERIALS AND METHODOLOGY

## 2.0 Introduction

The previous chapter discusses an overview of the bell metal industry, possible research gaps and the objectives for this study. This chapter describes the road map followed to fulfill the requirement of each objective defined in the previous chapter and the methodology or standards followed in this study to carry out the experiments.

## 2.1 Background

Plano-Clark and Creswell (2009) [189] outlined seven steps of Ph.D. works as a) introducing the research problem, b) reviewing of the literature, c) identifying the objectives, d) choosing research design and data collection method, e) analysis of data and reporting the results, f) interpreting and discussing the data and g) publishing papers. Conventionally, it is believed that defining objectives cover 50% of total Ph.D. work. However, achieving the objectives within a stipulated time requires a proper roadmap. Roadmap also helps the researcher to stay focused within the research boundary by alleviating the confusions that may arise during the Ph.D. work [190]. In view of this, a roadmap has been prepared and described in the next sections.

## 2.2 Road map

The present work starts with a field study and literature survey to find the research gaps. Then the objectives have been defined to carry out the works for the thesis. Figure 2.1. shows the road map followed to complete the objectives for the present thesis work. The first objective, i.e., the preparation of the database for the mechanical properties of bell metal, has been accomplished by collecting, preparing and investigating the bell metal samples processed in different conditions. The second objective, i.e., exploring the joining methods to find a suitable joining technique for bell metal, has been completed by recommending the welding techniques through hit and trial method followed by sample preparation and investigation of the bell metal weldments. The third objective, i.e., the assessment of drudgery level present in the bell metal industry, has been accomplished by collecting different data during the field survey and then carrying out the statistical analysis of the data collected from the production centers of Sarthebari followed by digital human modelling to confirm the field report. The fourth objective, i.e., developing an ergonomically correct workstation for the bell metal items production center, has been achieved by collecting and analyzing the anthropometric data of bell metal workers from the Sarthebari area and then utilizing the data in designing the workstation by following the MSLP tools. The fifth objective, i.e., the investigation of copper leaching property of bell metal utensils, has been completed by measuring the amount of copper leached from the bell metal utensils in drinking water for different periods of time, followed by investigating the leaching surfaces.

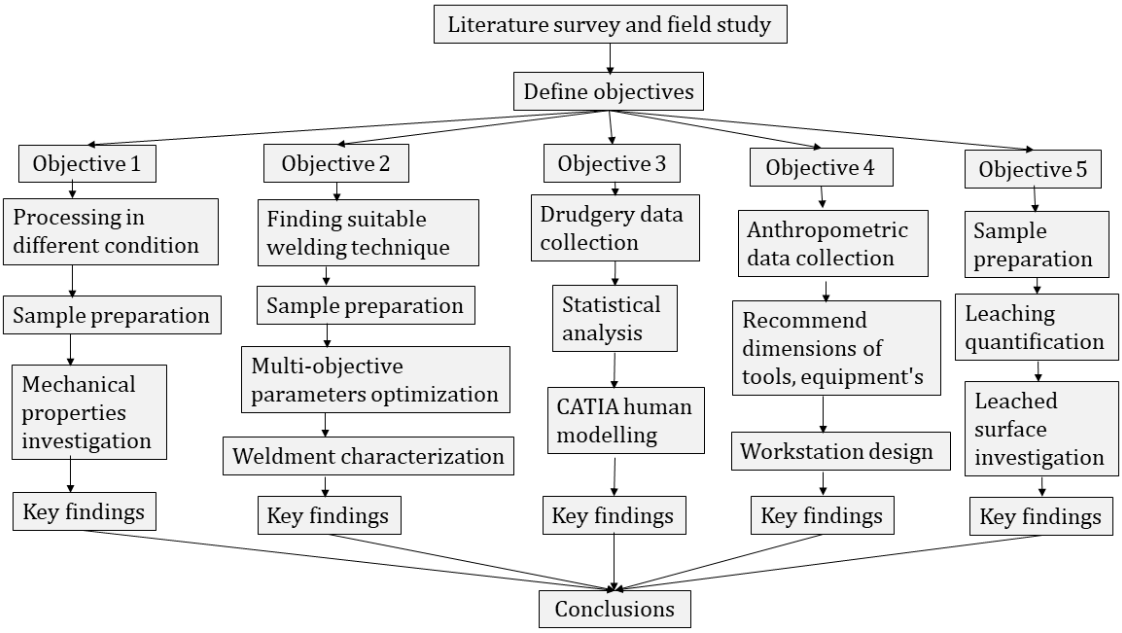

**Figure 2.1 Road map**

Again, the outcome of any research works depends on the selection of appropriate methodology or standards, techniques of sample identification or preparation and types of instruments used to collect the data. In view of this, the next section describes the data collection methods from the field surveys.

## 2.3 Data collection methods from the field surveys

Field survey is one of the most common methods rigorously used by researchers for the process of primary data collection. The selection of the study area for the field survey and types of data collected from the field survey have already been discussed in Chapter 1. In this section, methods followed for data collections have been discussed.

The first types of data i.e., the source of raw material, the quantity of raw material processed per day, types of product manufactured, number of artisans involved, total annual transection, etc. have been collected from the **Assam Cooperative Bell Metal Utensils Manufacturing Society, Sarthebari** through telephonic discussions. Few data like production time, types of activities need to perform, amount of waste generated per day etc. were collected directly from the production centers by interviewing the artisans during the field surveys on 8th to 15th June 2017. The casting temperature and forging temperature were also measured in the production centers with a 4-point noncontact infrared thermometer (Make: **Testo, Germany**).

The second field survey was carried out from 4th to 8th January 2020 to measure the level of drudgery associate with the present production system. The data were collected through questionnaire-based interviews of workers consist of personal information like name, age, educational experience, years of experience, weight, grip force, etc. Drudgery data collections were performed by following the World Medical Association of Helsinki protocol as described by Rennie (2013) [191]. The Borg scale was used to collect the data on body discomfort and determine the occurrences and intensity of pain in the various body parts of workers. The participants reporting any previous history of pain due to accidents, diseases or any injuries were excluded from this study. An electronic hand dynamometer (Make: **Camry Scale, China**) was used to collect the changes in handgrip force of artisans in the morning and afternoons. A commercially available portable weighing scale with a range of 0 – 125kg was used for measuring the body weight of workers. Further, direct observations were made to identify the posture adopted by the workers during performing the task in the bell metal production centers. Videos and still photos of workers while performing the tasks were also captured during the survey for further analysis. Appendix A shows the questionnaire used to collect the drudgery data.

The third survey was carried out from 1st to 10th February 2021 to collect the anthropometric data of artisans. The anthropometric data were collected by direct measurements. Appendix B shows the questionnaire used to collect the anthropometric data. Standard terminologies as given by Bhattacharjya and Kakoty (2020) [151] and Dewangan et al. (2005, 2010) [152, 174] standards were followed to collect the anthropometric data of the bell metal workers.

A commercially available anthropometer rod (Make: **Siber Hegner and Co., Switzerland**) was used to measure most of the body dimensions, viz., height and length. A measuring tape with an accuracy 1mm was used to measure the circumference data of artisans. Again, a Vernier caliper with a least count of 0.1mm was used while measuring the hand dimensions. The procedure described in ISO (2017) [192] standards was followed to collect the data. Figure 2.2 shows the picture from the field survey.

**Figure 2.2 Picture from field survey**

## 2.4 Data analysis

Data collected from the field survey were statistically analyzed by following the different procedures proposed by researchers.

### 2.4.1 Drudgery data

The drudgery data were analyzed according to the method described by Meksawi et al. (2012) [193]. In this method, the score less than 3 is considered as "**no pain**" and a score greater than or equal to 3 is considered as "**pain**". The workers reporting any earlier history of discomforts because of accidents, diseases or any other injuries are excluded from this study.

The statistical analysis was performed using MINITAB 16 Statistical Software package and a Microsoft Excel software package. The descriptive statistical parameters, viz., minimum, maximum, mean, standard deviation (SD), standard error of the mean (SEM), coefficient of variation (CV), and percentile values ($5^{th}$, $50^{th}$, and $95^{th}$) of all the drudgery data in different body regions i.e., neck, shoulders, forearms, upper arms, lower back, upper back, wrists, palm, thigh, knee joint and eye irritation were then computed.

Moreover, to represent the personal data, two indices, namely body surface area

(BSA) and body mass index (BMI), were calculated using the following formulae as recommended by Bhattacharjya and Kakoty (2020) [151]:

$$\text{BSA (m}^2\text{)} = \sqrt{\frac{Height\ (cm) X\ Weight\ (kg)}{3600}} \qquad \textbf{2.1}$$

$$\text{BMI (kg/m}^2\text{)} = \frac{Body\ weight}{Stature^2} \qquad \textbf{2.2}$$

### 2.4.2 Anthropometric data

The statistical analysis of anthropometric data was performed using a MINITAB 16 software package and a Microsoft Excel software package. The raw data for each dimension and subject was directly fed to the software package, which sorted the data in ascending order based on participants stature. Outliers and unreasonable data caused by unaccountable errors were identified and discarded to minimize the effects of human error. Outliers discarded include the data value that lies beyond three folds of the interquartile range ($Q_3 – Q_1$) on both sides i.e., quartile one ($Q_1$) and quartile three ($Q_3$) [151, 194]. Thus, minimum and maximum values considered in the study were as follows: Minimum value = $Q_1$ – 3x interquartile range and Maximum value = $Q_1$ + 3x interquartile range. The descriptive statistical parameters, viz., minimum, maximum, mean, standard deviation (SD), standard error of the mean (SEM), coefficient of variation (CV), and percentile values (5th, 50th, and 95th) of all the body dimensions were also computed.

## 2.5 Digital human modelling

The Digital Human Modelling was carried out in Computer Aided Three dimensional Interactive Application (CATIA) version 5.0 software in the ergonomic environment to access the postures adopted by the artisans. The manikin models of artisans were made by using the mean value of the anthropometric data of the bell metal workers collected from the Sarthebari. Then the Rapid Upper Limb Assessment (RULA) score of the models was assessed to find the level of ergonomic risks of the artisans due to adopting the present awkward postures while performing the production tasks.

## 2.6 Workstation design

The drudgery-free workstation has been designed by using the modified systematic layout planning (MSLP) as recommended by many authors [143, 144, 150, 164]. Figure 1.6 shows the flow chart of the MSLP used for achieving a healthy worker posture through workstation modification.

Publish papers by Srinivasan (1994) [22] on the bell metal items production process and field survey report have been used to start the workstation design. Freshly collected anthropometric data of bell metal artisans has been utilized in designing the workstation in order to minimize the ergonomic risk factors of the workers.

The principle of "designing for adjustable range" proposed by Taifa and Desai (2017) [172] is used for designing the equipments and machines of the workstation. Again, Somatotype i.e., covering the extreme range of endomorph to ectomorph dimensions recommended by Tilley (1993) [195], has been used to design the workstation.

## 2.7 Materials preparation

The bell metal products were procured from the local market of Sarthebari to analyze the metallographic and mechanical properties. Further, research-grade i.e., 99.99% pure tin and copper blocks, were procured from the market and then the bell metal of different compositions were developed in the IIT Guwahati lab. The bell metal of different compositions was developed by casting process as discussed in the below sub-section.

### 2.7.1 Casting

The castings were done in the laboratory by co-melting the 99.99% pure virgin copper and tin in a graphite crucible inside a vertical furnace (Make: **Thermo, India**) to produce the bell metal samples. The amount of copper and tin were varied on weight basis to obtain the bell metal samples of different compositions. The casting temperature selected for this study is 1100ºC. To ensure complete melting, the crucible was kept inside the furnace for minimum 30 minutes. The molten metal was also stirred before pouring in a previously prepared clay mould for proper mixing. The molten metal was then allowed to cool in the air up to room temperature to form the 5mm thick cast disks of 120mm diameter. The quality of the cast bell metal disks was then investigated by various standard processes to determine the casting quality. Figure 2.3 shows the casting furnace and the casted sample.

### 2.7.2 Quenching

The cast samples were heated and socked for 30 minutes in a muffle furnace at different predetermined temperatures, called quenching temperature and then dipped in oil and water from that high temperatures to carry out the quenching process. The quality of the quenched bell metal ingots was then investigated by various standard processes to measure the mechanical properties.

**Figure 2.3 Casting: a) Furnace; b) Casted sample**

## 2.8 Testing methods and sample preparation techniques

Testing methods are the backbone to extract experimental data. The accuracy of the experimental data depends on the selection of testing methods and sample preparation techniques. Sample preparation techniques and the standards testing methods used for investigations of different properties viz., microstructure, phase, thermogravimetric properties, hardness, strength etc. of the bell metal have been discussed in the subsequent sections.

### 2.8.1 Microstructure

Specimens collected from Sarthebari and produced in the lab were cut and grounded in a single disk polishing machine (Make: **Chennai Metco Pvt. Ltd.**, **India**) to polish with different grade emery papers viz., 180, 220, 400, 600, 800, 1000, 1500 and 2000. Then the samples were polished in a velvet cloth with alumina powder for a mirror finish. The mirror-polished materials were then etched with the etchant 50ml distilled water + 4ml $H_2SO_4$ + 2mg $K_2Cr_2O_7$. American Society of Testing Materials (ASTM) E3 standards were followed during the preparation of the samples for microstructural examinations [196]. The microstructure of those etched samples was observed under an upright optical microscope (Make: **Leica**

**Microsystems, Germany**). Figure 2.4 shows the optical microscope and the prepared samples.

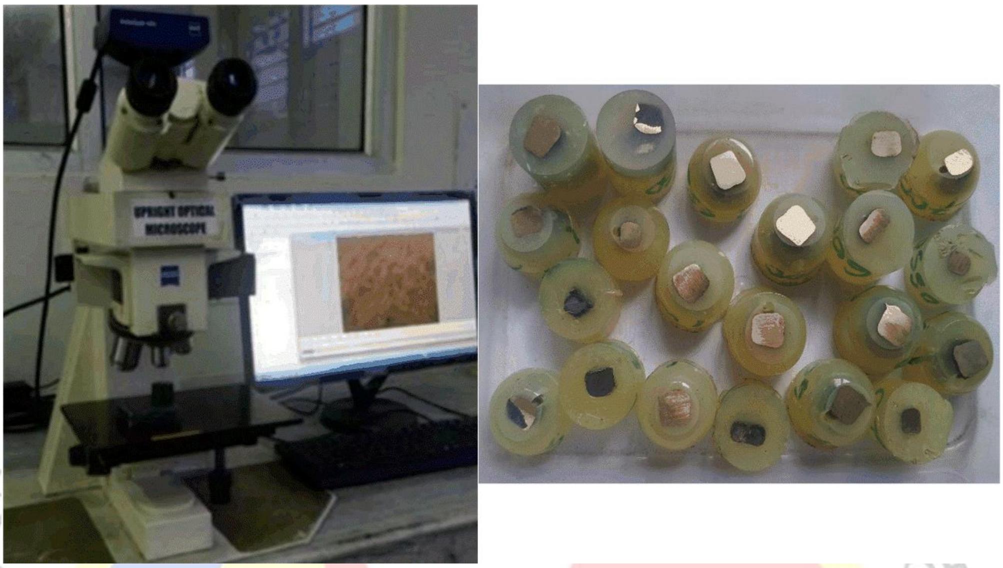

Figure 2.4 Microstructure: a) Optical microscope; b) Prepared sample

## 2.8.2 Compositions

The elemental compositions of the etched samples prepared for the microstructure observations were measured by an Energy Dispersive X-ray spectrometer (EDX) analyzer (Make: **Sigma, Carl Zeiss AG, Germany**) equipped in the Field Emission Scanning Electron Microscope (FESEM).

## 2.8.3 Hardness

Samples prepared for the microstructure observation were used to measure the hardness. Hardness values were measured according to ASTM standard E92 in a micro Vickers hardness tester (Make: **Buehler, Switzerland**) [197].

## 2.8.4 Thermogravimetric properties

For thermogravimetric analysis, samples were cut from the products collected from Sarthebari and then prepared according to ASTM E794 standards [198]. The thermogravimetric properties of the samples were investigated from the DSC curve obtained from a thermogravimetric analyzer (Make: **Netzsch, Germany**).

## 2.8.5 Fracture strength

The fracture strength of the bell metal samples was investigated by carrying out the tensile and compressive tests in a servo-hydraulic controlled dynamic Universal Testing Machine (UTM) (Make: **Instron, USA**) under the constant crosshead speed mode with a nominal strain rate of 1mm/min at different temperatures. For determining the tensile and compressive strengths, samples were prepared by using the wire electric discharge machines (WEDM) as per ASTM standard E8 and E9 respectively [199, 200]. The sample used for the tensile test has a thickness of 1mm, length of 100mm (25mm gauge length) and grip width of 10mm (6mm specimen width). The length/ diameter (L/D) ratio of 1.3 of the samples has been maintained throughout the thesis work to carry out the compressive tests. Figure 2.5 shows the universal testing machine and fractured samples under tensile and compression load.

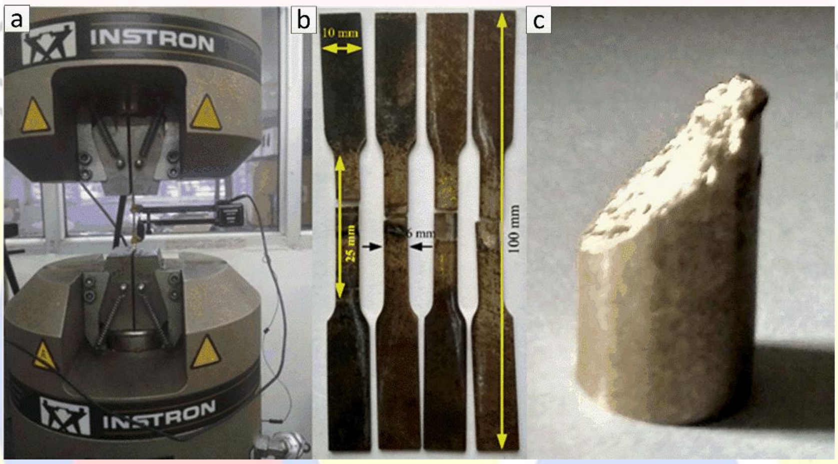

**Figure 2.5 Tensile test a) UTM machine; b) Tensile samples; c) Compression samples**

## 2.9 Summary

This chapter discusses the roadmap flowed to complete the objectives, material selection and preparation techniques, tools and instruments used for testing and different standards/ protocols used for sample preparations and data collections. This chapter also discusses data analysis techniques used in the present work.

In the next chapter, the metallographic and mechanical properties of cast and water quenched bell metal products collected from the Sarthebari have been discussed.

# Chapter 3 MECHANICAL PROPERTIES OF CAST AND WATER QUENCHED BELL METAL PRODUCTS

## 3.0 Introduction

The previous chapter discusses the methodology, sample preparation techniques and testing procedure followed in the present study. In this chapter, the mechanical properties of cast and water quenched bell metal products have been investigated and reported.

## 3.1 Background

For the last few decades, engineers have been making extreme efforts to find a material that can perform better under extreme environmental conditions during the period of service [63]. Bell metal has already been extremely used in different industries from ancient times for manufacturing of several products viz., canon, pump impeller, musical instruments, etc. that perform under various environmental conditions. So, the bell metal may have the properties that meet the engineers demand. However, from the literature survey, it was found that the mechanical properties of bell metal have not been extensively reported, which limits its applications. Therefore, investigations on mechanical properties of bell metal is essential to help the engineers to understand the behaviour of the material and hence the performance of the product during the service under different conditions. A general idea on the mechanical properties of bell metal will also be helpful for the engineers to make correct product design. So, there is a potential that a study on mechanical properties investigation of bell metal will increase its industrial demands. Therefore, in this chapter, the mechanical properties of cast and water quenched bell metal products have been examined.

## 3.2 Choice of experimental conditions

Few local cast and secondary processed products were collected from the local market of Sarthebari for analysis. The products were cut to prepare the samples and then analysed to investigate the microstructure, hardness, fracture strength and thermogravimetric properties of bell metal by following different standards as described in Chapter 2. Table 3.1 shows the experimental conditions used for this study.

**Table 3.1 Experimental condition**

| Experiments | Material | Condition | Standards |
|---|---|---|---|
| Microstructure | Cast and water quenched | 30ºC | ASTM E3 |
| Compositions | Cast and water quenched | 25ºC | |
| Hardness | Cast and water quenched | 30ºC | ASTM E92 |
| Fracture strength | Cast and water quenched | 30ºC, 550ºC, 700ºC | ASTM E8 & E9 |
| Thermogravimetric | Cast/ water quenched | 30 – 1000ºC | ASTM E794 |

# 3.3 RESULTS AND DISCUSSION

In this section, the results obtained from different experimental studies to investigate the properties of bell metal have been reported and then discussed.

## 3.3.1 Properties of cast products

### 3.3.1.a Microstructure

The microstructure of five cast ingots is observed under an optical microscope. Figure 3.1a & b shows the microstructure of the cast ingots a) at 5× magnification and b) at 20× magnification. From the microstructure, it can be seen that three different zones have been formed, namely i) A as cored dendritic zones, ii) B as inter-dendritic zones, and iii) C as the fringe zone between dendritic and inter-dendritic zones. The presence of continuous grain at the edges of cast products has also been observed. The compositions of the cast ingots in all three zones have been studied for minimum 10 different locations and the average values have been reported here. Figure 3.1c & d shows the percentage of Cu and Sn in A and B respectively. It has been found that Cu:Sn ratio in A is changing from 85.7:14.3 at the center of the arms to 84.1:15.9 at the end of the arms and in the B it is found to be 71.0:29.0. Figure 3.1e shows the percentage of Cu and Sn in C and Cu:Sn ratio is found to be 73.7:26.3. Figure 3.1f shows the electron-mapping image inside and outside of the dendritic arms. From Fig. 3.1f, it can be seen that Sn content is higher in B than A. This microstructure is in line with the microstructure of peritectic Cu-Sn alloys published by Scott (1991) [21]. The copper-tin alloy phase diagram published by Acharya (2001) [88] confirms the compositional results obtained from EDX analysis in all three zones. From the phase diagram published by Acharya (2001) [88] it has also been found that the dendritic zone is in the α phase, the inter-dendritic zone is in eutectoid the δ phase and the fringe zone is in the β phase. Again, many authors reported that the α phase has FCC (face-centered cubic) structure and the β phase has BCC (body-centered cubic) structure [14, 67–70]. Moreover, Saunders and Miodownik (1990) [70] reported that that the δ phase has SC (simple cubic) structure and is responsible for the brittle nature of cast ingots.

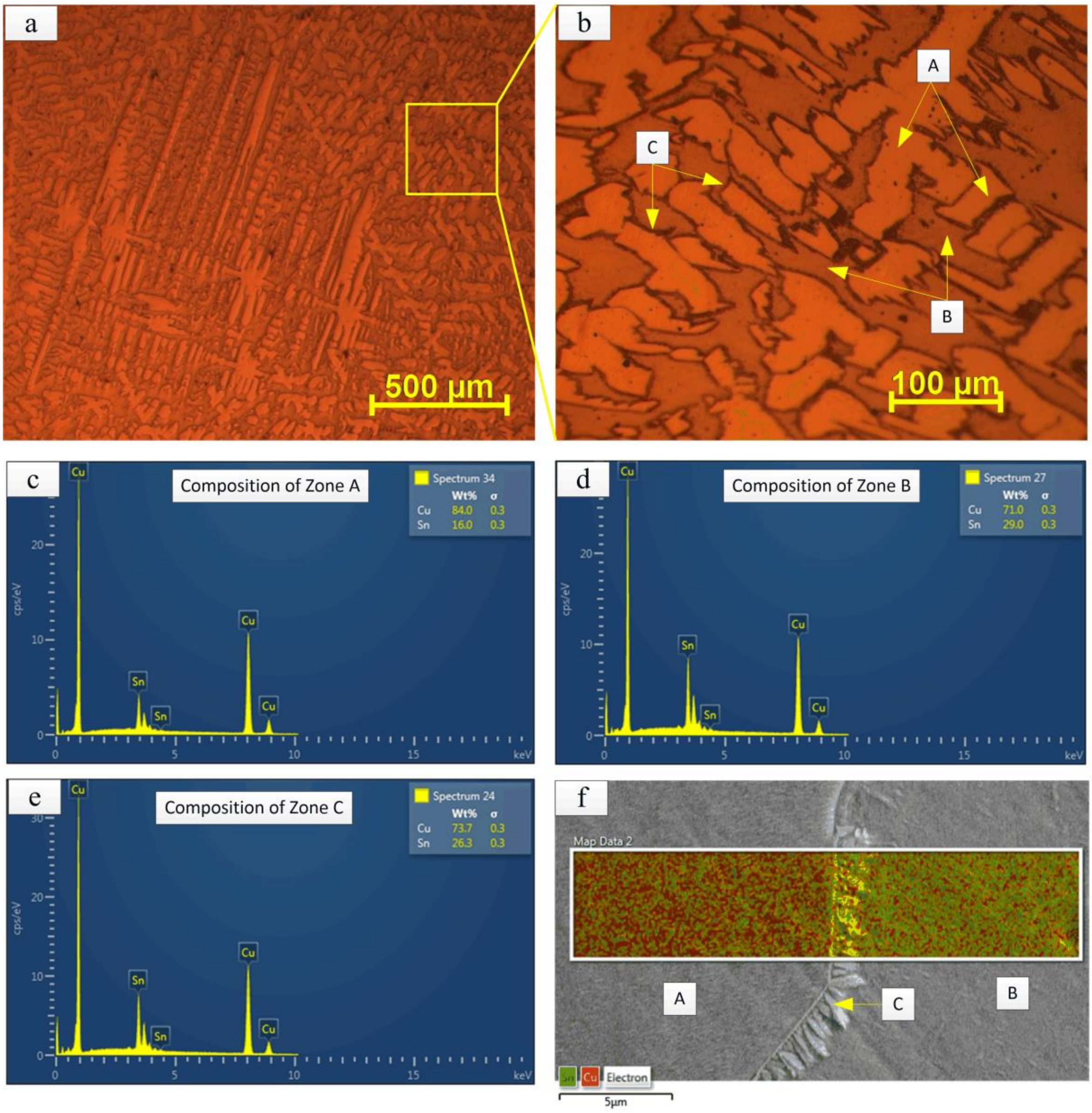

**Figure 3.1 (a) microstructure of the cast ingot at magnification of 5×; (b) microstructure of the cast ingot at magnification of 20×; (c) average composition in the α dendritic zone; (d) average composition in the inter-dendritic zone; (e) composition in the thin zone; (f) electron mapping image**

The increasing concentration of Sn from the center to the end of dendritic arms can be explained from the solidification process of molten bell metal. Solidification of molten bell metal is a complex phenomenon of simultaneous heat transfer and continuous solute precipitation termed as a thermo-solutal process [201]. The edge of the cast products cools much faster and does a catastrophic change of the equilibrium conditions of molten bell metal. High heat transfer in conduction mode from the molten bell metal to the mould cools the edge much faster in comparison to the other parts of the molten bell metal exposed to the surroundings due to the lower rate of convectional heat loss. Again, due to the higher melting point of copper, copper rich solutions solidifies at a much faster rate and start to precipitate in edges as the continuous α grains. Therefore, a very less amount of Sn could dissolve in the early precipitated grains. Early precipitated edge side α grains then act as a nucleus to precipitate more α grains to form columnar dendritic arms and continues to grow towards the center of ingots. As the α dendritic arm grows, the solidification time of dendritic arms increases and hence, more tin starts to deposit in the arms towards the end of it. The growth rate of dendritic columnar arms and parallel rate of fall of temperature of the molten metal are the major parameters controlling the final compositions of dendritic arms. As the solidification process goes on, a fringe zone surrounding to the α dendritic arms starts to precipitate as the β phase with a little higher Sn content than the α phase. Early precipitation of the α dendritic arms and surrounding β phase results in Sn rich solutions in the inter-dendritic zones, that solidifies as δ phase. Hence, the microstructure of cast ingots shows non-equilibrium solidification characteristics and form three different phases, namely the α phase inside the dendritic arms, the δ phase in the inter-dendritic zones and the β phase as fringe outside of the dendritic arms. The cumulative effects of the presence of these phases on the mechanical performance of bell metal products are discussed in the later sections.

### 3.3.1.b Hardness

Hardness is measured in minimum 10 locations for each sample and average values have been reported here. Micro-hardness and bulk hardness are measured in etched and non-etched samples respectively. The average bulk hardness in cast ingot is found to be 125 ± 5HV. The micro-hardness in the dendritic arms of cast ingots (see Fig. 3.1.b) is found to be 105 ± 5HV and in the inter-dendritic zones, it is found to be 135 ± 5HV. Audy and Audy (2008) [65] have reported an average hardness value of 180 ± 21.7HV in the dendritic α phase and 369 ± 52.3HV in the inter-dendritic eutectoid (δ) phase from the investigation of casted church bells manufactured in different eras; which are significantly higher than the value found in the present study.

A higher hardness value in the inter-dendritic zone compared to the α dendritic arms is attributed to the presence of the δ phase in the inter-dendritic zone (see discussion 3.3.1.a).

Hence, it is inferred that a higher δ phase will result in higher hardness values of cast bell metal ingots. Therefore, the lower hardness value of cast ingot selected in the present study from the study reported by Audy and Audy (2008) [65] may be attributed to the presence of more δ phase in the cast ingots. In general, the quantity of different phases present in cast ingots varies due to different cooling rates. Hence, there is a possibility that Audy and Audy (2008) [65] had used a different cooling rate than what is considered in the present study to solidify the molten metals from melting temperature to room temperature. Therefore, hardness values are different from each other. However, detailed investigations are required to ascertain the root cause of these differences.

### 3.3.1.c Fracture strength at room temperature

The fracture test of 10 samples cut from five different cast ingots has been carried out in the UTM at room temperature to find the stress-strain behaviour of bell metal. Figure 3.2 shows the typical stress-strain behaviour of cast bell metal ingots under tensile and compressive loads.

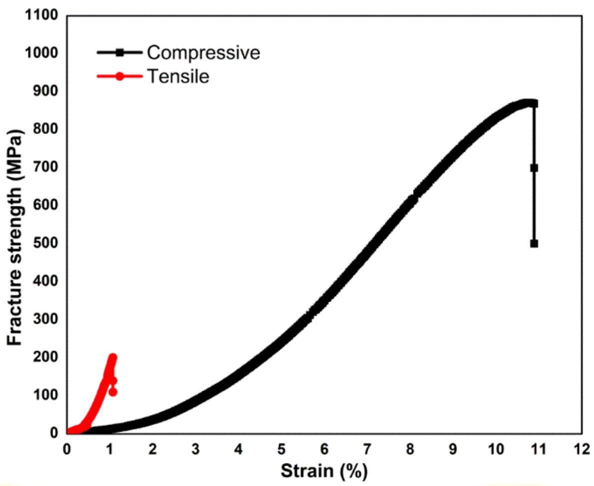

**Figure 3.2 Stress-strain behaviour of cast bell metal at room temperature**

From the test results shown in Fig. 3.2, it can be observed that cast bell metal fails in the brittle fashion at room temperature under both types of load. The average value of $R_{max\_c}$ (maximum compressive stress) has found to be 850 ± 10MPa and the average value of $R_{max\_t}$ (maximum tensile stress) is found to be 200 ± 5MPa. The average value of E (modulus of elasticity) is measured to be 17.5 ± 1GPa. The average value of $R_{0.2\_c}$ (compressive yield stress at 0.2% offset) is calculated from the stress-strain curve under compressive load and it is found to be 675 ± 5MPa. Nadolski (2017) [66] has reported $R_{max\_t}$ values of 229.78MPa in cast ingots; which is 30MPa higher than the present study.

Brittle mode of failure behaviour in stress-strain curves under both tensile and compressive types of loads suggests that the δ phase formed in the ingots controls the fracture strength of cast bell metals over the α dendritic and β fringe phases.

## 3.3.2 Properties of water quenched products

### 3.3.2.a Microstructure

The microstructure of water quenched bell metal samples is shown in Fig. 3.3. From Fig. 3.3 it is observed that the microstructures consist of two different types of zones as i) island zones A and ii) needle-like martensitic zones B. It is also observed from Fig. 3.3 that annealing twins are present in island zones A. On comparing the present work with Srinivasan (1994) [22], it can be understood that island zones A is in the α phase and needle-like martensitic zones B is in the β phase. The average Cu:Sn ratio in the α and β phase of the bell metal is found to be 84.5:15.5 and 75.0:25.0 respectively. Comparison of the Cu:Sn ratio of each phase to the Cu-Sn alloy phase diagram published by Acharya (2001) [65] also confirms the formation of the α phase in zone A and the β phase in zone B.

The formation of the α phase island zones is attributed to the fragmentation of the dendritic structures formed during the heating and forging process. On application of heat and force during the high temperature forging process, the dendritic structures formed during the casting process fragments into parts and form the island zones. Whereas the presence of the needle-like martensitic β phase in the microstructure is due to the transformation process of the δ phase to the β phase during heating. On the increasing temperature, the δ phase present in the cast ingots transform to the β phase and then, on quenching from that high temperature, the β phase arrest at room temperature as a needle-like martensitic structure [21, 71, 72]. Pandey et al. (1991) [69] studied the detailed martensitic transformation process for a wide range of Cu-Sn alloys and reported that the martensitic is formed due to the transformation of the β phase into the basal plane by lattice deformation shear followed by a lattice invariant shear.

Again, the annealing twins formed in the α phase are due to the recrystallization process of that phase. The annealing twins formed in the quenched bell metal are found to be of type II as reported by Mahajan et al. (1997) [75]. Huang et al. (2016) [74] reported that the annealing twins formed only in the FCC structured α island phase is due to the lower stack fault energy of that phase. A detailed study on the formation mechanism of annealing twins in FCC crystals was done by Mahajan et al. (1997) [75]. Since from the field survey, it was found that bell metal is processed in between the temperature range of 600 – 800ºC to formed the product; therefore, it may be inferred that the recrystallization temperature of the α phase is in the range of 600 – 800ºC. The cumulative effects of the presence of these phases and the annealing twins on the mechanical performance of bell metal products are discussed in the later sections.

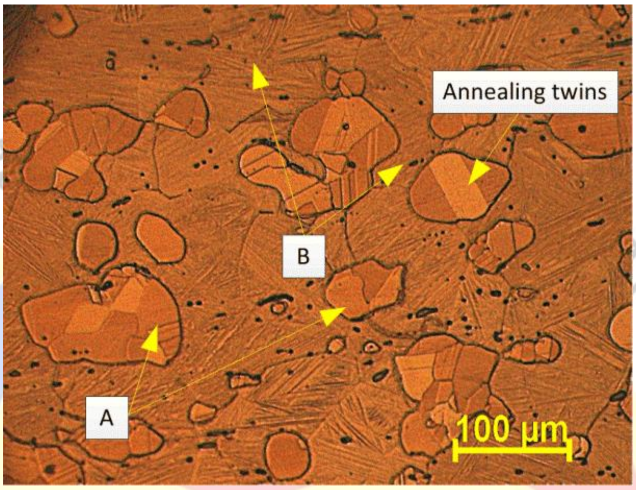

**Figure 3.3 Microstructure of bell metal product at a magnification of 20×**

### 3.3.2.b Hardness

Average macro hardness is measured in the non-etched water quenched bell metal products and it is found to be 295 ± 3HV. The hardness value is almost equal with the published results of Srinivasan (1998, 1994) [14, 22]; and 180HV lower than the value reported by Y. Li et al. (2013) [72]. The phase-wise micro-hardness in the α phase (zone A) and the β phase (zone B) (see Fig. 3.3) of the bell metal products are found to be 200 ± 2HV and 370 ± 1HV respectively. The higher hardness of the β phase in the products is attributed to the needle-like martensitic structure. Again, the lower hardness value of the present study in comparison to the value reported by Y. Li et al. (2013) [72] is attributed to the formation of the higher amount of needle-like martensitic β phase. On the increasing processing temperature, more amount of δ phase present in the cast ingots transform to the β phase and then, on quenching from that high temperature, higher amount of β phase arrest at room temperature as a needle-like martensitic structure [21, 71, 72].

### 3.3.2.c Fracture strength at room temperature

Figure 3.4 shows the stress-strain behaviour of the water quenched bell metal products under both tensile and compressive loads. Bell metal fails in the brittle mode under both tensile and compressive load at room temperature, as observed from Fig. 3.4. The ultimate tensile and compressive fracture strength of the bell metal product is found to be 570 ± 5MPa and 1100 ± 5MPa respectively. Present results could not be compared due to the unavailability of benchmark data. The brittle nature of the failure under both types of the load is attributed to the dominating nature of the martensitic β phase over the α phase.

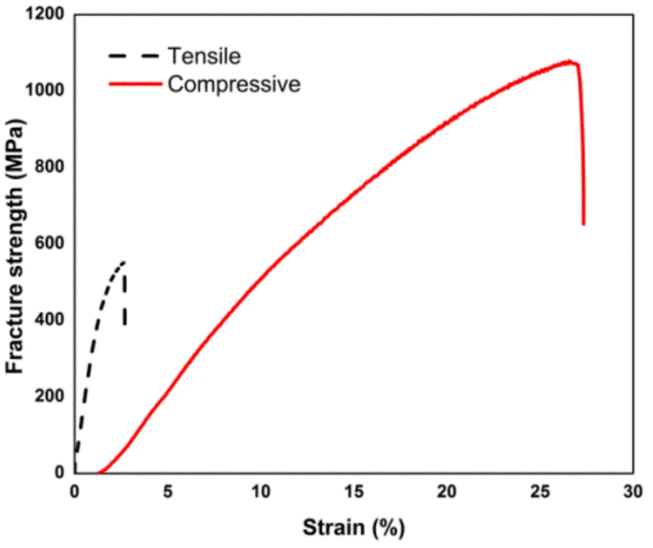

**Figure 3.4 Stress-strain behaviour of quenched bell metal at room temperature**

### 3.3.3 Fracture strength at elevated temperature

Figure 3.5 shows the stress-strain behaviour of the bell metal at elevated temperature under both tensile and compressive loads. From Fig. 3.5 several important results have been observed. First, the bell metal fails very quickly in the brittle mode under both tensile and compressive load at temperature 550ºC. Again, it is observed that the fracture strength reduces from 10MPa (8.5MPa) to 6MPa (5MPa) on increasing the temperature from 550ºC to 700ºC under the compressive (tensile) type of load. So, it can be inferred as the bell metal can be deformed at a temperature near 700ºC with a compressive force of 6N/mm$^2$ and the tensile force of 5N/mm$^2$. Further, form discussions of sections 3.3.1.c and 3.3.2.c, it can be deduced that the required deformation force at temperature 27ºC is 850 N/mm$^2$ and 500N/mm$^2$ (200N/mm$^2$ for cast bell metal) under compressive and tensile load respectively. Therefore, it can be said that with increasing temperature, the required deformation force decreases. Moreover, it is observed that the bell metal has not failed in the 700ºC under compressive load. The drastic change in stress-strain behaviour of bell metal at temperature 700ºC is attributed to the super plasticity behaviour of the β phase.

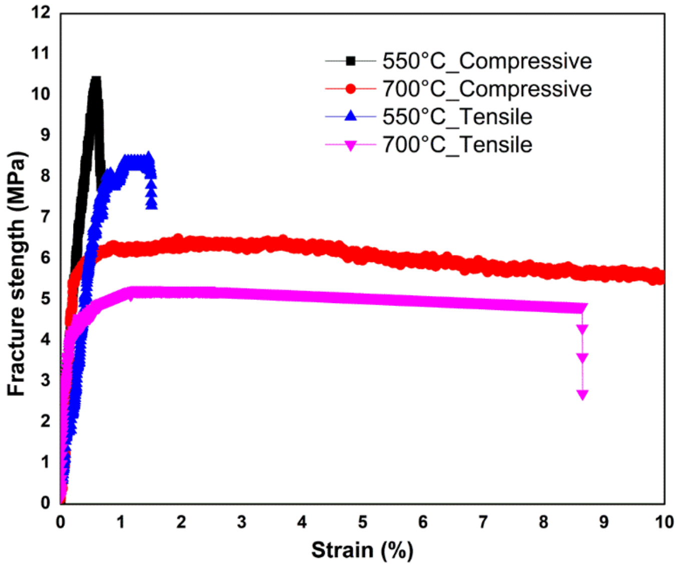

**Figure 3.5 Stress-strain behaviour of quenched bell metal at elevated temperature**

Again, from the field survey and literature review (section 1.5 and 1.6.3), it has been observed that the bell metal products are manufactured by forging at a temperature near 550–700ºC. Therefore, it can be said that the lower deformation force with increasing temperature is an advantageous criterion cleverly utilized by the artisans to provide the necessary shapes for the production of bell metal products. Further, a number of thin-walled bell metal products have been recently discovered from different archaeological sites. Y. Li et al. (2013) [72] discussed the bell metal vessels (manufactured during 1200–1000 B.C.) of thickness 0.2–0.4mm unearthed from the Jinsha site of Sichuan Province in China. Park et al. (2009) [38] discussed about 0.2mm thick spoon (from Choseon period, 1392–1910 A.D.) and vessels (from Koryo period, 918–1392 A.D.) excavated from historical site Cheongju, Korea. Srinivasan (1998) [14] has reported about 0.2–1mm thick bowls unearthed from India (800 B.C.) and Pakistan (1000 B.C.). Srinivasan (1994) [22] also reported about 1–1.5mm thick bell metal vessels fabricated in the present day in Kerala. Since, from the experimental results, it was evident that the bell metal does not fail under compressive load on processing above 700ºC due to its super plasticity nature; therefore, it is very much possible that the artisans have utilized the super plasticity nature of bell metal at 700ºC to produce these thin-walled products. So, it can be inferred that it is possible to produce thin walled bell metal items (up to 0.2mm) on processing at 700ºC due to its super plasticity nature. Park et al. (2009) [38] reported that despite of major scientific limitations such as the unavailability of precise instruments for measuring temperature, pressure, force etc., the discovery of thin-walled bell metal products used in various ages and excavated from the archaeological sites reflects the label of technological maturities of the industry. How the technological information related to the processing of bell metal has traveled throughout the world can be a future research topic.

### 3.3.4 Thermogravimetric properties

Four endothermic peaks in the DSC curve of the bell metal product is found at temperature 519.7ºC, 581.2ºC, 796.3ºC and 873.2ºC and can be seen as P, Q, R and S points respectively in Fig. 3.6. From the Cu-Sn alloy phase diagram published by Acharya and Mukunda (1988) [64], it has been observed that the endothermic peaks in P, Q, R and S reflects the phase transformation process of i) $\alpha + \delta \rightarrow \alpha + \gamma$; ii) $\alpha + \gamma \rightarrow \alpha + \beta$; iii) $\beta \rightarrow \alpha$ along with decompositions of the β phase to liquid phase and iv) melting of the α phase/ melting point of bell metal respectively. The DSC curve clearly shows that the β temperature range (i.e., 581.2 – 796.3ºC) is the widest high-temperature transformation range in comparison to the γ temperature transformation range (519.7 – 581.2ºC) and α temperature transformation range (796.3 – 873.2ºC). Again, in the α temperature range 796.3 – 873.2ºC, the bell metal starts to become semi-liquid due to the presence of the β phase in molten states. The deepest peak at point R reflects that maximum energy is required to melt the β phase.

Again, the DSC curve shows, only the α and the β phases are present in bell metal in the temperature range of 581.2 – 796.3ºC. Therefore, it can be said that quick/ immediate cooling (like quenching) from the temperature range of 581.2 – 796.3ºC will result in the retention of only α and β phases at room temperature. However, Fürtauer et al. (2013) [89] reported an absence of the β phase in water quenched Cu-Sn alloy containing 22% Sn (quenching temperature is 690ºC) from the X-ray diffraction (XRD) pattern analysis. Again, from the field survey and literature review (section 1.5 and 1.6.3.a), it has been observed that the bell metal products are manufactured by water quenching from a temperature above 700ºC and subsequent microstructural analysis of water quenched product shows retention of only the α and the β phases. Therefore, it has been inferred that the retention of high-temperature β phase at room temperature in bell metal products is possible on water quenching from the temperature range of 690 – 796.3ºC. The non-retention of β phases on water quenching between the temperature range of 581.2 – 690ºC may be explain as early transformation of β phase to γ phase due to non-uniform heating of the material; but need further detailed investigations. Further, from the previous section, it has been observed that bell metal shows supper plasticity at 700ºC. All the results combinedly can be inferred that in the temperature range of 690 – 796.3ºC, the bell metal can be plastically deformed in the solid state and it is practically advantageous because of the deepest and widest high-temperature transformation range.

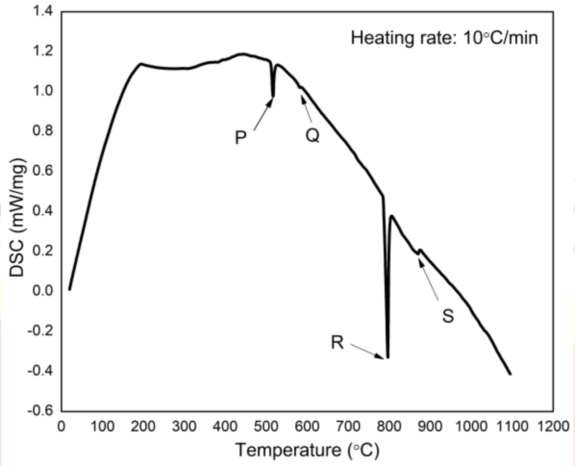

**Figure 3.6 DSC curve of bell metal products**

## 3.4 Key findings

From the above results and discussions, the following points can be summarized:

a) Practically the most suitable condition to do hot workings of bell metal is in the temperature range of 690 – 796.3ºC, being the widest high-temperature range and the requirement of negligible force for the highest degree of deformations.

b) Hot deformations accelerate the defragmentation of the FCC structured α phase and the formation of annealing twins in the α phase. Cumulative effects of these effects result in alternation in mechanical properties viz., hardness and fracture strength of bell metal.

c) The hardness and fracture strength of bell metal can also be controlled by controlling the heating temperature before the water quenching process.

# Chapter 4 EFFECT OF PROCESSING PARAMETERS ON MECHANICAL PROPERTIES OF BELL METAL

## 4.0 Introduction

The previous chapter discusses the mechanical properties of bell metal products manufactured in Sarthebari. In this chapter, the effect of processing parameters on the mechanical properties of bell metal has been investigated.

## 4.1 Background

Generally, the mechanical properties of a material depend on its microstructure; and the microstructures and hence the properties can be influenced by controlling the processing parameters and its compositions. Again, it has been found that a large quantity of bell metal products (nearly 1kg per day) fails in the production centers due to processing faults. Moreover, from the literature survey, it was found that the effect of processing parameters on the mechanical properties of bell metal has not been reported properly. Therefore, in this chapter, the effect of processing parameters on the mechanical properties of bell metal has been examined.

## 4.2 Choice of the experimental conditions

Experiments are performed to estimate the mechanical properties of bell metal processed in different conditions. The bell metal samples of different compositions were prepared in the lab as described in section 2.7.1 and then processed in different conditions as described in section 2.7 to measure the effect of processing parameters. The compositions are chosen to cover the whole range of bell metal alloy (20% tin to 25% tin) used for making different items. The composition, quenching temperature and quenching medium considered for the experiments have been presented in Table 4.1. The specimens are cut from the lab cast and processed bell metal samples and then tested by following the different standards as described in section 2.8.

**Table 4.1 Input matrix for experiments**

| Input parameter | Range |
|---|---|
| Cu:Sn (wt. basis) | 75:25, 76:24, 77:23, 78:22, 79:21, 80:20 |
| Quenching temperature (°C) | 650, 700, 750 |
| Quenching medium | Oil, Water |

## 4.3 Results and discussion

Experiments are carried out to investigate the effects of processing parameters on mechanical properties of bell metal samples and the results are discussed in the subsequent sections.

### 4.3.1 Cast bell metal

#### 4.3.1.a Effect of composition

Figure 4.1 shows the effect of compositions on the hardness and fracture strength of cast bell metal samples under compressive load. From Fig. 4.1, it has been observed that with the 5% increase in the percentage of Sn, the mechanical properties of cast bell metal samples increased by almost 50%. Park and Joo (2016) [78], from their study, concluded that the mechanical properties of bell metal depend on the amount of secondary phase *i.e.*, the amount of δ phase present in the microstructure. Therefore, it can be inferred that with an increase in Sn% in the composition, the amount of δ phase increases and hence the mechanical properties increases.

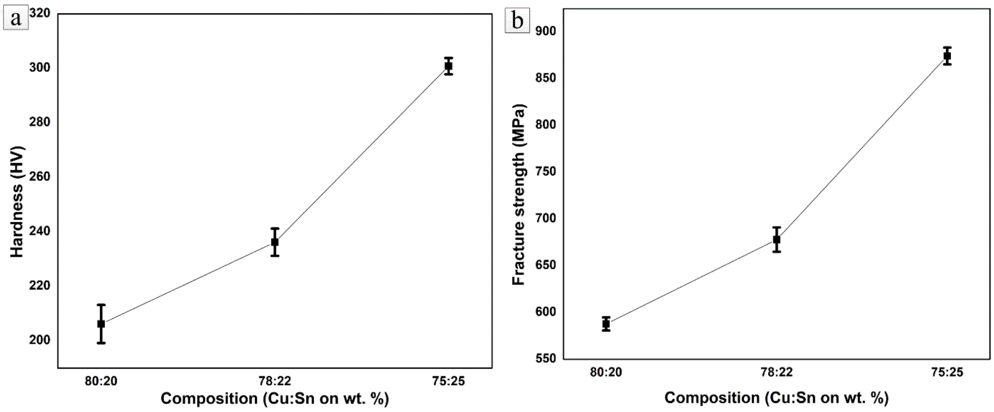

**Figure 4.1 Effect of composition on (a) Hardness; (b) Fracture strength**

## 4.3.2 Quenched bell metal

### 4.3.2.a Effects of the quenching medium on microstructure

Figure 4.2 shows the microstructure of oil and water quenched bell metal samples having composition 78:22 (Cu: Sn). From Fig. 4.2, it is observed that the microstructure of the oil quenched bell metal samples has a dendritic structure and inter-dendritic zones. The microstructure of the water quenched sample is in the same line with the various work published by different authors [21, 23, 35, 72, 78] and has already been discussed in the previous chapter. No published benchmark results have been found to compare the microstructure of oil quenched samples. The formation of different microstructures can be attributed to the different thermal properties of the quenching medium. The compositions of the different zones of oil and water quenched samples are also studied and represented in Table 4.2. By comparing the compositions with the Cu-Sn alloy phase diagram published by Acharya and Mukunda (1988) [64], it has been found that the dendritic structure of the oil quenched sample is in the α phase. Whereas, the inter-dendritic zone of the oil quenched samples is in the β phase. The effects of these phases on the mechanical properties of bell metal have been discussed in the next sections.

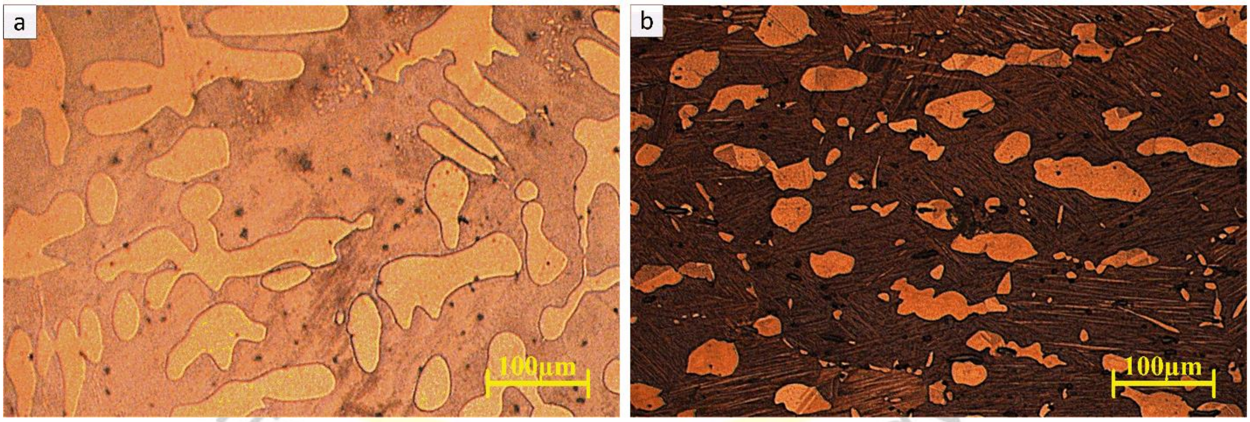

**Figure 4.2 Microstructure of different samples: (a) Oil quenched; (b) Water quenched**

**Table 4.2 Compositions of different zones of heat-treated samples**

| Samples | Zone | Cu:Sn (wt. basis) | Cu:Sn (atomic wt. basis) |
|---|---|---|---|
| Oil quenched | Dendritic Zone | 85.7: 14.3 | 90.9: 9.1 |
| | Inter-dendritic Zone | 76.4: 23.6 | 85.6: 14.4 |
| Water quenched | Dendritic Zone | 85.9:14.1 | 91.3: 8.7 |
| | Inter-dendritic Zone | 76.6: 23.4 | 85.9: 14.1 |

### 4.3.2.b Effects of composition on mechanical properties

Figure 4.3 shows the effect of compositions on the hardness and fracture strength of bell metal samples quenched in different quenching mediums from a temperature of 700ºC. From Fig. 4.3, it has been observed that with the increase in the percentage of Sn, the mechanical properties, viz., hardness and fracture strength under compressive load, increases irrespective of the quenching medium. For a 5% increment of Sn in the composition, the mechanical properties of the oil and water quenched samples have increased by almost 30% and 80% respectively. The increase in mechanical property with an increase in Sn% is attributed to the change in the amount of phases present in the respective samples as observed from the microstructure. Park and Joo (2016) [78], from their study, have concluded that the mechanical properties of bell metal are controlled by the secondary phases present in the microstructure. Therefore, it can be said that with an increase in Sn% in the composition, the amount of secondary phase i.e., the β phase increases and hence the mechanical properties improve. It has also been observed that the mechanical properties of oil quenched samples are relatively less than water quenched samples for all Sn percentages considered in this study. In general, a decrease in hardness value enhances the workability of material at room temperature to carry out the required cold works for finishing the products. So, it can be inferred that oil quenched the bell metal products will be easier to do finishing work at room temperature due to reduced hardness.

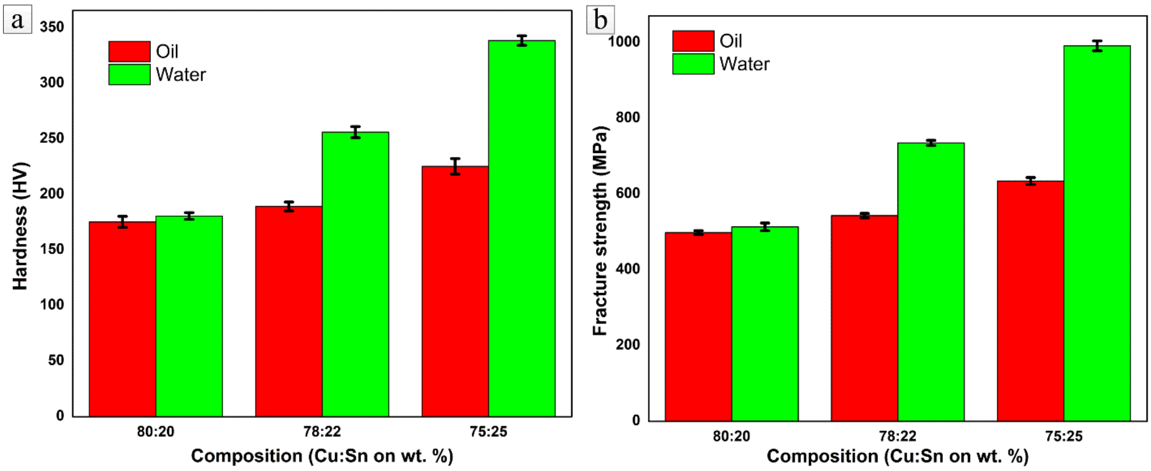

**Figure 4.3 Effect of quenching medium on (a) Hardness; (b) Fracture strength**

Again from the field survey report and literature review (section 1.5.3 and 1.6.3.a), it has been observed that water has been commonly used as a quenching medium in bell metal production centers from ancient time. The criterion, it seems, of the production of items was to retain higher strength of the product. This is the practice followed not only in ancient times, but also has been continuing till date. Because of the practice, it has been observed that the artisans used to have a tough time to provide finishing of the products, which is normally carried out at room temperature. Many a time, the products also fail during the finishing exercise, as evident from the field survey (see Fig. 1.2).

### 4.3.2.c Effects of quenching temperature on mechanical properties

Figure 4.4 shows the effect of quenching temperature on the mechanical properties of the bell metal sample having the composition of 78:22 (Cu: Sn) quenched in oil and water. From Fig. 4.4, it has been observed that as the quenching temperature increases, the mechanical properties of oil and water quenched samples increase. Again from Fig. 4.4, it has been observed that the percentage of increase in mechanical properties with an increase in temperature is higher for the water quenched sample compared to the oil quenched sample. Further, it has also been observed that the temperature of 700ºC plays a very significant role in controlling the mechanical properties of bell metal. The mechanical properties of the oil and water quenched sample have increased by 8% and 25% respectively on increasing the quenching temperature by 50ºC above 700ºC. The increase in mechanical properties with an increase in quenching temperature is attributed to the arrest of a higher amount of the β phase. As the quenching temperature increases, the higher amount β phase arrest in the quenched sample as the BCC structured β phase [69, 202].

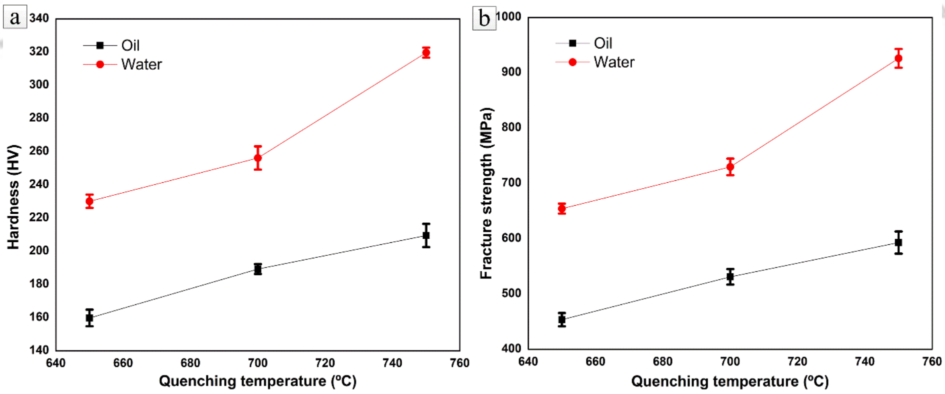

**Figure 4.4 Effect of quenching temperature on (a) Hardness; (b) Fracture strength**

Again from the field survey and literature review (section 1.5 and 1.6.3), it has been observed that the bell metal products are manufactured by quenching from a temperature above 700ºC. So, it can be inferred that in the bell metal items production centers the water quenching is done from a temperature above 700ºC to achieve the higher strength of the products. Practical constraints related to the processing of bell metal at room temperature having high hardness have already been discussed in the previous section.

The present study has helped in understanding the benefit of oil quenching. It is recommended that the products, which require finishing at room temperature, should better be oil quenched.

## 4.4 Comparative mechanical properties of brass and bell metal

From the background (section 1.1), it has been observed that in India, both the brass (a copper-zinc alloy having 70% copper and 30% zinc on weight basis) and bell metal products have been extensively and alternatively used from ancient times for the production of utensils. Products of both this alloy represent rich cultural heritage [9, 63]. Therefore, the mechanical properties of the brass metal have been compared with the bell metal.

### 4.4.1 Microstructure

Generally, the microstructure controls the mechanical properties of a material and hence the performance of the product. The cast brass has a granular dual phase microstructure consisting of 21% α phase and 79% β phase [203]. Whereas the microstructure of cast bell metal has non-granular dendritic and inter-dendritic zones. The microstructure of brass changed to a single α phase granular structure on annealing at 500ºC for 1hr and again to dual phase granular structure on quenching in water after heating at 810ºC for 70 minutes [204, 205]. The grain size fully annealed brass is 28.2μm [206]. The microstructure of water quenched bell metal has non-granular α island phase and needle-like martensitic β phase.

### 4.4.2 Tensile strength

The UTS of cast brass has 450MPa against 200MPa of cast bell metal [203]. The UTS of brass changes to 220MPa on annealing at 500ºC for 1hr and to 270MPa on quenching in water after heating at 810ºC for 70 minutes [204, 205]. The water quenched bell metal has a UTS of 570MPa (300MPa higher than the water quenched brass).

In general, the tensile strength of a material is defined as the ability to resist the pulling force, which tends to apart the parts and in the manufacturing industry, the material that has higher tensile strength draws greater demand. From this, it can be infrared that quenched bell metal may find higher industrial demand over quenched brass metal for the development of products with higher strength due to higher UTS. Further, a list of mechanical properties of bell metal processed in different conditions along with few other Cu-based alloys has also been attached in Annexure A to create a database. This database will help the engineers to choose the appropriate processing condition of bell metal for specific applications over other alloys.

## 4.5 Key findings

From the above results and discussions, the following points can be summarized:

a) Higher Sn content and higher quenching temperature promote the formation of the β phases in the inter-dendritic zone and hence mechanical properties improve.

b) Practically the most suitable quenching medium is water for the higher strength of bell metal products.

c) The quenching temperature should be above 700ºC for rapid improvements in the mechanical properties of quenched bell metal products.

d) The bell metal products that require finishing at room temperature should better be oil quenched to reduce the in-house failure of items during production.

# Chapter 5 JOINING OF BELL METAL

## 5.0 Introduction

The previous chapter discusses the effects of processing parameters on the mechanical properties of bell metal products. From the study, it has been observed that the mechanical properties of the bell metal products can be improvised by controlling the processing parameters viz., temperature and medium, etc. In this chapter, the joining of bell metal has been investigated.

## 5.1 Background

From the field survey, it was observed that bell metal products are generally produced in a single piece by following a series of manufacturing processes, namely casting, heating, forging and quenching. It was also found that few products are manufactured in parts and joined by riveting. However, the riveted products are not well accepted due to handling and cleaning difficulties. Moreover, the riveting of bell metal parts is a very difficult process due to its brittle nature [21, 22]. Bell metal products are also sometimes joined by the brazing process, but weaker joint strength and mixing of filler material restrict the use of brazed products [100, 101]. Moreover, tin segregation on the joining surface during preheating complexes the brazing process [102]. Further, many products are rejected either at the production center while manufacturing or during service by the end-users due to the small cracks developed in the products (see section 1.6.3). Lucien (1993) [98] has proposed pouring of a calculated amount of molten metal in the fracture slit to form the join between the parts. This method is successful but requires highly skilled workers and is not efficient when cavity size is larger. Ernesto and José (2014) [99] have proposed pouring powder in the crack cavity and then melting the powder with a torch flame to join the two pieces of bell metal. This method is a very simple but very costly process due to the high cost of powder. Further, there is a possibility of spreading the powder in the unwanted areas during heating, which will result in some additional production costs.

It was also realized that many other products might be produced by adequately joining two or more parts, which will open up diversification of product range by introducing new products. Therefore, a little S&T intervention in the joining process of bell metal may result in extended durability of products with small cracks and also to produce new products. The copper and brass metal industry utilize welding process to extended durability of products with small cracks and to produce new products [207, 208]. In view of the above, in this current chapter, an attempt has been made to explore the feasibility of the welding process of bell metal.

## 5.2 TIG welding

Recently, Tungsten Inert Gas (TIG) welding process has gained popularity due to its excellent ability of heat control and environmental friendliness because of zero fume production during the process [209]. TIG welding process is regularly used in industry for joining of steel, copper, aluminium etc. But have never been applied to join bell metal. Again, the range of TIG welding parameters and the process efficiency varies depending on the joining materials and hence, needs to be optimized for the specific material [210]. Das et al. [211] have defined the optimization of the welding process as the "identification of suitable input welding parameters for a defined output quality of weldments", which can be represented by Eq. (5.1) as described by Tamjidy et al. (2017) [212] and Ajith et al. (2015) [213].

$$Y = f(a, b, c \dots) \qquad \mathbf{5.1}$$

Where Y is the desired output quality criteria of the weldments and a, b, c are the input welding parameters depends on the types of welding process used to join the parts. Optimization of the welding process implies solving Eq. (5.1) for a maximum or minimum value of Y. The next section describes the selection procedure of these parameters followed in this study to optimize the bell metal welding process.

## 5.3 Selection of welding parameters

Optimization of the welding process implies solving equation 5.1 for a maximum or minimum value of Y. Researchers have used numbers of parameters to define the weldment output quality (i.e. Y), ultimate tensile stress (UTS), elongation %, yield strength, hardness etc. In general, the length of the heat-affected zone (HAZ) is the most critical parameter of the welding process as it affects the corrosion resistance and the creep resistance properties of the material [214–219]. Again, many authors have emphasized on the area of fusion zone (FZ) of weldment as the output criteria to have an idea of the distortion of the welded structure [220–225]. Based on the above findings, the length of HAZ and the area of FZ of the weldments have been selected to define the output quality (i.e., Y) for the present study.

Again authors have selected numbers of welding process parameters viz., welding current, welding voltage, welding speed, tool rotational speed, stand-off distance, shielding gas flow rate, etc., as the input parameters to the Eq. (5.1) (i.e. a, b, c). The selection of the input welding process parameter depends on the types of welding processes. For the TIG welding process, welding current, stand-off distance and welding speed are found to be the most influential parameters [210, 226, 227]. Therefore, welding current (I), stand-off distance (d) and welding speed (S) are the only welding parameter selected as input parameters for the present study.

Further, to find the upper limit and lower limit of the selected input parameters, numbers of hit and trial experiments were carried out at different combinations of the selected input parameters. To perform the experiments, the books "***Welding copper & copper alloys***" published by the *American Welding Society* [228] and "***Cost-effective manufacturing: Joining of copper and copper alloys***" and published by *Copper Development Association* [103], were considered as a guide book. It was found that outside of the limits, no weldment can be produced due to poor or over the melting of the base metal (see Annexure B).

The exact correlations between the weldments quality and welding process parameters is generally obtained by carrying out minimum $P^Q$ numbers experiments, where P is the level of input parameters and Q is the number of input parameters influencing the quality of weldments; which is a time consuming and energy-expensive laborious work [229, 230]. To reduce the number of experiments, researchers extensively use different factorial design processes. The factorial design process provides sets of input parameters in different combinations to reduce the number of experiments that need to be carried out to find the exact correlations between the weldments quality and welding process parameters. Many authors claim that RSM based factorial design provides better correlations because of continuous variations of input parameters against the discrete variations in the Taguchi method [231–233]. Therefore, in the present work, the RSM based factorial design has been used to obtain the minimum set of input parameters required to find the exact correlation equation with the output quality of bell metal weldments.

**Table 5.1 RSM based factorial design of experiments**

| Standard order | Welding current (A) | Stand-off distance (mm) | Welding speed (mm/s) |
|---|---|---|---|
| 1 | 45 | 1 | 2 |
| 2 | 90 | 1 | 2 |
| 3 | 45 | 3 | 2 |
| 4 | 90 | 3 | 2 |
| 5 | 45 | 1 | 4 |
| 6 | 90 | 1 | 4 |
| 7 | 45 | 3 | 4 |
| 8 | 90 | 3 | 4 |
| 9 | 29.5 | 2 | 3 |
| 10 | 105.5 | 2 | 3 |
| 11 | 67.5 | 0.3 | 3 |
| 12 | 67.5 | 3.7 | 3 |
| 13 | 67.5 | 2 | 1.3 |
| 14 | 67.5 | 2 | 4.6 |
| 15 | 67.5 | 2 | 3 |
| 16 | 67.5 | 2 | 3 |
| 17 | 67.5 | 2 | 3 |
| 18 | 67.5 | 2 | 3 |
| 19 | 67.5 | 2 | 3 |
| 20 | 67.5 | 2 | 3 |

The RSM based set of 20 number input parameters, namely welding current (I), welding speed (S) and stand-off-distance (d), at five-level in Composite Central Design (CCD) with eight factorial points ($2^3 = 8$), six center points, and six-star points, as shown in Tables 5.1 were obtained by using MINITAB version 16 software.

## 5.4 Materials, experiment procedure and testing methods

Water quenched bell metal plates of thickness 1.5mm were collected from the local market of Sarthebari to use as the base material for the present study. The bell metal plates were cut by WEDM to produce the samples for welding.

The TIG bell metal weldments were produced in an AC/DC TIG welding machine (Make: **Ador Fontech Ltd., India**) by using Direct Current (DC) straight polarity welding mode. No filler material was used to join at least two pieces of bell metal in order to reduce the cost of filer material and to avoid contamination of filer rod material in the weldments. A titanium rod of 3mm diameter was used as a non-consumable welding electrode to produce the weldments. Argon gas at a constant flow rate of 150cm$^3$/s was used as shielding gas during the production of the butt weldments. Figure 5.1 shows the experimental setup used for the bell metal welding process and the welded samples.

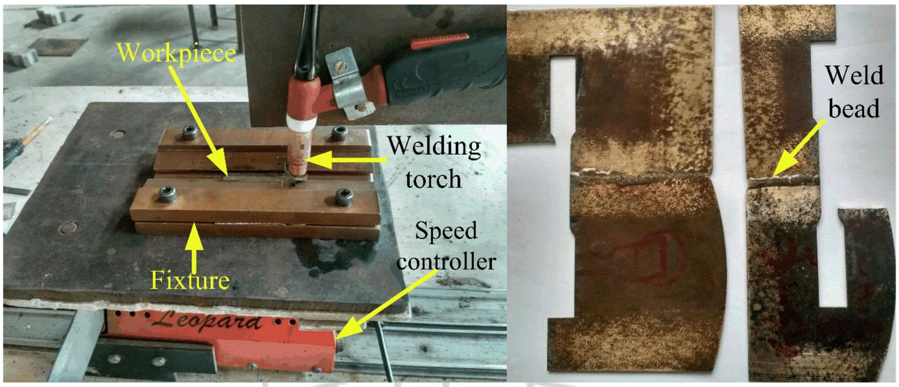

**Figure 5.1 Welding: a) Experimental setup; b) Welded samples**

Further, the prepared weldments were cut in a WEDM as per standards described in section 2.8 to investigate the mechanical properties of the weldments in order to optimize the bell metal welding process. The length of the HAZ and area of FZ of the weldments were measured by a software package of NIKON SMZ 25 Stereo Microscope available at the Indian Institute of Technology Guwahati.

## 5.5 Results and discussion

### 5.5.1 Experimental results

Figure 5.2 shows the cross-sectional view of the bell metal weldments for different sets of input parameters presented in Table 5.1. Three different zones, namely the FZ, the HAZ and the unaffected base metal zone of all samples, can be clearly observed from Fig. 5.2.

Again, the regression analysis has been effectively utilized as described by Gosh and Rao (1996) [234], Mason et al. (2003) [235] and Montgomery (2001) [236] to find the cumulative effects of the independent input welding parameters on the measured dependent output welding qualities. The regression models were obtained by using MINITAB at the confidence level (φ) of 0.05 and have been represented by the equations shown in Eq. (5.2) and Eq. (5.3).

$$Length\ of\ HAZ = 3.14 + 0.21 \times I + 0.63 \times d - 0.43 \times S + 0.003 \times Id + 0.005 \times IS - 0.16 \times Sd - 0.0002 \times I^2 + 0.049 \times d^2 + 0.06 \times S^2 \qquad \mathbf{5.2}$$

$$Area\ of\ FZ = 7.1 - 0.023 \times \mathrm{I} - 0.86 \times \mathrm{d} - 1.88 \times \mathrm{S} + 0.0059 \times \mathrm{Id} - 0.0783 \times \mathrm{IS} - 0.24 \times \mathrm{Sd} + 0.0008 \times I^2 + 0.27 \times d^2 + 0.37 \times S^2 \qquad \mathbf{5.3}$$

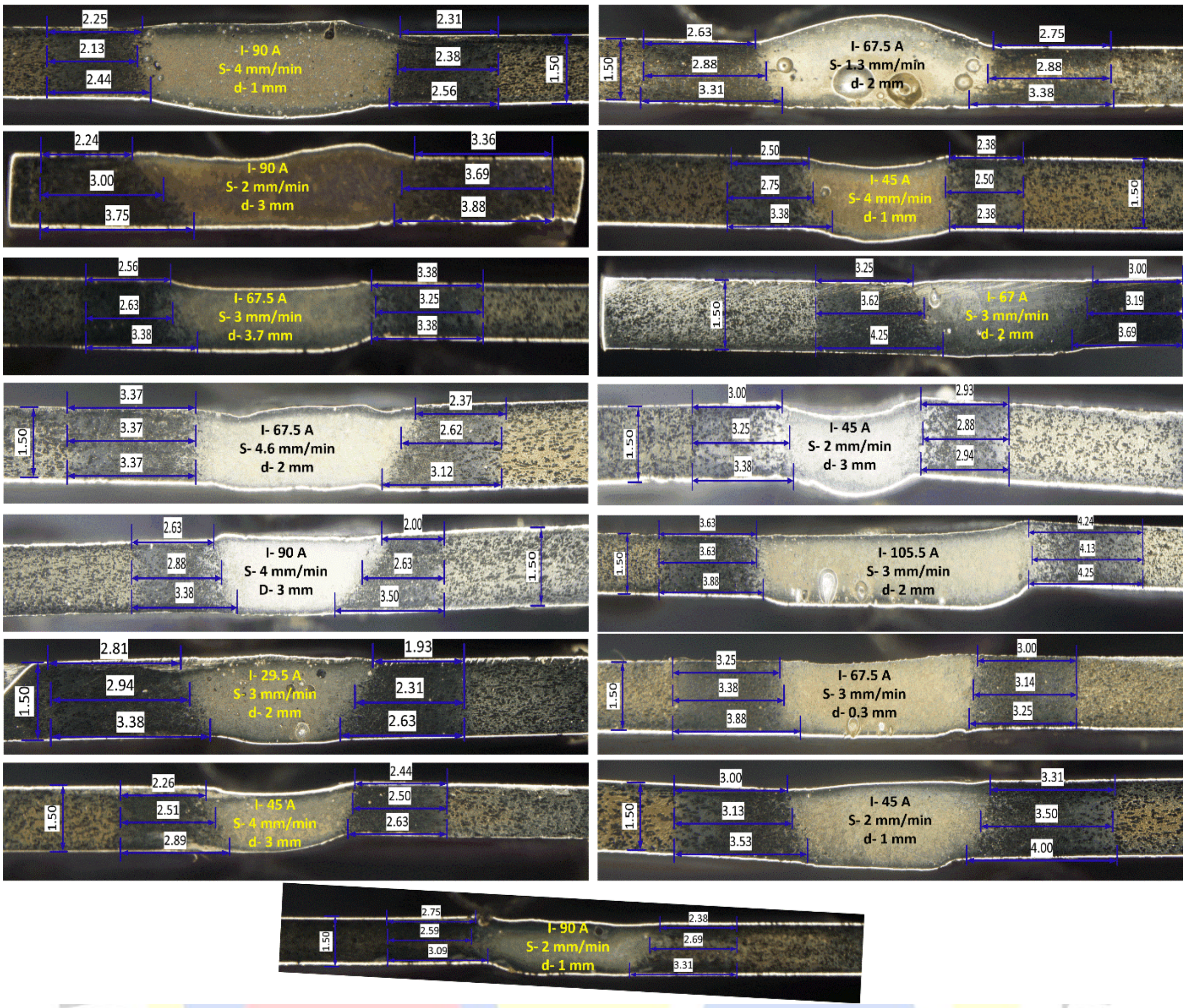

**Figure 5.2 Cross sectional view of welded samples**

Table 5.2 shows the comparative analysis of the mathematical regression model and experimental results for the length of HAZ and the area of FZ of bell metal weldments. From Table 5.2, it has been observed that the predicted regression models provide a maximum 9.7% error with the experimental results, i.e., based on the selected input range of parameters, a minimum of 90.3% accurate result can be obtained from the regression model presented in Eq. (5.2). and Eq. (5.3) for the defined bell metal weldment criteria. The analysis of variance (ANOVA) has been carried out on the regression models to investigate the significance level of process parameters on the bell metal weldments quality and reported in Annexure C & D.

Further, from Table 5.2, it was observed that both the selected criteria are independent. Optimization of such a welding process means finding the solution of both the regression correlation equations [210]. But, solving each equation individually often leads to the wrong decision; because for each output quality, there is a definite set of optimized input parameters

[237]. So, it requires a multi-objective optimization analysis to find the optimized sets of welding parameters that will satisfy both the output qualities at a time.

**Table 5.2 Comparative analysis between regression model and experimental results**

| Stand. order | Length of HAZ (mm) | | | Area of FZ (mm$^2$) | | |
|---|---|---|---|---|---|---|
| | Model prediction | Average Experimental results | Absolute Error (%) | Model prediction | Average Experimental results | Absolute Error (%) |
| 1 | 4.08 | 3.99 | 2.24 | 8.19 | 8.22 | **0.34** |
| 2 | 4.02 | 3.96 | 1.49 | 6.81 | 6.49 | 4.72 |
| 3 | 3.56 | 3.61 | 1.34 | 4.54 | 4.52 | 0.47 |
| 4 | 3.99 | 4.02 | 0.83 | 8.55 | 8.65 | 1.16 |
| 5 | 3.72 | 3.68 | 1.19 | 5.44 | 5.48 | 0.20 |
| 6 | 3.72 | 3.88 | 4.18 | 5.44 | 5.49 | 0.90 |
| 7 | 2.78 | 2.77 | 0.36 | 3.01 | 2.96 | 1.73 |
| 8 | 3.72 | 3.87 | 3.91 | 5.44 | 5.46 | 0.35 |
| 9 | 3.79 | 3.88 | 2.32 | 6.03 | 5.72 | 5.20 |
| 10 | 3.72 | 3.89 | 4.45 | 5.44 | 5.47 | 0.53 |
| 11 | 3.40 | 3.39 | **0.27** | 4.66 | 4.29 | 7.94 |
| 12 | 4.24 | 4.35 | 2.48 | 10.16 | 9.89 | 2.67 |
| 13 | 3.72 | 3.83 | 2.84 | 5.44 | 5.51 | 1.08 |
| 14 | 4.37 | 4.25 | 2.64 | 8.61 | 9.02 | 4.76 |
| 15 | 4.34 | 4.28 | 1.35 | 9.09 | 9.86 | **8.44** |
| 16 | 3.93 | 3.94 | 0.19 | 6.38 | 6.32 | 0.88 |
| 17 | 3.76 | 3.92 | 4.13 | 6.16 | 6.07 | 1.52 |
| 18 | 2.88 | 3.16 | **9.70** | 3.71 | 3.99 | 7.52 |
| 19 | 3.45 | 3.47 | 0.70 | 4.53 | 4.88 | 7.72 |
| 20 | 3.72 | 3.79 | 1.76 | 5.44 | 5.48 | 0.72 |

## 5.5.2 Multi-objective optimization

The multi-objective optimization of welding parameters is a complex process [231]. Researchers have developed numbers of evolutionary algorithms viz., NSGA-II, SPEA2, PESA-II, IBEA, MOEA/D, PSO, GDE3 etc. to solve the multi-objective optimization problems [238]. Many authors have used the Non dominated Shorting Genetic Algorithm II (NSGA II) to solve the multi-objective welding process problems [239–242]. The inbuilt MATLAB function "***gamultiobj***", developed based on NSGA-II [243], has been used in this study to carry out the multi-objective optimization of the bell metal welding process. The RSM based regression models i.e., Eq. (5.2) and Eq. (5.3), have been feed to MATLAB to find the optimum values of the input welding parameters by using the optimtool for the defined criteria of the bell metal weldments. The parameter setting in the optimtool has been presented in Annexure E. The sets of the optimal solutions obtained by solving the regression models with the help of NSGA II have been presented in Table 5.3.

**Table 5.3 Optimized solutions obtained by solving the NSGA II**

| Length of HAZ (mm) | Area of fusion (mm$^2$) | Welding current (A) | Stand-off distance (mm) | Welding speed (mm/S) |
|---|---|---|---|---|
| 2.80 | 8.14 | 29.5 | 2.81 | 3.5 |
| 3.20 | 7.64 | 29.5 | 3.70 | 4.6 |
| 2.85 | 7.98 | 29.5 | 3.20 | 3.8 |
| 3.07 | 7.75 | 29.5 | 3.45 | 4.4 |
| 3.14 | 7.68 | 29.5 | 3.70 | 4.5 |
| 2.87 | 7.93 | 29.5 | 3.20 | 4.0 |
| 3.00 | 7.83 | 29.5 | 3.20 | 4.3 |
| 2.96 | 7.83 | 29.5 | 3.45 | 4.2 |
| 3.12 | 7.70 | 29.5 | 3.70 | 4.4 |
| 3.03 | 7.77 | 29.5 | 3.45 | 4.3 |
| 2.95 | 7.84 | 29.5 | 3.37 | 4.2 |
| 2.80 | 8.14 | 29.5 | 2.81 | 3.5 |
| 2.87 | 7.93 | 29.5 | 3.20 | 4.0 |
| 3.14 | 7.68 | 29.5 | 3.70 | 4.5 |
| 2.82 | 8.05 | 29.5 | 2.87 | 3.8 |
| 3.20 | 7.64 | 29.5 | 3.70 | 4.6 |
| 3.08 | 7.72 | 29.5 | 3.70 | 4.3 |
| 2.80 | 8.14 | 29.5 | 2.81 | 3.5 |

### 5.5.3 Pareto optimality

All the sets of optimum weldment output qualities obtained by solving the RSM based models with the help of NSGA II have been present in Fig. 5.3. It can be observed that the output qualities have followed a pattern (pink dots) and it is known as the Pareto optimal front [212, 241]. The Pareto optimal front helps the industry to make a strong managerial decision of the desire output quality based on the market demand [244].

From the Pareto optimal front, it can be observed that there is a trade-off between the length of HAZ and the area of FZ. The managerial decision can be explained as follows if the industry is devoted to producing corrosion free products, the welding process must be carried out to minimize the length of HAZ. Generally, a higher length of HAZ in weldments reduces the corrosion resistance properties by altering the microstructure and increases the cracking susceptibility from that zone; hence lower length of the heat-affected zone is preferred in the industry [214–217]. Particularly for bell metal, the lower HAZ helps to maintain the maximum golden luster of the weldments (see Fig. 5.2). So, the welding must be carried out at 29.5A welding current, 2.81mm stand-off distance and 3.5mm/s welding speed to produce a minimum length of HAZ. Again, if the industry is dedicated to producing decorative and scientific products, where smooth surfaces finish is the prime concern, the welding process must be carried out to minimize the area of FZ i.e., the welding must be carried out at 29.5A welding current, 3.7mm stand-off distance and 4.4mm/s welding speed. Further, many authors have suggested for selecting the knee point solution of the Pareto optimal front for the minimum operating cost of the welding process [213, 245]. The knee point solution is the maximum perpendicular distance of the Pareto optimal front from the chord (shown as black line in Fig. 5.3) drawn by connecting the endpoints of the front [245, 246]. The knee point solution for minimum operating cost is 29.5A welding current, 2.87mm stand-off distance and 3.8mm/s welding speed.

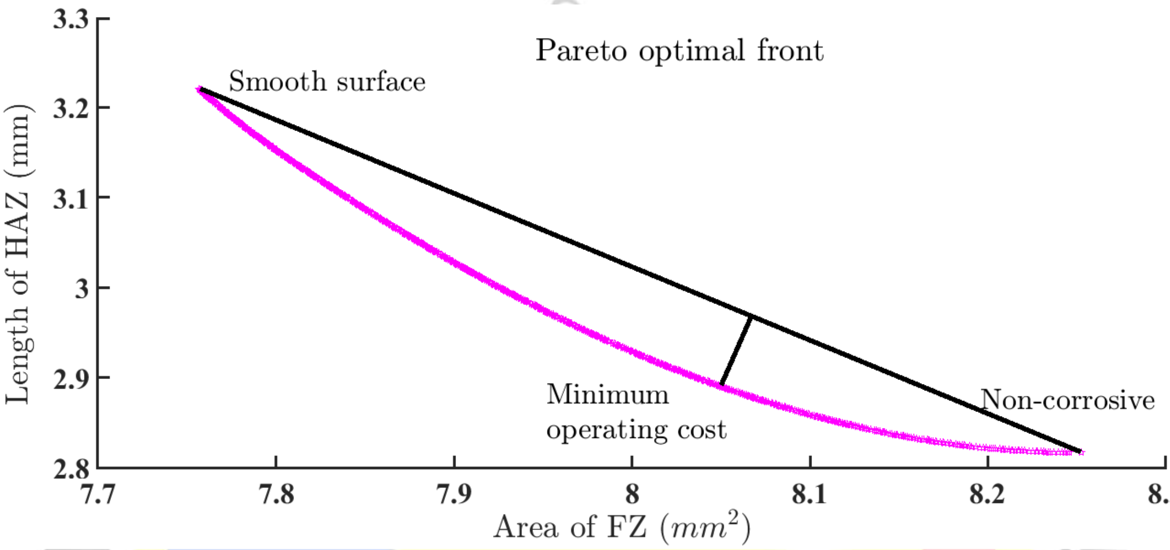

**Figure 5.3 Pareto front between length of HAZ and area of FZ**

From the ongoing discussions, it has been observed that the Pareto optimal front helps to select the different sets of TIG welding process parameters for the defined criteria of bell metal weldments. The results obtained from the Pareto optimal front have been further confirmed by carrying out few more experiments. The next section discusses the confirmation test.

### 5.5.4 Confirmation test

Three new bell metal weldments were prepared at the knee point welding conditions. Figure 5.4 shows the cross sectional view of the weldment produced by using the knee point solution. From Fig. 5.4, it can be observed that the surface finish of the weldment has been much improved from the non-optimized condition (see Fig. 5.2).

The length of HAZ and the area of FZ of the new weldments are then measured. Table 5.4 shows the comparative analysis of the length of HAZ and the area of FZ of the new weldments. From Table 5.4, it has been observed that the knee-point solution of the Pareto optimal front provides 92.3% accurate results in comparison to the experimental results for the bell metal TIG welding process. The next section discusses the microstructure of the welded bell metal samples.

**Figure 5.4 Cross-section of bell metal weldment at the knee point solution**

**Table 5.4 Comparative analysis on quality of weldments at knee point solutions**

| | Length of HAZ (mm) | Area of FZ ($mm^2$) |
|---|---|---|
| Knee point solution | 2.89 | 8.05 |
| Experimental | 3.13 ± 0.15 | 8.35 ± 0.3 |
| Absolute Error (%) | 7.67 | 4.97 |

### 5.5.5 Microstructure of weldments

Figure 5.5 shows the microstructure images of various zones of the bell metal weldments prepared based on knee point solution. Figure 5.5a shows the microstructure of the unaffected area, i.e., the base metal present at the side of weldments. From Fig. 5.5a, it is observed that the microstructure of the unaffected area has α phase island zones and β phase inter-dendritic zones, a common microstructure of the water-quenched bell metal samples [22]. Figure 5.5b shows the microstructure of the FZ. From Fig. 5.5b, it is observed that the microstructure of the FZ has α phase dendritic structure and δ phase inter-dendritic zone, a common microstructure of the cast bell metal samples [21]. The presence of the α and δ phases in the FZ is attributed to the re-melting and solidification process of bell metal. During TIG welding, some portions of both the metal pieces are melt due to the input heat and then mixed together to form the joint. On cooling, the molten portion solidifies similar to the casting process and hence the microstructure of the parent/ base metal transform to the microstructure of the cast bell metal in the FZ. The amount of heat input and the cooling rate of the solidification process controls the microstructure of the FZ and hence the quality of the weldments. Higher heat input and slower cooling rate lead to the formation of the coarse grains or dendritic structure in the FZ, whereas lower heat input and faster cooling rate lead to the formation of the fine grains [217]. In the TIG welding process, a high amount of heat is applied to a very narrow zone of the base metal for the melting and joining process; hence, the dendritic structure has formed in the FZ of bell metal weldments. Figure 5.5c shows the microstructure of the HAZ. The HAZ is the transition zone between the welded and un-welded portions of the weldments. In Fig. 5.5c, all the three phases α, β and δ have been observed. The presence of all three phases in the HAZ is attributed to the welding heat conduction process. During welding, some amount of heat is transferred to the outside of the fusion zone by conduction process and hence the microstructure and therefore the properties of the base metal alter up to some distance called the HAZ [216]. The next section discusses the effect of the welding process on the mechanical properties of the bell metal.

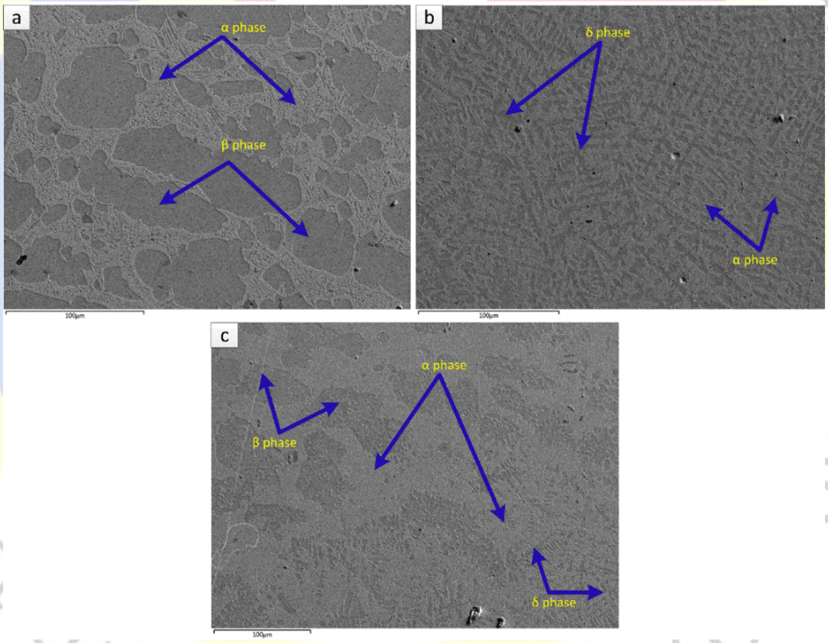

**Figure 5.5 Microstructure of a) unaffected base metal; b) FZ; c) HAZ**

### 5.5.6 Effect of welding process on mechanical properties

Figure 5.5 shows the comparative analysis of the fracture strength of un-welded and welded bell metal samples prepared based on the knee point solution. From Fig. 5.5, it has been observed that un-welded bell metal has ≈ 32% higher UTS in comparison to the welded bell metal samples. The UTS value of bell metal weldments will be different for other welding conditions.

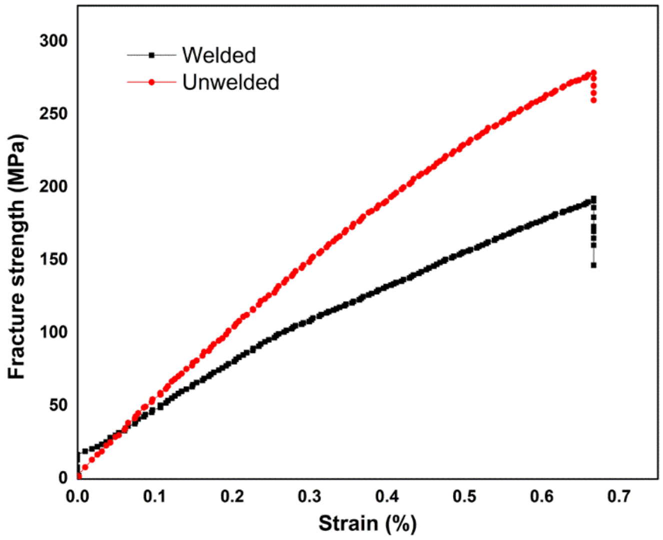

**Figure 5.6 Stress-strain curve of un-welded and welded bell metal samples**

Again, Fig. 5.6 shows the brittle failure nature of both un-welded and welded bell metal samples. Brittle failure of un-welded bell metal sample is attributed to the dominating nature of martensitic β phase over the α phase as discussed in section 3.3.2.c. The brittle failure of bell metal weldments is attributed to the dominating nature of the δ phase formed in the FZ during the welding process over the α and β phases, which is also responsible for the lower UTS value.

Again, attempts were also made to join the faulty cast and forged bell metal parts by the welding process and it was found that the TIG welding process can successfully use to join the cast and forged bell metal parts having small cracks. So, it can be inferred that the TIG welding process can be used for repairing intermediate faulty parts to save time and money by eliminating the reproduction process.

## 5.6 Key findings

The present study has helped in understanding the bell metal welding process. It has been observed that bell metal can be successfully welded in the range of welding parameters presented in this study. This study will allow the artisans to produce the diversified welded bell metal products for different applications. So, it can be inferred that this study will open new avenues for the industry and hence, will provide scope to develop the industry.

The observations and results presented in this paper can be summarized as follows:

a) Response surface methods can be used to model the quality of bell metal weldments with 90.3% accuracy. Further, the multi-objective genetic algorithm can be used to optimize the TIG welding process of bell metal.

b) The Pareto optimality front provides different sets of optimum welding parameters to produce bell metal weldment with various qualities for specific applications.

c) Knee solutions of the Pareto front chart provide 92.33% accurate results for the set quality criteria of bell metal TIG weldments.

d) The bell metal weldment produced at the knee point solution has approximately 32% lower UTS than the un-welded bell metal samples.

# Chapter 6 DRUDGERY ASSESSMENT AND WORKSTATION DESIGN

## 6.0 Introduction

The previous chapter discusses the joining process of bell metal. From the study, it has been observed that the bell metal can be joined by controlling the range of TIG welding parameters in direct current straight polarity mode without the filler material. In this chapter, the work-related drudgery present in the bell metal item manufacturing centers and its consequences have been investigated. Further this chapter discussess design process of an user-centric workstation based on anthropometric data of artisans along with the dimensions of tools and equipments commonly used in the bell metal industry.

## 6.1 Background

Generally, it has been observed that the SSIs enjoys certain inherent strength such as exploitation of local resources and skills, capacity to execute indigenous small orders, high employment to capital investment ratio, better use of scarce factors of production, higher heritage values with past glory, flexibility in production, informality in labour relations, the talent of dispersal to offer customized services and many more [1]. On the other hand, from the literature survey, it was found that the use of age-old TEWs and adopting awkward working postures by artisans at the workplace during performing the essential activities to complete the task are very common in all the SSIs; which results in different ergonomic related drudgeries viz., musculoskeletal disorders (MSDs), pain in different body parts, discomforts/ irritations, etc. of the workers [109, 112, 116, 118]. And as a consequence, many artisans stated to leave the SSIs in the demand of jobs has fewer drudgeries. Therefore, drudgery removal from SSIs through appropriate ergonomic interventions is essential to improve the health conditions of employees and hence to regain the attention of workers. However, as far as ergonomic interventions in bell metal industries are concerned, apart from reporting the presence of drudgeries due to the use of labour-intensive tasks as marked in the case of the production units present in Assam, Kerala and West Bengal of India, no literature has been found in the line of assessment and elimination of drudgeries [19, 22, 35, 52].

Many authors have shown that drudgery elimination through ergonomic interventions is beneficial for SSIs. For example, Guimarães et al. (2014) [134], from a study on Brazilian footwear company, has listed out areas required ergonomic interventions viz., 3 physical work environment (noise, temperature and lighting), 2 working condition (posture and workstation) and 19 physiological factors (monotonous, creativity, repetitive, nervousness, risks, responsibility etc.) to rectify the workers postures. This study has shown that ergonomic interventions reduce rework by 85% and hence, productivity increase by 3% due to decreased drudgeries of workers. Parimalam et al. (2006) [247] has shown that proper ergonomic interventions like the use of appropriate tools, correct illumination, an accurate inclination of working table, proper controlling of dust and noise etc. have the possibility to improve the work environment and hence, has the potential to reduce the drudgeries. Mukhopadhyay and Ghosal (2008) [133], from a study on incense stick manufacturing unit, has shown that on implementation of an ergonomically designed working table, the efficiency of the plant has increased by 15% due to reduced drudgeries in different body parts of the worker. Gangopadhyay and Dev (2014) [248], from a study on different SSIs viz., foundry, goldsmith, tea plantation, carpentry, agriculture, etc., have shown that ergonomic interventions like modification tools and workplace prevents work-related drudgeries. Govindaraju et al. (2001) [131] have reported that due to ergonomic interventions, workers efficiency increased by 23%, plant output has increased by 50% and injuries reduced by 19%. From the ongoing discussions, it can be said that there is a possibility that appropriate ergonomic interventions in the bell metal industry will increase productivity and will reduce the drudgeries. So, in this chapter, the health-related ergonomic issues among the workers associated with bell metal products manufacturing units have been assessed and addressed.

## 6.2 Methods

The study starts with the identification and investigations of different tasks related to the production of bell metal items. The study progressed with a collection of drudgery data associate with the artisans working in the bell metal items production centers. Finally, an ergonomically correct workstation along with plausible dimensions of a few tools/ equipment commonly used in the bell metal production centers has been presented.

### 6.2.1 Task characteristics

Bell metal products manufacturing techniques were observed to start with the casting task, followed by the forging and cleaning task. These tasks are classified as follows a) task 1- casting, melting of old scrap material at a temperature of nearly 1200ºC in an open charcoal furnace (Fig. 6.1a), b) task 2 - forging at a temperature between 600 – 800ºC using a *hammer of weight 1.5 – 2kg* (Fig. 6.1b) and c) task 3 – surface cleaning to remove the oxide layer by using a locally manufactured tool (Fig. 6.1c). The average total working hours per day was found to be 12hr.

**Figure 6.1 Different manufacturing techniques: a) Casting, b) Forging, c) Cleaning**

Different body part movements and postures involved during performing each task were identified according to the method proposed by Keyserling et al. (1992) [249] and the results were found as follows:

a) For "task 1", the trunk of the workers bent forward at some angle (i.e., flexion/ extension) accompanied with side bending. Few workers adopted a posture similar to squatting with flexion of the trunk.

b) For "task 2", one of the arms moves from the top of the head to chest level (i.e., the arm moves almost 90º) while holding a hammer. However, for heavy work, the arm moves from the top of the head to almost ground level (i.e., the arm moves almost 160º). The other arm remains constant in the power zone for holding the job in red hot condition. During forging, the trunk repeatedly flexions accompanied by side bending and the arms work across the side of the body.

c) For "task 3", both the hands are continuously engaged in holding the tool and the feet are used to provide support to the product. During cleaning, the trunk repetitively flexions to cover the whole surface and the arms work across the midline of the body.

### 6.2.2 Drudgery data collection and analysis

For this study, 40 male workers were randomly selected from 20 different bell metal items production units located in Sarthebari. The drudgery data i.e., discomfort/ pain in various body parts, were collected through the questionnaire-based interviews by following the **World Medical Association of Helsinki** protocol as described by Rennie (2013) [191]. The Borg scale was used to collect the data on body discomfort and determine the occurrences and intensity of pain in the workers various body parts as described in chapter 2.

Again, Sanjog et al. (2019) [112] study shows that artisans experience maximum drudgery on the lower back (82.6%), shoulder (56.5%), wrist (52.2%) and knee (34.8%). Dewangan and Singh (2015) [117] have reported that artisans experience maximum drudgery on the lower back (80%), shoulder (80%), neck (60%) and upper back (50%). Kushwaha and Kane (2016) [118] have found that artisans experience maximum discomfort in operator hip/thigh (66.6%), upper back (66.6%), neck (62.9%), knee (59.25%), lower back (51.8%), shoulders (44.4%), forearm (33.3%) and wrist (29.6%). Further, Chohan and Bilga (2011) [250] have reported eye infections of 32.5% of artisans working in a small scale steel plant located in Ludhiana, Punjab. Hence, the drudgery data of shoulders, forearms, upper arms, neck, lower back, upper back, wrists, thigh, knee joint and eye of the workers have only been collected. The collected data also consists of personal information like age, weight, grip force, etc. as described in chapter 2.

Collected drudgery data were analyzed by taking the discomfort scores less than 3 as "no discomfort" and score greater than equal to 3 as "discomfort" as described by Meksawi et al. (2012) [193]. The responses of the workers were analyzed for ascertaining the prevalence of discomfort as described in chapter 2. The workers reporting any earlier history of discomforts because of accidents, diseases or any other injuries are excluded from this study.

### 6.2.3 Digital human modelling

The working postures of the workers have been evaluated using direct observations at the workstations and then the ergonomic analysis has been carried out by using Digital Human

Modelling as described in chapter 2. Since, in all the production techniques, the upper limbs were mainly involved, Rapid Upper Limb Assessment (RULA) score was used as recommended by McAtamney and Corlett (1993) [251] to ascertain the level of ergonomic risks involved with the adopted awkward postures and the urgency of intervention. In RULA technique, score is calculated based on kinematics and loading effects of users [252]. RULA score has already been used by Singh et al. (2012) [113] and Singh (2012, 2010) [110, 111] to assess the ergonomic risks involved with the kind of postures and forces involved in the casting and forging industries as they often lead to pain related drudgeries of workers.

### 6.2.4 Workstation design

The modified systematic layout planning (MSLP) (see Fig. 1.6) has been used to design the workstation for the removal of drudgeries from the industry and hence, for achieving a healthy worker posture, as discussed in chapter 2. The principle of "designing for adjustable range" proposed by Taifa and Desai (2017) [172] has been used for designing the tools and equipments of the workstation. Again, Somatotype, i.e., covering the extreme range of endomorph to ectomorph dimensions recommended by Tilley (1993) [195], has been used to design the workstation.

## 6.3 Results and discussions

### 6.3.1 Characteristics of participants

#### 6.3.1.a Personal data of artisans

Table 6.1 shows the personal characteristics of workers engaged in the bell metal products manufacturing activities. It has been found that the average age of the workers is 33.15 years and it is in the range of 20 to 50 years. The average weight of the workers is found to be 70.14kg and it ranged between 47kg to 83kg. Again, it has been found that more than sixty percent (62.6%) of the workers are left-handed. The maximum, minimum and average handgrip forces have been found to be 55.3kg, 27.2kg and 40.65kg respectively. Further, the average grip force in the left hand and right hand are found to be 41.02kg and 40.27kg respectively.

**Table 6.1 Personal characteristics of workers (N = 40)**

| Characteristics | n (%) respondent | Range | Mean ± Std. deviation | SEM | CV (%) |
|---|---|---|---|---|---|
| **Age (year)** | 7 (17.5) | 20 – 30 | 26.21 ± 1.12 | 0.18 | 4.27 |
| | 21 (52.5) | 30 – 40 | 33.74 ± 1.53 | 0.24 | 4.53 |
| | 12 (30.0) | 40 – 50 | 47.37 ± 1.07 | 0.17 | 2.26 |
| **Weight (kg)** | | 47 – 83 | 70.14 ± 7.9 | 1.25 | 11.26 |
| **Grip force (kg)** | | | | | |
| Left hand | | 29.8 – 55.3 | 41.02 ± 6.64 | 1.05 | 16.19 |
| Right hand | | 27.2 – 51.6 | 40.27 ± 7.79 | 1.23 | 19.34 |
| **Indices** | | | | | |
| BSA ($m^2$) | | 1.38 – 2.14 | 1.87 ± 0.2 | 0.03 | 10.70 |
| BMI ($kg/m^2$) | | 15.8 – 26.3 | 21.4 ± 2.6 | 0.41 | 12.15 |

Again, the maximum, minimum and average BSA (body surface area) have been calculated from Eq. 2.1 and found to be 2.14$m^2$, 1.38$m^2$ and 1.87$m^2$ respectively. The BSA is the indicator of metabolic mass. Agarwal and Sahu (2010) [253], from a study on 300 adult male patients in Netaji Subhash Chandra Bose Medical College located in Jabalpur, have reported an average BSA value of 1.59$m^2$. Zafrir et al. (2016) [254] have reported that higher BSA is associated with a larger occurrence of co-morbidities, including obesity, hypertension and diabetes mellitus. Further, the maximum, minimum and average BMI (body mass index) has been calculated from Eq. 2.2 found to be 15.8$kg/m^2$, 26.3$kg/m^2$ and 21.4$kg/m^2$ respectively. As per WHO, 2014, the normal range of BMI values is 18.5–24.9 [151].

This study depicts that the majority of participants are in the normal range. However, few data were found to deviate from the normal range. The deviation of data from the normal range can be attributed to the improper diet of artisans. In general, the artisans start their work early in the early morning (6 am) and continue up to the late evening (6 – 7pm). In such a situation, the artisans do not maintain a proper diet throughout the day and hence the deviated BMI and BSA from the normal range have been observed among few artisans.

### 6.3.1.b Anthropometric data of bell metal workers and its comparative analysis

The study is carried out between craftsmen engaged with the production of bell metal objects. The result of the descriptive statistics for anthropometric data of the workers is shown in Table 6.2. The result shows that SD values for nearly all dimensions are below 6. These low SD values signify the maximum number of data is closer to the mean value. Relatively low SEM values (less than 1) for all anthropometric data signifies that the result is spread to a smaller extent and hence represents the data are reliable. In this study, comparative variability of the data by the mean value i.e., CV values for most anthropometric dimensions, are found to be low (less than 10).

**Table 6.2 Anthropometric data of the participants (N = 40)**

| Sl no. | Dimensions (cm) | Min | Max | Mean ± Std. dev. | SEM | CV (%) | Percentile | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | 5th | 95th |
| 1 | Stature | 163.2 | 184.4 | 171.6 ± 4.3 | 0.68 | 2.51 | 165.1 | 178.3 |
| 2 | Vertical reach | 208.4 | 236.5 | 222.1 ± 5.4 | 0.85 | 2.43 | 213.3 | 229.4 |
| 3 | Vertical grip reach | 201.3 | 225.4 | 216.7 ± 7.1 | 1.12 | 3.28 | 207.4 | 219.1 |
| 4 | Eye height | 152.7 | 173.3 | 159.1 ± 3.9 | 0.62 | 2.45 | 155.2 | 168.6 |
| 5 | Acromial/ shoulder height | 139.6 | 151.1 | 147.2 ± 4.1 | 0.65 | 2.79 | 142.2 | 149.8 |
| 6 | Elbow height | 98.4 | 114.2 | 105.1 ± 2.7 | 0.43 | 2.57 | 101.9 | 111.3 |
| 7 | Olecranon height | 99.8 | 116.1 | 106.9 ± 5.4 | 0.85 | 5.05 | 104.7 | 112.5 |
| 8 | Iliocrystale height | 88.3 | 107.2 | 94.1 ± 2.2 | 0.35 | 2.34 | 92.6 | 103.6 |
| 9 | Iliospinale height | 82.4 | 101.7 | 90.3 ± 3.0 | 0.47 | 3.32 | 84.1 | 98.9 |
| 10 | Trochanteric height | 70.5 | 97.3 | 86.4 ± 3.6 | 0.57 | 4.17 | 76.7 | 91.8 |
| 11 | Metacarpal height | 64.7 | 91.6 | 78.4 ± 3.9 | 0.62 | 4.97 | 69.2 | 84.7 |
| 12 | Knee height | 46.3 | 56.4 | 50.6 ± 3.1 | 0.49 | 6.13 | 49.3 | 53.4 |
| 13 | Arm reach from the wall | 77.4 | 109.2 | 85.3 ± 5.6 | 0.89 | 6.57 | 82.1 | 99.2 |
| 14 | Biacromial breadth | 35.7 | 47.8 | 39.4 ± 2.3 | 0.36 | 5.84 | 37.6 | 45.7 |
| 15 | Chest breadth | 34.6 | 42.7 | 37.2 ± 2.0 | 0.32 | 5.38 | 35.4 | 40.8 |
| 16 | Chest depth | 19.5 | 25.4 | 23.7 ± 1.1 | 0.17 | 4.64 | 21.9 | 25.0 |
| 17 | Waist breadth | 26.7 | 35.3 | 31.9 ± 0.9 | 0.14 | 2.82 | 29.2 | 33.9 |
| 18 | Hip Breadth | 31.4 | 44.1 | 39.3 ± 1.2 | 0.19 | 3.05 | 35.0 | 42.5 |
| 19 | Chest circumference | 84.3 | 105.0 | 91.7 ± 4.9 | 0.77 | 5.34 | 87.6 | 101.2 |
| 20 | Wrist circumference | 16.1 | 18.7 | 16.8 ± 0.2 | 0.03 | 1.19 | 16.3 | 18.1 |
| 21 | Waist circumference | 56.4 | 85.2 | 67.5 ± 3.8 | 0.60 | 5.63 | 62.1 | 78.4 |
| 22 | Thigh circumference | 38.2 | 52.3 | 46.1 ± 2.3 | 0.36 | 4.99 | 41.7 | 49.9 |
| 23 | Calf circumference | 29.4 | 40.7 | 33.6 ± 1.6 | 0.25 | 4.76 | 32.1 | 38.5 |
| 24 | Thumb tip reach | 75.5 | 94.4 | 86.2 ± 4.8 | 0.76 | 5.57 | 79.4 | 89.3 |
| 25 | Shoulder grip length | 69.1 | 81.2 | 73.4 ± 4.4 | 0.70 | 5.99 | 72.5 | 78.7 |
| 26 | Elbow grip length | 35.1 | 43.7 | 38.6 ± 1.3 | 0.21 | 3.37 | 35.8 | 41.1 |
| 27 | Forearm hand length | 39.6 | 55.4 | 44.3 ± 2.7 | 0.43 | 6.09 | 42.9 | 51.4 |
| 28 | Span | 172.3 | 191.8 | 178.1 ± 5.9 | 0.93 | 3.31 | 174.5 | 184.8 |
| 29 | Span akimbo | 77.4 | 119.3 | 99.1 ± 4.1 | 0.65 | 4.14 | 86.8 | 113.6 |
| 30 | Seating height | 100.1 | 112.5 | 105.4 ± 4.6 | 0.73 | 4.36 | 103.2 | 109.4 |
| 31 | Seating vertical grip reach | 139.8 | 159.7 | 141.1 ± 7.4 | 1.17 | 5.24 | 142.4 | 152.9 |
| 32 | Seating eye height | 88.5 | 99.7 | 93.6 ± 3.8 | 0.60 | 4.06 | 90.1 | 95.3 |
| 33 | Seating acromial height | 74.3 | 83.4 | 79.8 ± 2.5 | 0.40 | 3.13 | 77.4 | 81.2 |
| 34 | Popliteal height | 41.7 | 56.1 | 46.4 ± 1.3 | 0.21 | 2.80 | 44.5 | 52.7 |
| 35 | Seating knee height | 49.2 | 63.4 | 54.5 ± 2.2 | 0.35 | 4.04 | 52.8 | 61.1 |
| 36 | Thigh clearance height | 10.7 | 22.4 | 15.3 ± 0.7 | 0.11 | 4.58 | 12.6 | 19.9 |
| 37 | Seating elbow Height | 57.1 | 68.5 | 64.4 ± 0.3 | 0.05 | 0.47 | 59.2 | 66.6 |
| 38 | Buttock Knee Length | 47.4 | 64.7 | 55.3 ± 1.4 | 0.22 | 2.53 | 51.5 | 60.8 |
| 39 | Buttock popliteal length | 35.3 | 56.2 | 48.6 ± 1.9 | 0.30 | 3.91 | 39.7 | 53.4 |
| 40 | Seating hip Breadth | 33.8 | 48.2 | 42.7 ± 2.0 | 0.32 | 5.45 | 33.5 | 41.3 |
| 41 | Elbow-elbow breadth | 32.1 | 51.4 | 39.5 ± 1.7 | 0.27 | 4.30 | 37.7 | 48.1 |
| 42 | Hand length | 17.3 | 20.7 | 18.2 ± 0.1 | 0.02 | 0.55 | 17.8 | 19.6 |
| 43 | Palm length | 9.3 | 11.4 | 10.2 ± 0.7 | 0.11 | 6.86 | 9.7 | 10.9 |
| 44 | Grip diameter (inside) | 4.2 | 7.9 | 5.8 ± 0.3 | 0.02 | 1.19 | 5.1 | 7.2 |
| 45 | Maximum grip span | 10.8 | 17.4 | 14.3 ± 0.4 | 0.02 | 5.63 | 12.5 | 16.9 |
| 46 | Hand breadth at metacarpal-III | 5.2 | 10.8 | 6.6 ± 0.5 | 0.03 | 4.76 | 5.9 | 9.7 |
| 47 | Hand breadth across thumb | 7.1 | 11.3 | 8.9 ± 0.3 | 0.01 | 5.57 | 7.7 | 10.5 |
| 48 | Thickness at metacarpal-III | 2.6 | 5.2 | 3.7 ± 0.2 | 0.01 | 5.99 | 2.9 | 4.1 |

This study has been further compared with two previous studies carried out by Bhattacharjya and Kakoty (2020) [151] and Dewangan et al. (2010) [152] on the anthropometric data of Assam male workers. The anthropometric data of the artisans compared here are engaged in different occupations.

**Table 6.3 The mean value comparison of anthropometric data**

| Sl no. | Dimensions (cm) | Bell metal worker [a] (Present study) | Pottery worker [b] [151] | Farmer [c] [152] | a – b | a – c |
|---|---|---|---|---|---|---|
| 1 | Stature | 171.60 | 165.30 | 162.00 | 6.30 | 9.60 |
| 2 | Vertical reach | 222.10 | 207.10 | 203.00 | 15.00 | 19.10 |
| 3 | Vertical grip reach | 216.70 | 196.00 | 195.80 | 20.70 | 20.90 |
| 4 | Eye height | 159.10 | 154.20 | 150.10 | 4.90 | 9.00 |
| 5 | Acromial/ shoulder height | 147.20 | 136.30 | 134.50 | 10.90 | 12.70 |
| 6 | Elbow height | 105.10 | 104.20 | 100.50 | 0.90 | 4.60 |
| 7 | Olecranon height | 106.90 | 100.10 | 98.20 | 6.80 | 8.70 |
| 8 | Iliocrystale height | 94.10 | 94.20 | 92.80 | –0.10 | 1.30 |
| 9 | Iliospinale height | 90.30 | 89.50 | 86.70 | 0.80 | 3.60 |
| 10 | Trochanteric height | 86.40 | 80.50 | 79.10 | 5.90 | 7.30 |
| 11 | Metacarpal height | 78.40 | 70.30 | 68.70 | 8.10 | 9.70 |
| 12 | Knee height | 50.60 | 48.50 | 45.60 | 2.10 | 5.00 |
| 13 | Arm reach from the wall | 85.30 | 79.70 | 80.40 | 5.60 | 4.90 |
| 14 | Biacromial breadth | 39.40 | 38.20 | 39.30 | 1.20 | 0.10 |
| 15 | Chest breadth | 37.20 | 29.10 | 31.00 | 8.10 | 6.20 |
| 16 | Chest depth | 23.70 | 20.90 | 20.10 | 2.80 | 3.60 |
| 17 | Waist breadth | 31.90 | 28.80 | 27.30 | 3.10 | 4.60 |
| 18 | Hip Breadth | 39.30 | 31.90 | 31.20 | 7.40 | 8.10 |
| 19 | Chest circumference | 91.70 | 85.80 | 86.30 | 5.90 | 5.40 |
| 20 | Wrist circumference | 16.80 | 16.50 | 16.00 | 0.30 | 0.80 |
| 21 | Waist circumference | 67.50 | 75.20 | 74.90 | –7.70 | –7.40 |
| 22 | Thigh circumference | 46.10 | 44.70 | 47.50 | 1.40 | –1.40 |
| 23 | Calf circumference | 33.60 | 33.50 | 34.50 | 0.10 | –0.90 |
| 24 | Thumb tip reach | 86.20 | 85.30 | 75.20 | 0.90 | 11.00 |
| 25 | Shoulder grip length | 73.40 | 81.90 | 71.30 | –8.50 | 2.10 |
| 26 | Elbow grip length | 38.60 | 43.00 | 36.70 | –4.40 | 1.90 |
| 27 | Forearm hand length | 44.30 | 42.90 | 44.50 | 1.40 | –0.20 |
| 28 | Span | 178.10 | 167.20 | 166.30 | 10.90 | 11.80 |
| 29 | Span akimbo | 99.10 | 85.00 | 84.90 | 14.10 | 14.20 |
| 30 | Seating height | 105.40 | 85.20 | 83.60 | 20.20 | 21.80 |
| 31 | Seating vertical grip reach | 141.10 | 125.90 | 116.90 | 15.20 | 24.20 |
| 32 | Seating eye height | 93.60 | 76.90 | 72.10 | 16.70 | 21.50 |
| 33 | Seating acromial height | 79.80 | 59.00 | 56.70 | 20.80 | 23.10 |
| 34 | Popliteal height | 46.40 | 41.50 | 39.70 | 4.90 | 6.70 |
| 35 | Seating knee height | 54.50 | 51.30 | 49.50 | 3.20 | 5.00 |
| 36 | Thigh clearance height | 15.30 | 15.10 | 13.60 | 0.20 | 1.70 |
| 37 | Buttock Knee Length | 55.30 | 52.80 | 53.20 | 2.50 | 2.10 |
| 38 | Buttock popliteal length | 48.60 | 41.90 | 41.50 | 6.70 | 7.10 |
| 39 | Seating hip Breadth | 42.70 | 38.90 | 32.30 | 3.80 | 10.40 |
| 40 | Elbow–elbow breadth | 39.50 | 39.10 | 42.50 | 0.40 | –3.00 |
| 41 | Hand length | 18.20 | 17.30 | 17.50 | 0.90 | 0.70 |
| 42 | Palm length | 10.20 | 9.90 | 9.90 | 0.30 | 0.30 |

Table 6.3 shows the mean value comparison of the worker from Assam engaged in different occupations. The result shows that anthropometric dimensions vary across occupations. Therefore, it can be inferred that special care is necessary for ergonomic

intervention initiatives to reduce the drudgeries. Otherwise, accidents, injuries, drudgery, or health-related issues may arise among the workers due to dimension mismatches between the artisans and tools/equipments/machines.

## 6.3.2 Drudgery assessment

### 6.3.2.a Discomfort in different parts of body

Table 6.4 shows the occurrence of discomforts in different parts of the body of the bell metal artisans. Approximately 80% of the artisans have reported discomfort in at least a minimum of one body part. The highest percentage of workers informed discomfort in the shoulder (77.5%), followed by palm (72.5%), eye (67.5%), upper arm (65%) and lower back (60.0%).

In bell metal production centers, the artisans perform different tasks throughout the day. During performing the tasks like breaking the old scrap materials for melting, forging, surface cleaning, artworking etc., the artisans either hold a hammer or some other tools and forcefully turn the upper arm for a number of times. Again, it has been observed that many times the artisans abduct the upper arm to carry out the necessary tasks for the production of bell metal items. These activities lead to high discomforts in the shoulder, upper arm and palms of the workers engaged in bell metal manufacturing industries. Whereas, the discomfort in the lower back is related to the adopted awkward postures by the artisans during performing the tasks. The forceful repetitive forward and side bending of the trunk along with twisting of the trunk (as observed from Fig. 6.1) is universally considered as a reason for discomforts in the lower back of the workers. The side bending and front tiling during performing the tasks is responsible for the discomforts in the neck of the workers. The discomforts in the forearm and wrists may be attributed to the weight of the hammer and other tools. Whereas, the discomfort in the upper back may be attributed to the side bending of the worker during performing the tasks. The awkward leg placement while carrying out the necessary activities in the bell metal item production center is the reason for the discomforts in the thigh and knee joints of workers. Higher discomforts in the eyes of the workers are combinedly attributed to the carbon shooting, sparking and smoking phenomena of the charcoal combustion process inside the open flame furnace. Prolong looking task to the red hot metal during processing (especially during forging) is another source of discomforts in the eye of the workers. Improper lighting in the bell metal item production centers (especially in the art working units) may be another source of discomforts in the eye of workers. Moreover, it is well known that working near the charcoal fired open furnace i.e., in a hot environment, enhanced the risk of musculoskeletal disorders and hence, the level of discomforts of the artisans [104, 105]. So, it can be easily said that the drudgeries present in all the body parts of the artisans and hence attention must be paid to remove drudgeries from all the body parts of the workers.

**Table 6.4 Work-related discomforts distributions in different body parts (N = 40)**

| Parts of body | n (%) respondent | Maximum | Mean ± Std. deviation | SEM | CI (95%) |
|---|---|---|---|---|---|
| Neck | 17 (42.5) | 6 | 3.43 ± 1.6 | 0.25 | 2.91 – 3.94 |
| Shoulder | 31 (77.5) | 9 | 5.90 ± 2.0 | 0.32 | 5.26 – 6.54 |
| Upper arm | 26 (65.0) | 9 | 5.28 ± 2.3 | 0.37 | 4.53 – 6.02 |
| Forearm | 14 (35.0) | 7 | 4.33 ± 2.0 | 0.31 | 3.69 – 4.96 |
| Upper back | 12 (30.0) | 8 | 4.20 ± 1.9 | 0.31 | 3.58 – 4.82 |
| Lower back | 24 (60.0) | 9 | 6.08 ± 1.8 | 0.28 | 5.51 – 6.64 |
| Wrists | 5 (12.5) | 7 | 3.33 ± 2.0 | 0.32 | 2.68 – 3.97 |
| Palms | 29 (72.5) | 7 | 3.43 ± 1.8 | 0.29 | 2.85 – 4.00 |
| Thigh | 5 (12.5) | 7 | 2.85 ± 1.8 | 0.29 | 2.26 – 3.44 |
| Knee joint | 12 (30.0) | 8 | 4.58 ± 2.3 | 0.36 | 3.85 – 5.30 |
| Eye | 27 (67.5) | 9 | 5.08 ± 2.1 | 0.34 | 4.39 – 5.76 |

### 6.3.2.b Ergonomic risks assessment using RULA score

Figure 6.2 shows the CATIA model of various postures adopted during performing different tasks.

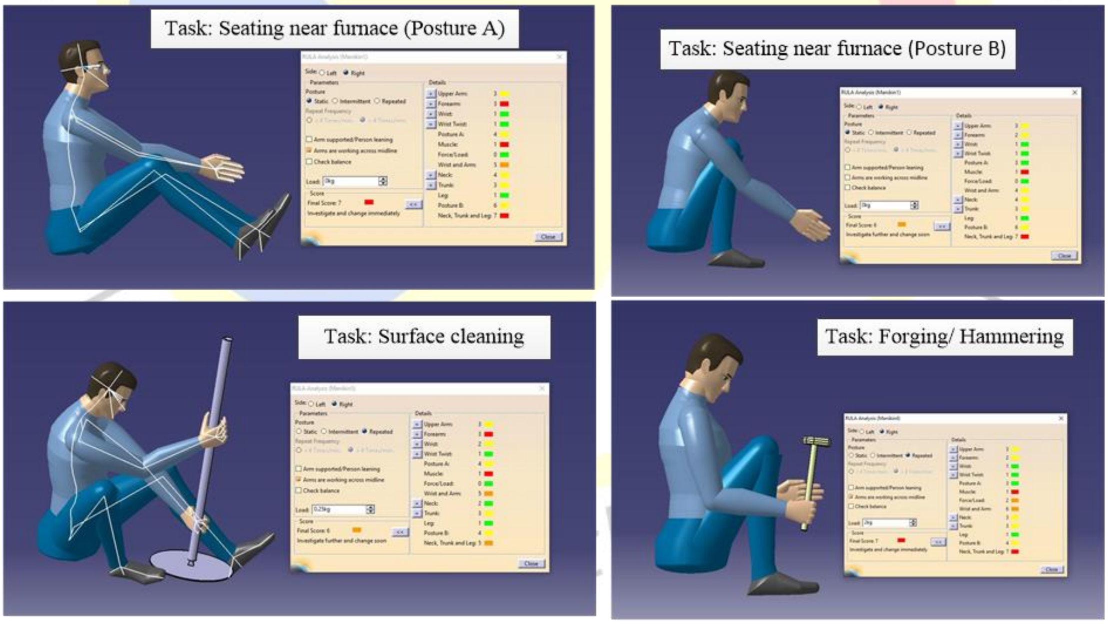

**Figure 6.2 RULA score assessment**

Table 6.5 shows the RULA scores distribution for different tasks in various body parts of the worker acquired from digital human modelling. The RULA score for the upper arm is found to be 3 for all three tasks due to more than 20° extension along with the abduction of the arm. The RULA score for forearms is measured to be 2 for task 1 and task 2; but, in the case of task 3, the forearm crossed the midline and hence the RULA score is 3. The wrists RULA score for tasks 1 and 2 is found to be 2 due to bending away from the neutral axis. It is observed that the RULA score for the neck is different for all three tasks due to a different level of forward and sidewise bent during the production activity. For trunk, the RULA score for all the tasks is 3 due to sidewise and forward bent during the operations. It is observed that the grand scores for all the tasks are more than equal to 6 due to the repeated poster of more than 4 times in a minute, which is interpreted as instant injury risk and urgent need for quick research and actions. However, for task 2 the grand score is 7, which indicates immediate change.

Therefore, from the ongoing discussions, it can be inferred that artisans perform all the tasks under very high ergonomic risks. Further, it has been observed that task 2, i.e., the forging at an elevated temperature near the furnace or breaking the old scraps for production of raw material for the next batch, has the highest risk among all the tasks performed in the bell metal production centers. For safe work conditions, the RULA grand score must be below 3. The next section discusses the workstation design process to reduce the drudgeries and hence the ergonomic risk of the bell metal workers.

**Table 6.5 RULA score for various parts of body**

| **Body parts** | **Task 1** | **Task 2** | **Task 3** |
|---|---|---|---|
| Upper arm | 3 | 3 | 3 |
| Forearm | 2 | 2 | 3 |
| Wrist | 2 | 2 | 3 |
| Neck | 4 | 3 | 2 |
| Trunk | 3 | 3 | 3 |
| Leg | 1 | 1 | 1 |
| Wrist and arm | 4 | 6 | 5 |
| Neck, trunk and leg | 7 | 7 | 5 |
| **Final score** | **6** | **7** | **6** |

## 6.3.3 Workstation design

Workstation design/ redesign is a scientific art. Design of workstation depends upon several factors viz., design of products to be manufactured, production techniques, required machines, production rate, available area etc. [162]. Workstation design means space allocation for man, machine and material movement in the production line, starting from the entry of raw materials to the production of the finished goods. Appropriate placement of machines in the production line reduces the cost of the product by optimal use of available space and effectively utilizing the resources i.e., man, machine and materials [159]. A properly designed workstation increases the safety of workers and reduces the delay between intermediate activities and capital investment. The workstation design starts with the development of a relationship chart.

#### 6.3.3.a Relationship chart

A relationship chart is a tabulated chart developed based on the qualitative ratings between each pair of shops [163, 255]. The main factors considered to develop the relationship chart are raw material flow in the process line, worker flow and interaction among operations.

Figure 6.3 shows the developed relationship chart between different operating units of bell metal production centers. The main factors considered to develop the relationship chart are raw material flow in the process line, worker flow and interaction among the operations. The warehouse is found to be the most necessary unit in a wrokstation for storing raw materials and finished products; hence code A has been used to represent the relation of the warehouse with the casting and packaging units. The casting, forging + quenching, surface cleaning, art working and packaging are especially important units and need to place in sequence to continue and complete the manufacturing process of bell metal items as described in section 1.6. Therefore, code E has been used to represent the relationship between these units. Some items are sell as cast products but require surface cleaning before the delivery process. Therefore, code I has been used to representing the relation between the casting and surface cleaning units. Again, some customer requires cleaned water quenched products without the artworks. These customers either prefer to do the artworks by them according to their own custom or used without any artworks. However, packaging needs to be done before the delivery of the non-art worked products; therefore, the code I has been used to represent the relation between the surface cleaning and packaging units. The surface cleaning and art working are time consuming operations and require the large attention of the workers. These two operations sometimes do not complete in the same day because of the above said reasons and hence need to store the unfinished works in the warehouse. Therefore, the code O has been used in the relationship chart to represents ordinary relations between these two operations and the warehouse. In general, the artwork is not done in cast product hence the code U has used in the relationship chart to represent the unimportant relation between casting and art working operations. The working environment of the forging + quenching unit is very hot and uncomfortable because of the use of high-temperature furnace to carry out different activities. Whereas the art working unit requires a very pleasant working environment to carry out necessary activities. Therefore, code X has been used in the relationship chart to represent the undesirable relation of the art working unit with the forging + quenching unit. In the packaging unit, different polymeric materials, foam etc. are regularly used as packaging materials, which are very prone to deteriorate at high temperatures. Therefore, code X has been used in the relationship chart to represent the undesirable relation of the packaging unit with the casting and forging + quenching units. Further, there is no relation between the forging + quenching unit and warehouse unit; hence the code X has been used to represent the undesirable relation between these units.

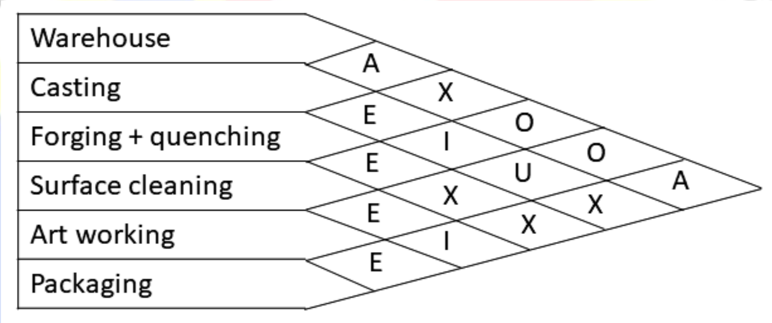

Figure 6.3 Developed relationship chart

### 6.3.3.b Recommended dimension of machines/equipments

Figure 6.1 shows the typical working conditions in the bell metal industry, which isthe major reason for health related drudgeries among the workers. The adopted awkward sitting posture by the workers and the condition of the workplace can be improved through ergonomic interventions. Thus, the subsequent sections discuss the recommended ergonomic interventions viz., dimensions of the tools, equipments and machines to be used in the bell metal product manufacturing units for designing the workstation in order to achieve a healthy working condition.

***Furnace***

In metal industries, two types of induction furnaces, namely vertical and horizontal furnaces, are regularly used. The vertical furnace has an opening from the top surface and is used in very high-temperature operations such as the melting of materials, pyrolysis, etc. The minimum exposer of heat to the worker during operation is the main advantage of the vertical furnace. In contrast, horizontal furnaces are used in industries for almost all general activities that require a comparatively lower temperature. The working height of both types of furnaces is the critical parameter that needs to be addressed for designing an ergonomically correct workstation.

As per the standard norms, the artisans standing eye height should be the determining criterion for the maximum height of the vertical furnace top surface in the workstation for easy visualization. An inclined top surface of the furnace will enhance the visualization process but it is very risky due to the possibility of direct heat exposer to the eye and hence, in practice, the inclined surface furnace is not preferred. Therefore, a horizontal or vertical top surface furnace is used in all the industry. The depth of the furnace is determined as per the required volume of raw materials that need to be melt at a time.

Again, as per the standard norms, the artisans standing eye height should be the determining criterion for the maximum height of the door of the horizontal furnace in the workstation for easy visualization. And the elbow height should be the determining criterion for the bottom working surface inside the horizontal furnace in the workstation for easy loading and unloading.

In the bell metal industry, melting of raw material and heating before the forging and quenching process are the essential activities carried out in an open fired charcoal based furnace (see Fig. 6.1). In order to reduce the discomforts in the eye of artisans by eliminating shoot and smoke inside the workstation, the use of electrically powered induction furnaces has been recommended. This intervention will also improve the indoor air quality inside the workstation to further reduce any other discomforts not mentioned in the above sections. A vertical furnace for melting and a horizontal furnace for heating is recommended for the bell metal item production centers. The height of both the induction furnace top should be 155.5cm, which is ≈ the 5th percentile value of standing eye height for all artisans. The minimum working height of the horizontal furnace should be 105cm, which is ≈ the mean value of elbow height for all artisans.

***Machines***

In metal industries, different machines viz., forging, drilling, welding, grinding etc., are regularly used to perform different activities. Manual loading and unloading of materials in these machines are one of the primary causes of musculoskeletal disorders among workers. Manual loading and unloading activities from different heights should be avoided for effective ergonomic intervention. Manual loading and unloading activities, if necessary, should be done gradually. No load should lift manually above the elbow height. The iliocrystale/ hip height to elbow height should be the determining criterion for the working surface of these machines for ease of doing loading and unloading activities. Again, as per the standard norms, the vertical grip reach and metacarpal height should be considered for the maximum and minimum height of the power switch of all these machines for easy reach.

Particularly for the bell metal industry, grinding machines are used to carry out the polishing activities. The raw materials used in the grinding machines are 1–5cm thick. Therefore, the working height of these machines can be maintained as 105cm, which is ≈ the mean value of elbow height for all artisans. The maximum height of the power switch is considered to be 207.5cm, which is ≈ the 5th percentile value of the vertical grip reach and the minimum height of the power switch is considered to be 84.5cm, which is ≈ the 95th percentile value of the metacarpal height of all artisans.

Since no forging machine particular to the bell metal industry has been developed, for this moment manual forging process may be continued. However, the forging conditions can be improved to reduce the drudgery of the bell metal workers. Following are the few recommendations that can be followed to reduce the drudgery during the forging operations:

a) Forging must be carried out in standing condition without bending the back.
b) The working surface of the anvil must be maintained at the height of 105cm, which is ≈ the mean value of elbow height for all artisans.
c) The working surface of the anvil must be placed at such a distance from the artisans that the summation of the working length of the hammer and the standing elbow grip length of the workers (which is 38 cm for the bell metal artisans of Sarthebari) reach the forging zone.

***Hand tools***

SSIs use different hand tools viz., hammer, file, punch, hand drill, saw, chisel, pliers, wrench, spanner etc., to perform different regular necessary tasks. Lewis and Narayan (1993) [256] have reported that approx. 9% of drudgeries in SSIs are because of using poorly designed hand tools. This study has also indicated that tool shape and size of handle plays the most crucial role in the design of hand tools and hence, the level of drudgeries experienced by the workers. On using poorly designed hand tools may lead to cumulative trauma disorders of artisans [257]. Bisht and Khan (2013) [258] have published a detailed review paper on the commonly used hand tools in SSIs along with 64 assessment techniques viz., task time, grip type, output work quality, questionnaire-based interviews, etc.

In general, since the shape of the tool handle will affect the posture of the artisans, for the greatest comfort of use and least stress, the tool handle should be oriented in such a way so that, while working, the hand and the forearm remain aligned [256]. Again, the gripping capability of the tools is affected by the position of the wrist. Bent wrist position can cause inflammation, chronic pain, and possibly permanent injury to synovial sheets and the median nerve; hence the wrist should be in the straight position while performing the tasks [259]. Further, Lewis and Narayan (1993) [256] have advised not to use any finger grooves in the tool handles to wave off the variations in finger anthropometry of the artisans. This study has also recommended designing the tool handle in such a way that it extends beyond the hand when gripped to allow full spanning of the palm in breadth to generate maximum gripping force. Moreover, organizations like California Occupational Safety and Health Administration, National Institute for Occupational Safety and Health and Centers for Disease Control and Prevention have recommended designing of hand tools depending on the specific tasks viz., precision work, power work, striking work, driving work, etc. [260]. Haque (2018) [261] has recommended grip diameter should be 20% of hand length and grip length should be pi ($\pi$) time of grip diameter. Sengupta and Latta (2012) [262] have recommended the use of an elliptical handle without sharp edges for improved grip comforts.

In the bell metal industry, the hammer is the most common hand tool used for breaking the old scraps to use as raw material for the production of next batch items and carrying out the forging activities to provide the shape to the cast material. The 20% of average hand length for all artisans is found to be 3.64cm, which is 2.16cm lower than the average grip diameter. On selecting the 3.64cm diameter of the hammer handle, there is a possibility that some figures will experience a compressive strain; hence, 5.8cm hammer handle diameter has been recommended, which is ≈ the mean grip diameter of all artisans. Generally, the higher handle length of the hammer is considered to be better to avail the advantage of getting maximum effect with minimum effort according to the lever rule. However, from an engineering prospect, a higher handle length will increase the risk of bending failure. Hence, 32cm handle length, as recommended by Haque (2018) [261], has been suggested.

Different tongs are also used in the bell metal industry for lifting the crucibles during melting and holding the materials while forging and quenching. A well designed tong should dampen the shocks and vibrations, improve the grip and reduce the strains coming from the weight of the component [263]. Generally, it is recommended to use a minimum 5mm thick cover of visco-elastic polymer (also known as elastomer) in the tongs to reduce the shocks and the same has been suggested for the bell metal industry. Again, Howard and Welsh (2004) [260] have recommended that the maximum jaw opening of the tong should not be more than the open grip span of the artisans and the closing jaw position must be equal to the closed grip span. For the bell metal industry, the tong in open jaw condition should not exceed 14.3cm, which is ≈ the average maximum grip span of all artisans; and in closed jaw condition the tong handle should maintain 5.8cm distance between the handles, which is ≈ the average minimum grip diameter of all artisans.

Different files viz., round, flat, triangular, circular, half-circle etc., are regularly used in the bell metal industry for cleaning the oxide layers and smoothing the sharp edges formed during production. The file handle grip diameter is recommended to be 5.8cm, which is ≈ the average grip diameter of all artisans for perfect gripping. The handle length is recommended to be 11.5cm, calculated by using the formula suggested by Haque (2018) [261].

All other bamboo-based hand tools used in the bell metal industry for cleaning and art working (see Fig. 6.1c) are recommended to replace with standard tools. However, if the standard tools are not available, the handle diameter should be 5.8cm, which is ≈ the average grip diameter of all artisans for better gripping.

***Tables***

Essential attention should be given to the dimension of tables for correct ergonomic intervention. The table height is the working surface height minus the height of the workpiece. Das and Grady (1983) [264] have said that without compromising the comfort, the height of the working surface may be changed to few centimeters down or up. However, Konz (1990) [265] suggested 2.5cm lower value from the sitting elbow height should be the height of the working surface. Das and Sengupta (1996) [144] have recommended that the artisans thumb tip reach should be the determining criterion for the work surface width for ease of full reach while performing the task. As per the standard norms, the span length should be used to determine the maximum length of the table for an easy side reach. Further, for reading and writing activities, an inclined surface of 25 – 35° with the horizontal is recommended as per standard norms for easy visualization.

In particular to the bell metal industry, the height of the workpiece varies from a few mm to cm. Therefore, a table with an adjustable facility of a few cm is recommended for the bell metal industry. During seating work, the working surface should maintain a height of 64.5cm, which is ≈ the mean value of sitting elbow height along with a horizontal inclination of 25 – 35° for correct posture and maximum comfort of all artisans. While for standing activities, 105 cm should be the working height, which is ≈ the mean value of standing elbow height along with a horizontal inclination of 25 – 35° for correct posture. The width of the table is considered to be 79.5cm, which is ≈ the 5th percentile value of thumb tip reach for a comfortable end reach of people with both long and short thumb tip reaches. The maximum length of the table is considered 175.5cm, which is ≈ the 5th percentile value of span length for all artisans.

***Seating position***

In general, performing different activities while standing for prolonged periods has typically been found to be associated with significant amounts of fatigue and discomforts [266, 267]. Therefore, maximum attention should be given to modify the seating position for effective ergonomic intervention. The correct sitting position for minimum stress in tissue is 90° angle between the thigh and calves and 90° angle between the upper and lower arms [268]. Moreover, to attain an efficient man-machine interface, several geometrical parameters viz., backrest slope angle, seat height, seat width, seat pan angle, lumbar support etc., also need to be considered designing the sitting position [151].

Das and Sengupta (1996) [144] have reported that the artisans popliteal height should be the seating position height for comfort. Again Shao and Zhou (1990) [269], for comfort, recommended a vertically and horizontally adjustable sitting place arrangement. Therefore, the adjustable seating position is proposed to rectify the current working posture, thereby permitting the worker to adjust the space between the craftsperson and work surface according to comfort needs. Mehta et al. (2008) [270] have reported that the seating hip breadth of the artisan should be the determining criterion for the width of the seating place. This study has also reported that the buttock popliteal length of the artisan should be the determining criterion for the length of seating place. If the length of the seating place is designed for 95th percent of workers dimensions, artisans with shorter dimensions will not be able to sit comfortably and vice versa. Again, Bhattacharjya and Kakoty (2020) [151] have suggested U-shaped seat in activities requires serious attention of workers, like artwork, for necessary hip support. This will enable the worker to retain the knee angle and trunk/thigh angle at 90º while performing the task. This arrangement will also help to reduce the forward tilt of the head and neck. Ghaderi et al. (2014) [271] have reported that a minimum 5cm lower value from the acromial height of the artisan should be considered for the backrest height of the seating place for the necessary support of the operator's back and full movement to the shoulder and arm.

In particular to the bell metal industry, the minimum and maximum seating height is 44.5cm and 52.5cm recommended based on the ≈ 5th and ≈ 95th percentile value of the popliteal height respectively. The seat pan width is 46.5cm which is ≈ 95th percentile of seating hip breadth with a 5cm clearance value. The seat pan length is 58.5cm which is ≈ the mean value of buttock popliteal length with a 5cm clearance value. The backrest height is measured as 72.5cm, which is 5cm lower than the ≈ 5th percentile value of sitting acromial height. As per the standards, 95–105º backward inclination of the backrest from the horizontal position is suggested for workers sacrum and lower back support. Guo et al. (2016) [272] and Carcone and Keir (2007) [273] suggest that 10mm lumbar support thickness for comfortable is maintained in this study.

***Storage rack***

The storage rack is another most important element of the workstation that needs to be designed perfectly to reduce the drudgeries related to manual loading and unloading. Proper dimensions of the storage rack also help to attract the customer by achieving high product accessibility, delivering quickly and reducing order throughput times [274, 275]. The inventories are stored in the racks according to different models viz., consumption rate, price per unit, goods weight etc., depending on the industry. Generally, loading and unloading in the storage racks are done automatically; however, most companies, especially the SSIs, still depends on manual loading and unloading to confirm high tractability levels and to avoid capital investments. Generally, the heavy items are stored in the ground or bottom rows to prevent any accidental injuries during work and the lighter items are placed at the top of the rack. As per the standard ergonomic norms, the artisans standing eye height should be the determining criterion for the maximum height of the top storage rack for easy visualization. And the metacarpal height should be the height of the bottom rack for easy reach without bending the trunk. If it is necessary to store materials on the ground, a separate seating arrangement design is recommended as per standard practice to avoid the wrong working posture.

In the bell metal industry, storage racks are used for storing finished goods, hand tools and files. The weight of the hand tools and bell metal items viz., utensils, decorative items etc., generally vary from a few hundred grams to 3–4kg. Therefore, the heights of the top and bottom racks are considered to be 155.5cm and 84.5cm, which is ≈ the 5th percentile value of standing eye height and ≈ the 95th percentile value of the metacarpal height of all artisans for all artisans respectively.

### 6.3.3.c Space relationship diagram

The space relationship diagram (SRD) is the spatial arrangement between different units [163]. It is the most critical part of the workstation design process. The plants productivity depends on the facility layout of the workstation. Moreover, a properly designed SRD reduces the movement of the worker inside the workplace and hence, decreases the drudgeries of artisans.

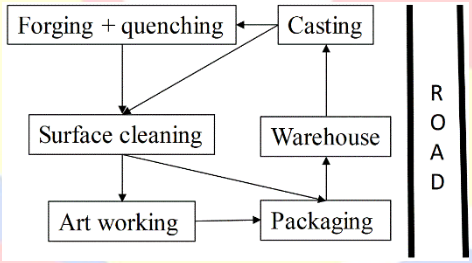

**Figure 6.4 Optimized space relationship diagram**

Numbers of SRD have been developed based on the relationship chart and sequence of the manufacturing process (see Annexure F) and the optimized SRD proposed for the bell metal industry is shown in Fig. 6.4. The minimum risk of the workers has been selected as the optimization criteria for designing the workstation. The minimum movement of the worker inside the workplace has been considered to reduce the risk of artisans. In this connection, the casting unit has been placed in the neighbourhood of the forging and surface cleaning unit for easy transportation of failed products in the production line. Again, the warehouse has placed between the casting and packaging unit of the proposed optimized SRD to facilitates the use of a single delivery/ receive point for minimum interaction with outside. This placement will help to store both the raw materials and finished products in a single warehouse and hence will minimize the movement of workers. Further, the warehouse has been kept on the roadside for easy loading and unloading. The art working unit requires a very pleasant working environment to carry out necessary activities. Whereas the packaging unit regularly uses different polymeric thin sheets as packaging materials, which are very prone to deteriorate at high temperatures. Hence, these two units have been placed at the farthest distance from the casting and forging units which employ high-temperature furnaces. Again, for safety and easy maintenance purpose, the casting and forging units have been kept on one side of the proposed workstation. The warehouse has been placed in the adjacent near to the surface cleaning and art working units to take advantage of intermediate storage facility if required. Again, in order to avail the benefits of minimum intermediate transportation time, the subsequent units have been placed in neighbourhoods according to the manufacturing flow line. Therefore, it can be inferred that the proposed optimized SRD will minimize the man movement inside the workstation to reduce the drudgeries of workers.

#### 6.3.3.d Facility layout

Facility layout is the spatial arrangement of man and machines inside the units [163]. The production and delay time of a workstation depends on the facility layout. Figure 6.5 shows the facility layout developed for the bell metal production centers. This facility layout has been developed by selecting the equipments like furnaces, tools, storage racks, seating chairs, working tables, etc., and machines designed based on the anthropometric dimensions of the bell metal workers as discussed in the previous section. The placement of the equipments/macines have been carried out based on the sequence of the production process followed in the bell metal item manufacturing units. Smooth and uninterrupted movement of man and material inside the workstation was considered as the prime parameters in developing the facility layout. The direction of the man and material movement inside the workstation has been shown in Fig. 6.5. The uninterrupted movement of man and material will reduce or eliminate any tardiness that may present between the units because of intermediate transportation delay inside the workstation. Further, account sections inside the facility layout have been proposed to facilitate the documenting, monitoring and accounting of man and material movement in each stage inside the workstation. This facility will ease the tracking of production quantity, failure rate and time of production. These data will be helpful for future research to further develop the bell metal production units. Figure 6.5 shows the placement of account sections. Again a testing setup has been proposed to ensure quality delivery of the final product to satisfy the end customer. Since, from the field survey, it was found that inside the production centers, the bell metal products fail during the cleaning process; therefore, the proposed testing setup has been placed inside the cleaning unit. The testing procedure of the final product should be based on any available non-destructive inspection methods viz., optical, electrical, magnetic, radiographic etc.

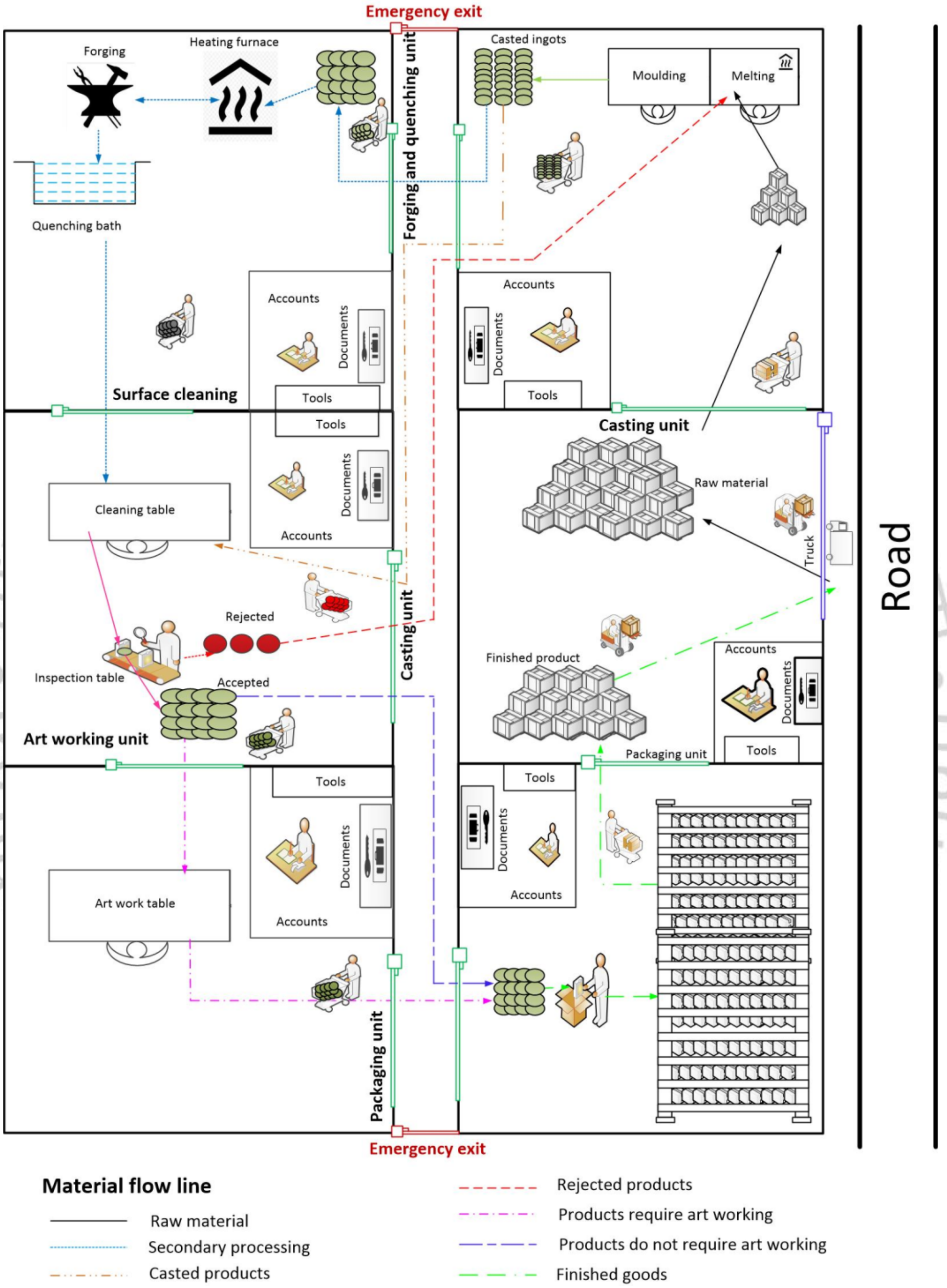

Figure 6.5 Facility layout design

Therefore, from the ongoing discussions, it can be inferred that on implementation, the proposed layout will allow uninterrupted movement of man and material inside the workstation and hence will reduce the tardiness because of intermediate transportation delay.

Again, the proposed facility layout will ensure the delivery of defect-free final products. Defect-free delivery of the final products will increase the customer satisfaction level and hence, may increase the market demand for bell metal products.

### 6.3.3.e Space calculations

In general, space is a major constrain in the designing of a workstation. But the small scale production industries are generally located in rural areas, where abundant space is available. Therefore, space is not a design constrain in workstation designing for small scale production industries. However, to have a general idea of the tentative space required to build a new production plant, a civil layout has been developed based on Guwahati Metropolitan Development Authority (GMDA) bylaws and shown in Fig. 6.6. Figure 6.6 also shows all the essential facilities like parking area, dumping zone, safety room, washroom, cafeteria, powerhouse, security office, etc., that must be present in the industry for its smooth and safe operation. The areas of different units inside the workstations have been calculated based on the commercial tools in conjunction with the dimensions of equipments and machines discussed in previous sections. Again, the doors inside the workstation (shown in green colour) and corridor dimension of 2m is recommended based on the dimension of the commercial trolley (80cm length, 50cm width and 120cm height) in together with the GMDA bylaw. The main door opening to the workplace (shown in blue colour) is suggested as 5m to facilitate direct loading and unloading to and from the truck (length 8m and width 3m) inside the warehouse. This facility will reduce the weather dependency during loading and unloading activities. The campus gate opening (shown in pink colour) is proposed as 10m to facilitate the simultaneous crossing of two vehicles. Again, the set back (defined as the distance from the road to the boundary wall), open space (defined as the distance from the boundary wall to the outer wall of the building) and pick up/ dropping bay length has been determined as 2m, 3m and 6m respectively based on the recommendation mentioned in the GMDA bylaw. Disposal of the scraps produced in the form of slag in the bell metal industry is one of the major challenges faced by the artisans. For the time, it can be stored in the dumping zone and then later can be transported to the municipal waste disposal area; but it needs a permanent solution. An investigation on the recovery of copper and tin from the slags by using the pyro-hydrometallurgical techniques may be helpful for the industry to solve the disposal problem. The pyro-hydrometallurgical technique is already being in use to recover copper from copper and brass slags [276, 277].

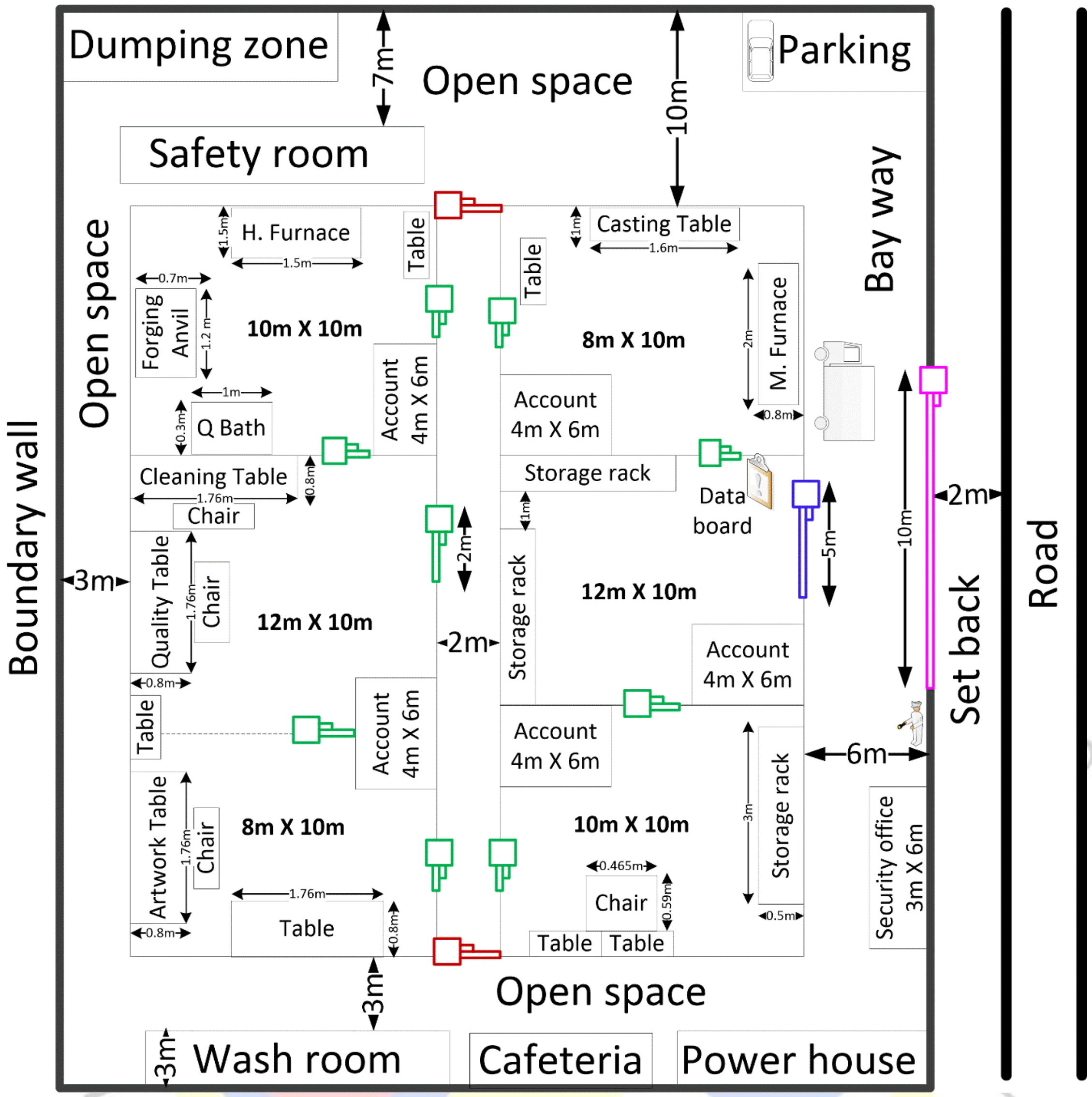

Figure 6.6 Civil layout design

### 6.3.3.f Illuminations

An optimum illumination at the workplace reduces the risk of errors, prevents premature fatigue and improves the concentration of workers to increase the quality of processing and hence the efficiency of the workstation [278, 279]. The eye related discomforts of artisans can also be reduced by applying the right amount of illumination at the workplace. Again, the illuminance level for a given operation depends on the age of the workers. Therefore, during the designing of the workstation, a range of Illumination levels required for different activities has been determined according to code BIS (1992) 3646 [280] based on the personal data of the bell metal workers (see Table 6.1). Table 6.6 shows the illuminance level of different areas inside the proposed workstation.

**Table 6.6 Illumination level**

| Location | Illuminance (lux) |
|---|---|
| Work way, floor, conveyors | 50 – 100 |
| Area around furnaces | 100 – 150 |
| Casting and forging room | 200 – 300 |
| General workbench | 300 – 500 |
| Art work, inspection table | 500 – 750 |

Therefore, it can be inferred that the proposed illumination level in the different places inside the workstation will reduce artisans eye related discomforts. The next section discusses the other practical constraints of workstation design.

### 6.3.3.g Practical constraints

Mauro et al. (2015) [106] have reported that the cost-benefit analysis of the SSIs is the main practical constraint on workstation development and it often leads to implementation failure. This study has reported that in cost-benefit analysis, the artisans do not consider the long-term effects of ergonomic health hazards and hence, the worker group shows unresponsive interest in the development/ modifications of the workstations. This study has also suggested that repeated discussions to clarify the ergonomic related health-hazards to the members of the targeted workgroup may reduce the practical constraints and increase the success rate of achieving the goal.

## 6.4 Key findings

When numbers of conclusions are made based on the present study and accordingly, recommendations are made to design a drudgery-free workstation. Few major conclusions are highlighted here as follows:

a) It is expected that upon using the furnace, tools, machines, tables, seating places, storage racks and equipments designed based on the recommended dimension will allow the artisans to adopt a healthy posture while performing the tasks at the workplace and hence the health conditions of the artisans will improve.

b) It is also expected that on using an electric furnace instead of conventional open-fired charcoal-based furnaces for heating and melting of the bell metal will definitely improve the indoor air quality by reducing the smoke and shoot and hence eye irritations of workers will reduce.

c) Again, from the analysis of the published work of Peköz and Rao (2002) [274] and Calzavara et al. (2017) [275], it has been predicted that on using the proper dimensions of storage racks, more customers will be attracted due to high product accessibility, quick delivery and reduced order throughput times.

d) The developed, optimized space relation diagram on implementation will minimize the man and material movement inside the workstation and hence, the drudgeries of workers will minimize.

e) The proposed facility layout on execution will allow uninterrupted movement of man and material inside the workstation and hence will reduce any tardiness present in the production centers because of intermediate transportation delay between the units and therefore, will reduce any unexpected accidental drudgeries that may occur inside the workstation.

f) The proposed testing unit will ensure the delivery of defect-free final products, which will increase the customer satisfaction level and hence, the market demand for bell metal products.

g) It is further expected that on use of an optimum level of illumination at the workplace will reduce the risk of errors, prevent premature fatigue and improves the concentration of workers and thereby, the processing quality will increase and hence the efficiency of workers will enhance; therefore, the productivity of the workstation will improve.

h) The calculation of the required area based on the proposed facility layout will help the new entrepreneur to make a cost estimation in establishing a new bell metal item production center.

i) Overall it has been foreseen that due to reduced drudgery and increased efficiency of the bell metal item production centers, there is a potential that on implementation of the newly designed workstation, the young artisans who began to leave the trade will start to return to the occupation and hence the manpower scarcity problem will be resolved.

# Chapter 7 LEACHING PROPERTY OF BELL METAL UTENSILS

## 7.0 Introduction

The previous chapter discusses the level of drudgeries associated with the bell metal production units and workstation design technique to rectify the worker postures and thereby to mitigate the ergonomic-related drudgeries of the artisans. From the study, it was expected that on implementation of the proposed workstation, the young entrepreneurs who started to leave the occupation would start to return to the trade due to reduced drudgery and improved working conditions. In this chapter, the copper leaching properties of bell metal utensils in drinking water have been addressed.

## 7.1 Background

Generally, the utensils affect the nutritional compositions of the food and hence on the health [281]. Different utensils made up of several materials like metals, mud and stone are regularly being in use from ancient times. Some most commonly used utensils are made up of aluminium, brass, bronze, bell metal, cast iron, copper, silver, stainless steel, food-grade plastics, clay and soapstone. Saxena et al. (2021) [281] have presented the advantages and disadvantages in terms of durability, convenience, and cost of these utensils.

Clay utensils are ancient Indian utensils still in use for cooking and storage purposes due to its low cost [282]. The higher heat transfer capacity of clay utensils helps to keep cool the storing materials like beverages, vegetables, etc. Moreover, in Ayurveda, the use of clay utensils are recommended in the treatment of many diseases like diabetes [281, 283]. However, recently few authors viz., Bandeira et al. (2021) [284], Belgaied (2003) [285] and Villalobos et al. (2009) [286] have discussed the lead toxicity from earthen utensils. Lead leaching toxicity has also been reported by many authors viz., Baczynskyj and Yess (1995) [287], Gould et al. (1983) [288], Gellert (1993) [289], Karahagopian (1981) [290], Koo et al. (2020) [291], Lynch et al. (2008) [292], Mania et al. (2018) [293], Raghunath and Nambi (1998) [294], Sheets (1999, 1998a, 1998b) [295–297], Tesfaw et al. (2018) [298], Villalobos et al. (2009) [286], Weidenhamer et al. (2014) [299], Welton et al. (2018) [300], Wigle and Charlebois (2013) [301], etc. from the use of ceramic and aluminium utensils.

Copper and its alloy (brass, bronze, bell metal) utensils are regularly used in India from an age-old time due to its high thermal conductivity, aesthetic appearance, light weight and antimicrobial activity [281]. Copper in drinking water also kills the diarrhoeagenic bacteria like *Vibrio cholerae* O1, *Shigella flexneri* 2a, enterotoxigenic *Escherichia coli*, enteropathogenic *E. coli*, *Salmonella enterica Typhi*, and *Salmonella Paratyphi* [186]. It is recently only, Banavi et al. (2020) [302] have studied the leaching property of thin tin walled copper utensils during cooking and storing of deionized water, citric acid solution and 1% sodium hydroxide solution. This study has revealed that very negligible amount of copper leached from utensils in solutions with pH 7.

Quintaes et al. (2007) [303] and Bansal and Jain (2018) [304] have reported that the use of cast iron utensils drastically improves the iron level in food, an essential element for the production of red cells in humans blood and decreases *Anaemia*. The Canadian government has published a report stating that around 20% of the total iron required for an adult person comes from cast iron utensils [281]. Cheng and Brittin (1991) [305] have demonstrated that older cast iron utensils add more iron to food during cooking than the new ones and suggested that cooking in iron cookware enhances the adsorption of non-heme iron, which makes it more bioavailable. Food scientists and researchers are recommending cast iron utensils as a potential remedy to cope up with anemia despite decreasing effects on the colour and flavour of the food [281]. Geerligs et al. (2003b, 2003a, 2002) [306–308], from different studies, have concluded that cast iron utensils are not an appropriate strategic intervention to reduce anemia due to its lower acceptability because of rust/ corrosion and heavy weight.

Recently, stainless steel utensils have become one of the most popularly used metals utensils due to its various advantages like excellent durability, low cost, light weight, high heat and wear resistance properties etc. [281]. Most of the authors viz., Accominotti et al. (1998) [309], Alexandru et al. (2010) [310], Bassioni et al. (2015) [311], Koo et al. (2020) [291], Kuligowski and Halperin (1992), Kumar et al. (1994) [313], Pavesi and Moreira (2020) [314], Szynal et al. (2016) [315], Wallach (1985) [316], etc., have reported a mixed opinion on using stainless steel utensils due to beneficial effect of leached chromium and iron and adverse effect of nickel on the human health.

Aluminium utensils are the latest metal utensils introduced in India by the British ruler in jail and are presently most commonly used in every household due to its lightweight and better cooking efficiency [281]. However, from the last few decades, many authors viz., Ankar-Brewoo et al. (2020) [317], Bi (1996) [319], Lin et al. (1997) [318], Liukkonen-Lilja and Piepponen (1992) [320], Mathee and Street (2020) [321], Meshref et al. (2015) [322], Mohammad et al. (2014, 2011) [323, 324], Ndiaye et al. (2014) [325], Rajwanshi et al. (1999, 1997) [326, 327], Rao and Rao (1995) [328], Rittirong and Saenboonruang (2018) [329], Veríssimo et al. (2006) [330], Weidenhamer et al. (2017) [331], Tennakone et al. (1992) [332], Trapp and Cannon (1981) [333] have repeatedly reported in hundreds of documents, from different parts of the world, about aluminium leaching toxicities and related diseases like *Alzheimer*, *Osteomalacia*, *Encephalopathy* etc. due to use of aluminium utensils.

Now a days, in India, plastic utensils have almost replaced 90% of the total utensils and it is very much popular in every household due to its light weight, attractive colours and low cost [334]. Plastic is also an attractive packaging material and is extensively used in almost all industries due to its remarkable flexibility [334, 335]. Only one paper written by Inthorn et al. (2002) [336] has been found till date reporting about the lead leaching toxicities from the pigments used in the plastic industry. However, Cavaliere et al. (2020) [334] have said that the use of plastic utensils can be a threat to the environment in the very near future due to the non-availability of proper disposal techniques.

From the ongoing discussions, it has been found that utensils are used to fight with different diseases by altering the nutritional compositions of the food and water. However, all the commercial utensil materials, except copper, have suspicious lurking of leaching toxicity; hence there is a high demand for utensil materials that do not adversely affect the health of the user. Certainly, the bell metal utensils are already extensively used in India due to the existing perception of different health benefits might be because of the leaching copper. Therefore, a study to investigate the copper leaching phenomena from the bell metal utensils may be helpful for the industry. So, in this chapter, copper leaching properties from bell metal utensils have been investigated. The next section describes the experimental procedure followed to calculate the amount of copper leached from the bell metal utensil in drinking water.

## 7.2 Experimental procedures

The casted and water quenched bowls collected from Sarthebari were cut into the size of 1cm x 1cm x 1cm to prepare the samples. Some cut samples were then polished by silicon carbide (SiC) sandpapers on a single disc polisher down to different fineness, with grit 180 and grit

2000 being the roughest and the finest respectively for the experiments. Both polished and unpolished cast and water quenched samples were then dipped into the water collected from Aquaguard of pH 7.05 at 25 ºC for 1hr, 4hr and 24hr. The copper concentration in water samples collected after the immersion test was measured according to the guidelines of the Food Safety and Standards Authority of India (FSSAI) published in 2015 by using the Atomic Absorption Spectroscopy (AAS) techniques. Further, a FESEM coupled with EDX has been used to find the leaching area and compositions of the samples before and after the immersion test. Figure 7.1 shows the composition of the bell metal samples used in this study.

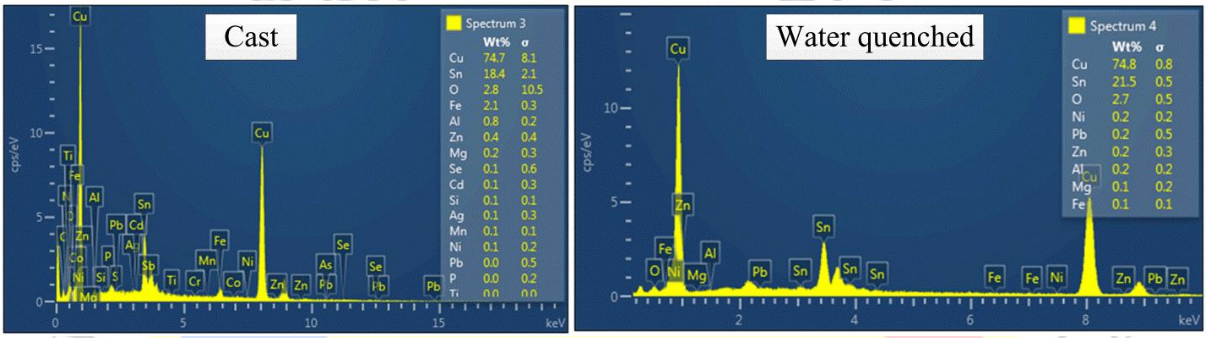

**Figure 7.1 EDX composition of bell metal samples used in the experiment**

## 7.3 Results and discussions

### 7.3.1 Leaching from cast utensils

Figure 7.2 represents the amount of copper concentration variation in drinking water with the time when the cast bell metal sample has been immersed in water. From Fig. 7.2 it is observed that there is a very minimal increase in copper concentration in drinking water after 4 hours and almost no increment after that up to 24 hours.

Figure 7.3 represents the microstructure and EDX compositions of the cast bell metal samples dipped in water for a different period of time. Figure 7.3 shows that no leaching of copper from the surface of cast bell metal samples after 24 hours. However, a small increment in copper concentration in drinking water may be because of the copper erosion from the voids present in the cast samples, as observed from Fig. 7.3. Therefore, it can be inferred that using cast bell metal utensils is not beneficial for health in utilizing the copper leaching property of bell metal.

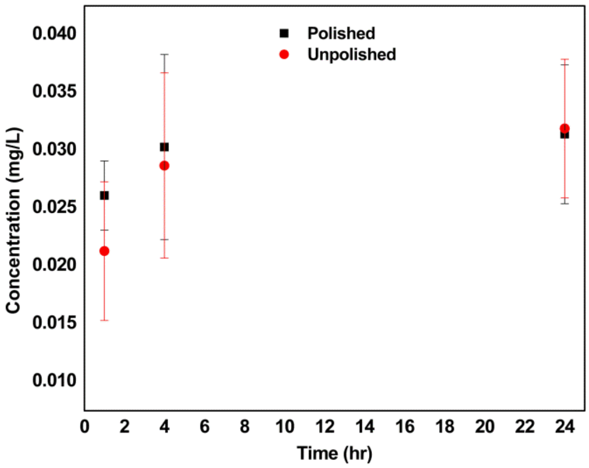

**Figure 7.2 Copper concentration in drinking water with time**

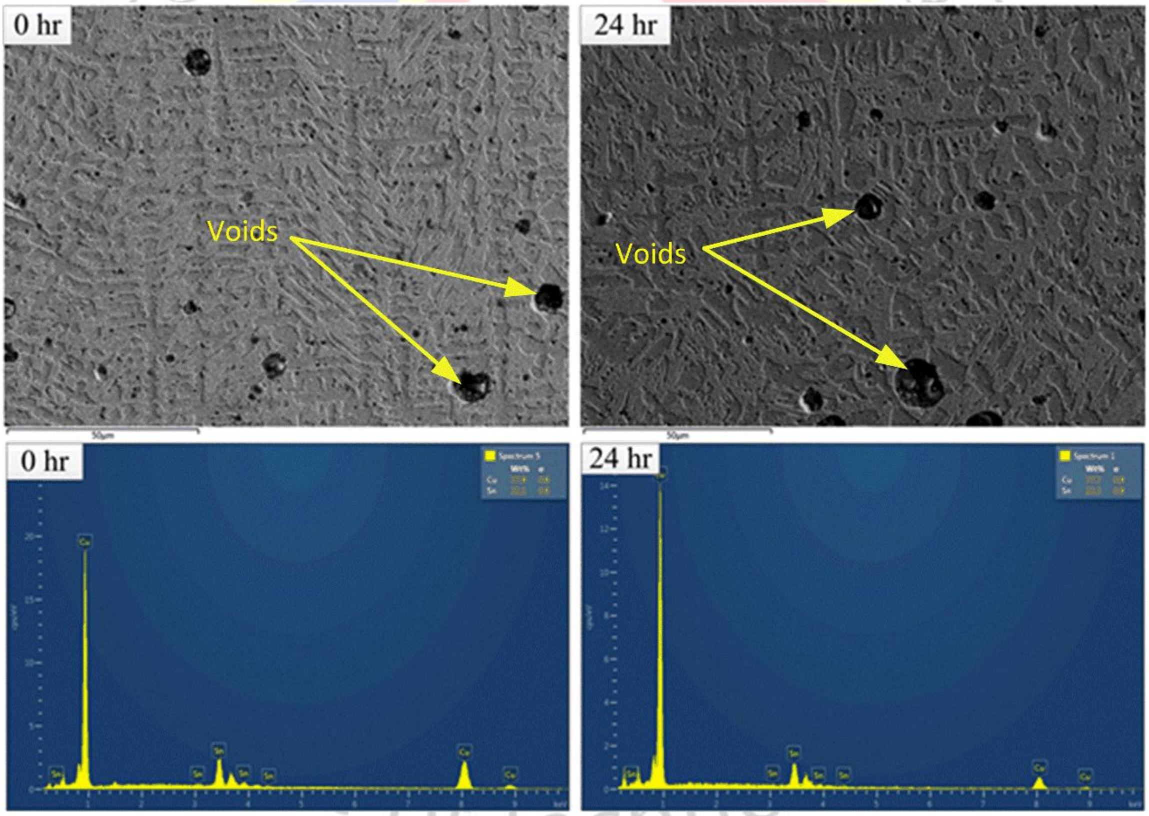

**Figure 7.3 Microstructure and EDX compositions of cast bell metal**

### 7.3.2 Leaching from waters quenched utensils

Figure 7.4 shows the variation in copper concentration in drinking water with time when polished and unpolished water quenched bell metal samples have been immersed in drinking water. From Fig. 7.4, it has been observed that copper concentration in water is continuously increasing with time up to 24 hours. Again, the increment in copper concentration in drinking water for the polished samples is higher than the unpolished samples. It can also be observed from Fig. 7.4 that the concentration of copper in the drinking water after 24 hours is maximum for polished samples and it is 0.12mg/L. This value has been found to be within the permitted range of 1.5 mg/L copper concentration in drinking water as recommended by WHO (World Health Organization) [187]. So, it can be inferred that drinking water in bell metal utensils is not harmful because of leached copper concentration is within the permitted level of WHO.

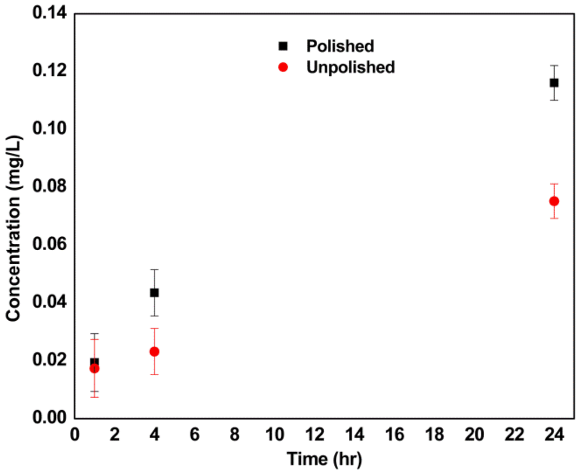

**Figure 7.4 Copper concentration in drinking water with time**

Figure 7.5 shows the SEM images and EDX compositions of water quenched bell metal samples dipped in water for a different period of time. From the SEM images, it can be clearly observed that copper has leached from the surface of the water quenched bell metal samples. Varying copper: tin ratio observed from the EDX compositions of different samples further confirms the leaching of copper from the water quenched bell metal samples. From Fig. 7.5, it has been observed that the copper leached only from the grey phases, which is the α phase of the material and the brighter phase is the β phase. The α phase is the copper-rich zone formed during the solidification of bell metal from the molten state. The formation of different phases has been described in detail in chapter 3. The composition of the α phase has a minimum 85% copper and a maximum of 15% tin, whereas the tin percentage varies from 22 – 26 percent in the brighter β phase. Therefore, it can be inferred that the water quenched bell metal utensils provides the advantage of different health benefits due to copper leaching property in drinking water. Again, it has been deduced that the bell metal utensils can be used to mitigate the copper deficient disease by increasing the α phase of the bell metal utensils. The α phase of the bell metal utensils can be increased by changing the manufacturing process.

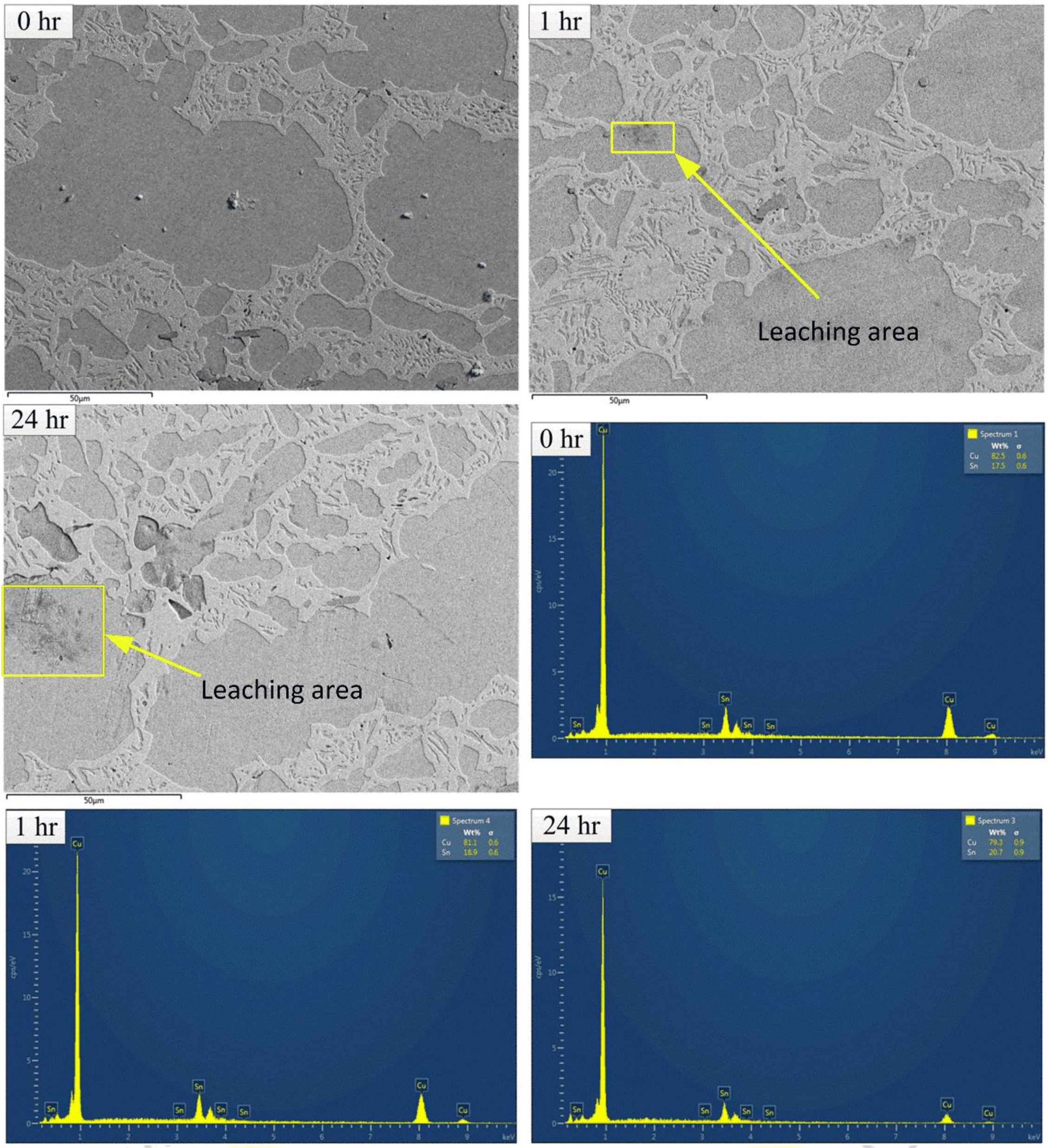

**Figure 7.5 Microstructure and EDX compositions of water quenched bell metal**

Again, the copper leaching mechanism from the utensils was investigated. Few authors studied the copper leaching mechanism from the plumbing items and reported that free chlorine (mixed with the water during employment of disinfection) or dissolved oxygen present in the water initiates and propagates the leaching phenomena [337–339]. However, none of the studies has described the conclusive leaching mechanism of copper in drinking water from the copper or copper alloy surfaces. Therefore, the leaching mechanism of copper from bell metal in drinking water may be considered as future scope of the study.

## 7.4 Key findings

From the above results and discussion, the following point can be summarized:

a) Copper leached in drinking water from the water-quenched bell metal utensils only. More appropriately, copper leached from the α phase present in the water-quenched bell metal utensils only.

# Chapter 8 KEY CONTRIBUTIONS AND CONCLUSIONS

## 8.0 Introduction

The previous chapter discusses the copper leaching property of bell metal utensils. From the study, it has been established that the use of water quenched bell metal utensils may have health benefits due to its copper leaching property in drinking water and it can also be used to reduce copper deficient diseases. This chapter describes the key contributions of the present thesis works along with few recommendations. Further, concluding remarks, limitations and future scope of the present study have also been presented in this chapter.

## 8.1 Background

Bell metal industry is one of the major and important SSI presents all over the world. In India, it is present particularly in places like Assam, Kerala, Karnataka, Manipur, Odisha, Tamil Nadu, Uttar Pradesh and West Bengal [15, 20]. The bell metal industry shares nearly 3% of total India's SSI economy and provides employment to nearly 1 million people. The bell metal is extensively used for manufacturing of different industrial products viz., bearing, bushing, gears, bells, valve, the impeller of pump etc. and domestic products viz., utensil, decorative item etc. due to its specific excellent properties viz., reverberating, resistance to corrosion and wear, high hardness and strength etc. [31, 32].

Bell metal products are manufactured by following a series of processes, namely casting, forging, quenching, surface cleaning and art working in sequence. The design of the products manufacturing workstations has mostly remained unchanged for hundreds of years. The artisans adopt various awkward postures during the production activities. This results in the presence of a very high level of drudgeries. Therefore, the artisans have started to leave the occupation and hence, the industry is facing the manpower scarcity problem [19, 20, 58–60]. Moreover, decreased income level of artisans has helped in the propagation of the manpower scarcity problem of the industry.

The present thesis work has been carried out with the aim to address the manpower scarcity problem of the industry by attracting the young entrepreneurs to the occupation. In achieving that, the total thesis work has been grouped into three major parts *viz.*, investigate the mechanical properties of bell metal, explore the joining techniques of bell metal and assessment and elimination of drudgeries from the industry. Further, a subsidiary work on copper leaching property from the bell metal utensils has also been carried out in this thesis work to help the industry. The next section discusses the key contributions of the present thesis works.

## 8.2 Key contributions from the present thesis work

The present work provides a number of contributions towards the development of the bell metal industry. Few of the key contributions are discussed in subsequent sections.

### 8.2.1 Mechanical properties of bell metal

Before this study, there was a lack of literature on the mechanical properties of the bell metal, which was limiting the range of bell metal products used in different industries. In this thesis work, mechanical properties of bell metal processed in different conditions, viz., cast, oil quenched and water quenched, have been analyzed and reported in chapters 3 and 4. From the analysis of the cast bell metal in section 3.3.1, it has been found that the tensile fracture strength is very low (200MPa) compared to the compressive fracture strength (850MPa). Therefore, it can be inferred that cast bell metal products are more suitable for applications where the compressive load is dominating and not exceeding 850N/mm$^2$. Again, it has been observed that the compressive fracture strength of bell metal increases on increasing the amount of Sn content in the composition due to the increased amount of secondary δ phase. So, it can be deduced that for higher compressive fracture strength of the cast bell metal products, the Sn percent should be in higher site, i.e., Sn percent should be near 25% and copper should be near 75% (on weight basis). However, from the published literature, it was found that with increasing amount of Sn, although the sound quality of cast bells increases; but because of increased brittleness, it is not preferred for manufacturing of bell [41]. These combined results can be concluded as a need for directive engineering decisions depending on the specific application. For example, in specific applications where better sound quality is the most desirable feature (like acoustic based signal processing instruments for medical, metallurgical and electrical applications), the bell metal with high Sn content should be used. Also, for applications where better compressive strength is required (like the frame of a machine, collar bearing etc.), the cast bell metal with higher Sn content should be used. Again, for all general applications, cast bell metal with lower Sn content must be used due to its reduced brittle nature.

Again, from the analysis of section 3.3.3, it was observed that the compressive stress (tensile) decreases from 850 N/mm$^2$ (200N/mm$^2$) to 6.5N/mm$^2$ (5N/mm$^2$) on increasing the temperature from 27 – 700ºC because of the super plasticity of bell metal. This can be inferred as, typically with a compressive (tensile) force of 6.5N/mm$^2$ (5N/mm$^2$), the bell metal can be deformed on processing at a temperature of 700ºC. Further, from the discussion in section 3.3.4, it was deduced that practically the most suitable zone to carry out the plastic deformations of bell metal is in the temperature range of 690ºC to 796.3ºC. Moreover, from the literature, it was evident that artisans can reduce the thickness up to a very great extent on processing above 700ºC [14, 38, 72]. These combined results can be concluded that light weight (due to minimum thickness) bell metal products perhaps may be produced by applying minimum force on processing at the temperature range of 700 – 796.3ºC. At present, light weight with high strength products has very high demand in the aerospace and automobile industry. So, in the future, an attempt may be made to replace few parts of the aerospace and automobile industries with bell metal for the better development of the industry.

Further, from the analysis of the water quenched bell metal product in section 3.3.2, it has been observed that the compressive strength is higher (1100MPa) than the tensile strength (500MPa). Again, it was found that the compressive strength can be increased by 25% on increasing the quenching temperature by 50ºC above 700ºC. So, it can be inferred that a higher quenching temperature results in better strength. Further, from the analysis in section 4.3.2, it has been deduced that the processing of oil quenched products at room temperature will be much easier in comparison to water quenched products due to reduced hardness and subsequently, it was recommended that the products, which require finishing at room temperature, should better be oil quenched to save time and money by reducing the failures during the cleaning process. Further, a database on mechanical properties of bell metal has been attached in Annexure A, along with the properties of other Cu-alloys. Overall this study will help the industrialist and researcher in selecting appropriate processing parameters of bell metal according to the need of the specific industrial applications.

### 8.2.2 Welding of bell metal

Prior to this study, there were no suitable techniques for joining the bell metals, which was further restricting the number of bell metal products used in different industries. In this thesis work, joining techniques of bell metal have been explored in chapter 5 and finally, it was invented that the TIG welding process can be used to join bell metal parts with a smooth surface. It has been evident that bell metal can be successfully weld over a range of TIG welding parameters presented in this study. It has been further observed that on welding, a fusion and a heat-affected zone has formed because of the heat interaction. The experimental result shows that the length of HAZ and the area of FZ varies depending on the input welding parameters. Therefore, a sequential multi-objective optimization process based on NSGA II has been used to optimize the welding process for the bell metal. From the study, different sets of welding parameters have been recommended to produce several welded bell metal products for various applications. It was expected that this invention will results in better sustainability of the industry in two ways a) by generating new avenues for the production of diversified welded products and b) by saving the production time and money by facilitating the intermediate repairing of faulty parts.

### 8.2.3 Drudgery assessment and elimination

Previously there was degeneracy on drudgery-related data for the bell metal production centers, and so forth, no research was found on the elimination of the same. In this thesis work, drudgeries data related to bell metal production techniques have been investigated, measured and reported in chapter 6. From the analysis of the drudgery data, it has been found that 80% of the artisans have discomforts in minimum one of the body parts. It was also witnessed that the workers have the highest percentage of discomforts in the shoulder (77.5%), followed by palm (72.5%), eye (67.5%), upper arm (65%) and lower back (60.0%). Therefore, it was deduced that the level of discomfort perceived in the present working condition is very high. Further, from the RULA score, it was confirmed that all the postures adopted by the artisans while performing the tasks have very high ergonomic risks. So, it was easily analyzed from section 6.3.2 that attention should be paid to reduce the drudgeries from all the body parts of the artisans.

Then as a part of objective 4, a workstation has been designed and discussed in chapter 6 to reduce the drudgeries of the artisans by modifying the adopted awkward postures and improving the condition of the present workplace. At first, a relationship chart between the different activities essential for the bell metal item production process was developed to design the workstation. From the developed relationship chart, it was observed that 3 units (warehouse, casting and packaging) have absolutely necessary, 4 units (casting, forging + quenching, surface cleaning, art working and packaging) has essential, 3 units (casting, surface cleaning and packaging) has important, 3 units (warehouse, surface cleaning and art working) has ordinary, 2 units (casting and art working) has unimportant and 5 units (warehouse, casting, forging + quenching, art working and packaging) has undesirable relations. Then based on the newly collected anthropometric data of the artisans, dimensions of various electrical furnaces, machines, tools, equipments, storage racks etc. have been determined. It is expected that upon using the machines, tools and equipments designed based on the recommended dimension will modify the present postures adopted by the workers i.e., the RULA score will decrease and hence the health conditions of the artisans will improve. On the other hand, on using the recommended electric furnaces instead of conventional open-fired charcoal-based furnaces for heating and melting of the bell metal will definitely improve the indoor air quality by reducing the smoke and shoot. Again, from the analysis of the published literature, it has been predicted that on using the proper dimensions of storage racks, more customers will attract due to high product accessibility, quick delivery and reduced order throughput times [274, 275]. Then an optimized space relation diagram has been developed to minimize the man and material movement inside the workstation. It is expected that due to reduced movement of man and material, the drudgeries of workers will minimize. Further, a facility layout has been designed to show the position of man and machine inside the workstation. The facility layout has been designed in view of the uninterrupted movement of man and material inside the workstation and hence to reduce any tardiness present in the production centers because of intermediate transportation delay between the units. It has been anticipated that an uninterrupted movement of man and machine will reduce any unexpected accidental drudgeries that may occur inside the workstation. Again, the position of a proposed testing unit has also been shown in the developed facility layout. The testing unit has been proposed to ensure the delivery of defect-free final products. It has been predicted that defect-free delivery of the final products will increase the customer satisfaction level and hence, may increase the market demand for bell metal products. Then to further reduce the eye-related discomforts of artisans, illumination level in the different places inside the workstation has been recommended based on the Bureau of Indian Standards (1992) [280] code. From past reports published by Katabaro and Yan (2019) [278] and Silvester and Konstantinou (2010) [279], it was expected that on use of an optimum level of illumination at the workplace will reduce the risk of errors, will prevent premature fatigue and will improve the concentration of workers and thereby, the processing quality will increase and hence the worker efficiency will be better; therefore, the productivity of the workstation will enhance. Further, to help the new entrepreneurs, a rough calculation on the required area to established a new bell metal item production center based on the proposed facility layout has also been carried out. Overall it was foreseen that due to reduced drudgery and increased efficiency of the bell metal item production centers, there is a potential that on implementation of the newly designed workstation, the young artisans who began to leave the trade will start to return to the occupation and hence the manpower scarcity problem will be resolved.

### 8.2.4 Copper leaching from bell metal utensils

Earlier, there was an absence of copper leaching data from the bell metal utensils. In this thesis work, the copper leaching property of the bell metal utensils has been examined and reported in chapter 7. From the present study, it was observed that copper leached only from the water quenched bell metal utensils in drinking water at a rate of 0.12mg/L per day. Further, from the literature, it was found that from a survey on 104 countries, the WHO has permitted 1.5mg/L of copper concentration in drinking water [187]. From this, it was inferred that drinking water in bell metal utensils is not harmful because the leached copper concentration in drinking water is within the permitted level of WHO.

Again, from the literature, it was found that a limited amount of copper, which must be accumulated from outside, preferably through food or water, is essential for the development of a healthy body [181]. Further, from the literature, it was observed that for increasing the nutritional value of food or water and hence to improve the health condition of people, scientists regularly recommend the use of utensils that allow leaching of different elements essential for the growth of the body [281, 308]. Therefore, it was deduced that the use of bell metal utensils is beneficial for improving health conditions due to the limited amount of leaching copper in drinking water.

Further, it was found from the literature that copper-deficient diseases are very prominent in different parts of the world, including India [188, 340]. Again from the analysis of the microstructure of the leached bell metal utensils, it was evident that the amount of copper in drinking water can be increased by increasing the α phase in the microstructure of the bell metal utensils. So, it was inferred that bell metal utensils could be used to mitigate the copper-deficient disease by specially processing the bell metal utensils to form a higher amount of the α phase in the microstructure. Therefore, overall it was concluded that due to the copper leaching property of bell metal in drinking water, the water quenched bell metal utensils provide different health benefits on regular use and can also be used to mitigate copper-deficient diseases by specially processing it during the production of utensils.

## 8.3 Recommendations from the present thesis work

Several ground breaking output results have been found from the present study. Typical output results of the present study have been discussed in chapters 3–7. When numbers of conclusions are deduced based on the results and discussions of the present study and accordingly, recommendations are made to improvise the bell metal product manufacturing process and to reduce the drudgeries from the workplace. Few important recommendations are highlighted here as follows:

- Cast bell metal with low tin content should be used for all general applications.
- Cast bell metal with high tin content should be used for an application where better compressive strength and good sound quality are required, like the frame of a machine, collar bearing, acoustic-based signal processing instruments for medical, metallurgical and electrical applications, etc.
- The processing temperature should be in the range of 700 – 790ºC for the production of light weight bell metal products with minimum force.
- The products, which require finishing at room temperature, should better be oil quenched to save time and money by reducing failures during cleaning in the production centers.
- The optimized set of TIG welding parameters should be used for joining the bell metal parts to produce new diversified products and to facilitate intermediate repairing of faulty parts at minimum operating cost.
- The proposed workstation designed for the bell metal item production centers along with the electric furnace, machines, tools and equipments designed based on the recommended dimensions should be used to attract the young artisans who began to leave the occupation to solve the manpower scarcity problem of the industry due to reduced drudgery and increased efficiency.
- The water quenched bell metal utensils must be used to take advantage of the copper leaching property of bell metal in drinking water for different health benefits.
- The bell metal utensils must be specially processed during the production of utensils

for higher amount of α phase to mitigate copper-deficient diseases.

## 8.4 Concluding remarks

The SSIs, including the bell metal industry, play vital roles in the employment generation and economic development of India. But the SSIs are presently facing manpower scarcity problems due to low income, the presence of several ergonomic-related drudgeries, low productivity and many more. To combat the problems in the SSIs, very urgent and extensive interest must be put forward by the researchers in scientific and technological (S&T) interventions through methodical research with the focus on increased income level and drudgery elimination. For example, in India, both brass and bell metal have been extensively used from ancient times for the production of different items. Products of both this alloy represent the rich cultural heritage of India. Although both the industry shares more than 500 years of existence in different parts of the world, but the brass metal industry has intuitively developed over the period of time due to rigorous amount of systematic and methodical research. The welding techniques to produce diversified brass metal products were first patented in 1872 and continuing till date [341–343]. Again, the hot and cold rolling techniques to produce brass metal sheets and hence to develop light weight products have been well studied before the 1950s and as a result, in Moubhandar, Jharkhand, India, the hot rolling and cold rolling machines were established in 1930 and 1950 respectively [13]. Further, the robotic brass stamping process to produce blanks was well studied around 40 years ago and it is continuously progressing till date [344–346]. Extensive numbers of papers have been published on different machining techniques of brass metal, starting from conventional turning to the latest photochemical machining process to enhance its industrial use [347–350]. The forging process of brass metal has also been extensively studied by researchers and achieved the perfection to produce different automobile and aircraft parts in the 1980s [351–354]. On the other hand, from the literature review, evidentially, it has been observed that the bell metal and its industry have rarely been studied by researchers. Therefore, the bell metal industry has not developed for hundreds of years.

However, the present thesis work has made an attempt as the first step of S&T interventions in the bell metal industry. Numbers of important and essential aspects of the bell metal product manufacturing units have been covered in the present study for the development of the industry. For example, the research related to the method of bell metal welding process on execution will open up new avenues for the creation of diversified different welded bell metal products and hence there is a possibility of market expansions. Similarly, the mechanical properties related studies will allow the industrialist to create a data handbook to ease the utilization of bell metal for other applications in different industries. Again, on implementation of the ergonomically correct workstation designed in this study, along with the recommended dimensions of tools and equipments will reduce the drudgery. The subsequent effect of this study will redraw the attention of artisans towards the industry to solve the labour scarcity problem and will uplift the economic condition /income level of workers engaged in the bell metal industry by decreasing the medical-related expenses. On implementation of the proposed workstation along with the tools, equipments, there is a potential to increase the plants productivity, besides improving the health condition of workers. Although few researchers earlier have claimed that the short term cost-benefit analysis of the SSIs often fails to assess the long-term effects of the ergonomic health hazards of artisans and hence, the worker group shows unresponsive interest in the development/ modifications of tools, equipments and workstations, which require capital investment. The present author believes that repeated discussions/ teaching about the ergonomic related health-hazards to the members of the targeted workgroup will definitely reduce the practical constraints of development/ modifications of tools, equipments and workstations for better health conditions of the workers and hence the cost-benefit ratio of the industry will increase. An approximately estimated cost-benefit analysis before and after the recommended modifications of the workstation has also been attached in annexure G & H. Further, the study related to the copper leaching property will help the researchers to utilize the bell metal utensils in mitigating the copper deficiency related diseases, which may further increase the market demand of bell metal utensils and hence the income level; therefore, the standard of living of the artisans will improve.

## 8.5 Limitations of present study and scope of future works

Serious efforts have been made to generate the best results. However, few errors are beyond the controls of the experimenter, faulty effects of those errors may present in the results. Again, due to limited period of time and repetitive lockdowns because of CoVID 19 pandemic has put further restrictions on the development and field testing of the workstation designed as part of the present study. However, the development, field testing and subsequent modifications of the workstation, if required, can be considered as a potential research area for future studies. In the future, research work for the immediate development of the bell metal industry and hence for better sustainability may also be focused towards the following directions:

- Study on machining properties viz., cutting force, cutting fluid etc., of bell metal and hence develop different tools for the industry.
- Study on dissimilar material weldability of bell metal i.e., weldability of bell metal with other materials for the development of further inter metallic diversified products.

# THESIS NOVELTY

The present thesis work represents a detailed investigation report on various important aspects of the bell metal industry in terms of process improvisation, product diversification and drudgery reduction. In this study, a pioneer work is made to reduce the traditional production difficulties during the manufacturing of bell metal items through process improvisation. In this thesis, the TIG welding process of bell metal parts is explored as an innovative work to decrease the production cost through intermediate repairing. Bell metal products diversification can also be achieved through the present innovation. For the first time, this study has identified and reduced the drudgeries associated with the production of bell metal items by designing an ergonomically correct workstation.

Few other highlighted novelties of the present thesis work are as follows:

- The thesis provides an important insight into the mechanical properties of bell metal towards its wide industrial applications.
- The thesis emphasizes the Pareto optimal relations between the weldment qualities and the welding input parameters to produce diversified welded bell metal products to expand the market range.
- The thesis reports the anthropometric data of bell metal workers. These data will be helpful for the industries dedicated to the design and development of industrial products viz., tools, equipments, machineries etc.
- The thesis includes a typical workstation design procedure for the bell metal industry to reduce the drudgeries associated with the production process.
- The thesis shows that the bell metal utensil can be utilized to reduce copper-deficient diseases due to its leaching property in drinking water.

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# Appendix A

**Personal information:**

Name:
Age:
Weight:
Height:
Education level:
Experiences in years:

**Drudgery informations:**

| Name of ergonomic discomforts | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Neck | | | | | | | | | | |
| Shoulder | | | | | | | | | | |
| Upper arm | | | | | | | | | | |
| Lower arm | | | | | | | | | | |
| Upper back | | | | | | | | | | |
| Lower back | | | | | | | | | | |
| Wrists | | | | | | | | | | |
| Palms | | | | | | | | | | |
| Thigh | | | | | | | | | | |
| Knee joint | | | | | | | | | | |
| Eye irritation | | | | | | | | | | |
| Other pain | | | | | | | | | | |

Grip force:

| *Morning* | *Afternoon* |
|---|---|
| Left hand | Left hand |
| Right hand | Right hand |

# Appendix B

**Personal information:**

Name: Age:

**Anthropometric information:**

| Sl. No. | Body parts | | Sl. No. | Body parts | |
|---|---|---|---|---|---|
| 1 | Stature | | 25 | Shoulder grip length | |
| 2 | Vertical reach | | 26 | Elbow grip length | |
| 3 | Vertical grip reach | | 27 | Forearm hand length | |
| 4 | Eye height | | 28 | Span | |
| 5 | Acromial/ shoulder height | | 29 | Span akimbo | |
| 6 | Elbow height | | 30 | Seating height | |
| 7 | Olecranon height | | 31 | Seating vertical grip reach | |
| 8 | Iliocrystale height | | 32 | Seating eye height | |
| 9 | Iliospinale height | | 33 | Seating acromial height | |
| 10 | Trochanteric height | | 34 | Popliteal height | |
| 11 | Metacarpal height | | 35 | Seating knee height | |
| 12 | Knee height | | 36 | Thigh clearance height | |
| 13 | Arm reach from the wall | | 37 | Elbow Rest Height | |
| 14 | Biacromial breadth | | 38 | Buttock Knee Length | |
| 15 | Chest breadth | | 39 | Buttock popliteal length | |
| 16 | Chest depth | | 40 | Seating hip Breadth | |
| 17 | Waist breadth | | 41 | Elbow-elbow breadth | |
| 18 | Hip Breadth | | 42 | Hand length | |
| 19 | Chest circumference | | 43 | Palm length | |
| 20 | Wrist circumference | | 44 | Grip diameter (inside) | |
| 21 | Waist circumference | | 45 | Maximum grip span | |
| 22 | Thigh circumference | | 46 | Hand breadth at metacarpal-III | |
| 23 | Calf circumference | | 47 | Hand breadth across thumb | |
| 24 | Thumb tip reach | | 48 | Thickness at metacarpal-III | |

# Annexure A

Table: Mechanical properties of bell metal and other copper alloys

| Composition (wt. basis) | Processed condition | Fracture strength (MPa) | Hardness (HV) | References |
|---|---|---|---|---|
| Bell metal | Cast | 850 ± 10 (C)<br>200 ± 5 (T) | 125 ± 5 | Present work |
| | Water quenched from 750°C | 1100 ± 5 (C)<br>570 ± 5 (T) | 295 ± 3 | |
| | Oil quenched from 750°C | 560 ± 10 (C) | 210 ± 3 | |
| | @ temperature of 550 °C | 10 (C)<br>8.5 (T) | | |
| | @ temperature of 700 °C | 6 (C)<br>5 (T) | | |
| 90% Cu and 10% Zn | high pressure torsion and then cold rolled | 700 (T) | | [355] |
| 86.5% Cu, 12% Sn and 1.5% Ni | Vacuum casting | 327.5 ± 11 (T) | 122 ± 2.5 | [356] |
| 94% Cu and 6 % Sn | Extruded | 137.5 (T) | 108 | [357] |
| 82% Cu, 9% Al, 4% Ni, 4% Fe and 1% Mn | 3D printing (wire arc additive) | 745 ± 8 (T) | | [358] |
| 85% Cu, 1% Br, 10% Al and 4% Fe | Selective laser melting | 550 ± 20 (T) | 330 ± 20 | [359] |
| 85% Cu and 15% Sn | Selective laser melting | 650 (T) | | [360] |
| 90% Cu and 10% Sn | Sever plastic deformation | 286 (T) | 94 | [361] |
| 93.5% Cu and 6.5% Sn | Annealed at 250°C | 225 @ 500°C and 50 @ 700°C (T) | | [362] |
| 85% Cu, 10% Sn and 5% Ni | Cast | 294 (T) | 112 | [363] |
| 88.16% Cu, 10% Zn, 1.5% Ni and 0.34% Si | Hot rolling followed by cold rolling and iso-thermal aging | 650 (T) | 130 @550°C and 220@ 350°C | [364] |
| 82% Cu, 10% Al, 4% Fe and 4% Ni | Centrifugal casting | 602 (T) | 136 | [365] |
| | Water quenched from 890°C + aged @ 450°C /1h | 663 (T) | 212 | |
| 86% Cu, 9% Al and 3.5% Fe | Cast | 450 (T) | | [366] |
| 72.5% Cu 17% Pb, 6% Sn and 4.5% Zn | Casting followed by heating @300°C/1h, water quenching and multi directional forging | 346 (C) | 175 ± 2 | [367] |
| 79% Cu, 9% Al, 4.5% Ni, 4% Fe, 1.2% Mn and 0.1% Si | Friction stir processing | 600 (T) | | [368] |
| Phosphor free cutting bronze | Annealed @ 700°C/8 h | 155 (T) | | [369] |

*C is used to represent compressive stress and T is used to represent tensile stress

# Annexure B

Fig. Poor and over melted samples during welding

# Annexure C

**Table:** ANOVA table for the length of HAZ

| Source | DOF | Sum square | Mean square | F-statistic | p value |
|---|---|---|---|---|---|
| Model | 9 | 3.19499 | 0.355 | 37.83 | 0 |
| Linear | 3 | 2.69253 | 0.89751 | 95.65 | 0 |
| I | 1 | 2.58988 | 2.58988 | 276.02 | 0 |
| d | 1 | 0.02387 | 0.02387 | 2.54 | 0.142 |
| S | 1 | 0.07878 | 0.07878 | 8.4 | 0.016 |
| Square | 3 | 0.18293 | 0.06098 | 6.5 | 0.01 |
| $I^2$ | 1 | 0.10543 | 0.08106 | 8.64 | 0.015 |
| $d^2$ | 1 | 0.02673 | 0.03424 | 3.65 | 0.085 |
| $S^2$ | 1 | 0.05077 | 0.05077 | 5.41 | 0.042 |
| Interaction | 3 | 0.31954 | 0.10651 | 11.35 | 0.001 |
| Id | 1 | 0.02761 | 0.02761 | 2.94 | 0.117 |
| IS | 1 | 0.09031 | 0.09031 | 9.63 | 0.011 |
| Sd | 1 | 0.20161 | 0.20161 | 21.49 | 0.001 |
| Residual Error | 10 | 0.09383 | 0.00938 | | |
| Lack-of-Fit | 5 | 0.08595 | 0.01719 | 10.9 | 0.01 |
| Pure Error | 5 | 0.00788 | 0.00158 | | |
| Total | 19 | 3.28882 | | | |

# Annexure D

**Table:** ANOVA table for the area of FZ

| **Source** | **DOF** | **Sum square** | **Mean square** | **F-statistic** | **p value** |
|---|---|---|---|---|---|
| Model | 9 | 70.5994 | 7.8444 | 53.92 | 0 |
| Linear | 3 | 65.3591 | 21.7864 | 165.18 | 0 |
| I | 1 | 64.5514 | 64.5514 | 183.06 | 0 |
| d | 1 | 0.1143 | 0.1143 | 2.21 | 0.039 |
| S | 1 | 0.6934 | 0.6934 | 5.15 | 0.047 |
| Square | 3 | 4.6266 | 1.5422 | 11.46 | 0.001 |
| $I^2$ | 1 | 1.8728 | 2.4829 | 18.44 | 0.002 |
| $d^2$ | 1 | 0.826 | 1.0862 | 8.07 | 0.018 |
| $S^2$ | 1 | 1.9279 | 1.9279 | 15.2 | 0.004 |
| Interaction | 3 | 0.6136 | 0.2045 | 1.45 | 0.269 |
| Id | 1 | 0.1402 | 0.1402 | 1.04 | 0.332 |
| IS | 1 | 0.0025 | 0.0025 | 10.66 | 0.045 |
| Sd | 1 | 0.4709 | 0.4709 | 7.2 | 0.091 |
| Residual Error | 10 | 1.3461 | 0.1346 |  |  |
| Lack-of-Fit | 5 | 1.3458 | 0.2692 | 3571.27 | 0 |
| Pure Error | 5 | 0.0004 | 0.0001 |  |  |
| Total | 19 | 71.9455 |  |  |  |

# Annexure E

**Table:** Optimtool settings in MATLAB

| Parameters | Settings |
|---|---|
| solver | gamultiobj |
| No of variables | 3 (I, d, S) |
| Lower bound | [29.5, 0.3, 1.3] |
| Upper bound | [105.5, 3.7, 4.6] |
| Population type | Double vector |
| Population size | 20000 |
| Creation function | Feasible population |
| Selection function | Tournament |
| Mutation function | Adaptive feasible |
| Crossover function | Twopoint |
| Migration | Both |
| Distance measure function | distancecrowding |
| Pareto population fraction | 0.35 |
| hybridfunction | fgoalattain |

# Annexure F

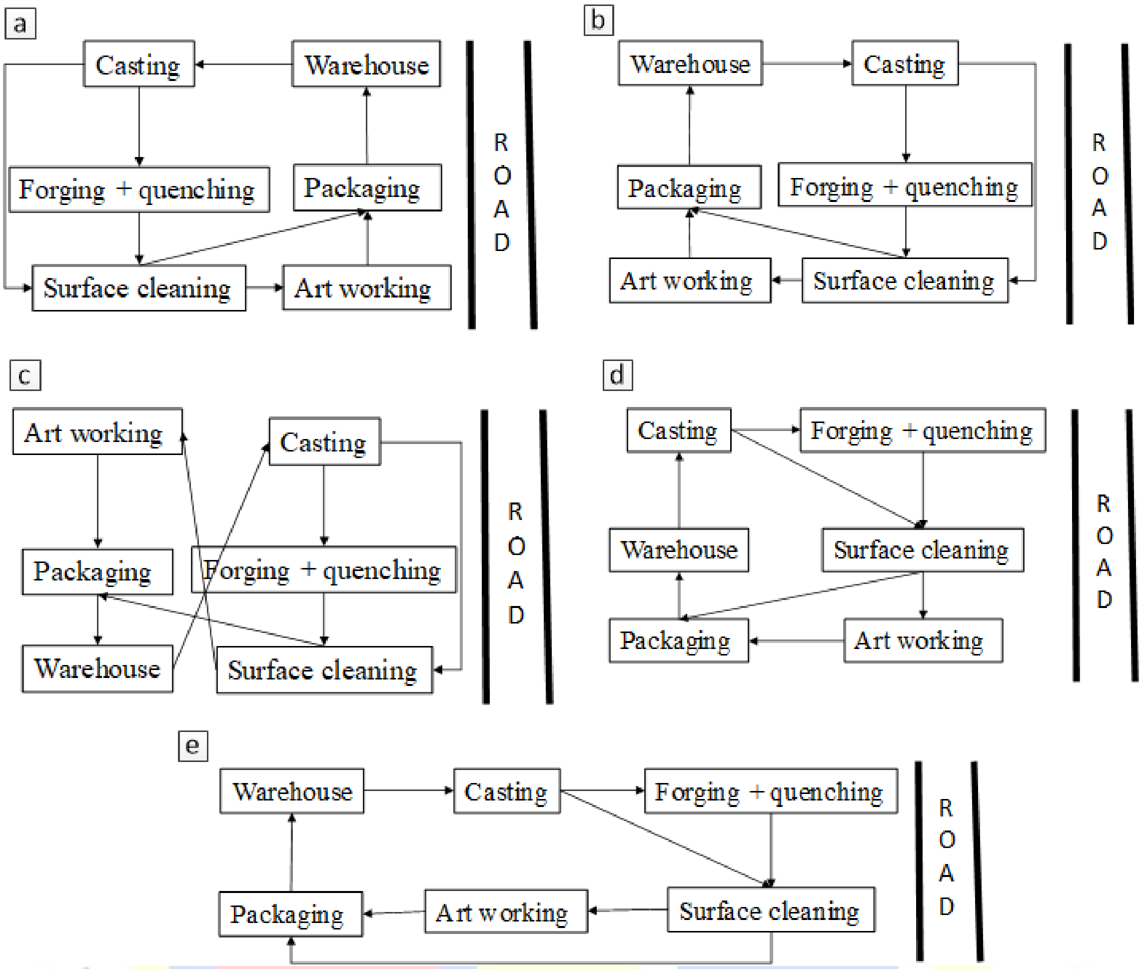

Fig.: Developed space relation diagrams

# Annexure G

## Cost-benefit analysis of the production system before the modifications

| **Running cost** | | **Cost in Rs. per day per unit** |
|---|---|---|
| Raw material cost | *Bell metal cost (10kg per day @ Rs 980/ kg )* | 9,800/- |
| Transportation and holding cost (Per month) | *Cost of transportation of raw material (2 times @ Rs 750/time)* | 50/- |
| | *Cost of transportation of finish product (2 times @ Rs 750/time)* | 50/- |
| | *Cost of holding (@1500/month)* | 50/- |
| Manufacturing cost | *Casting cost [Coal cost (70% bag @ Rs. 60/bag) + Labour & overhead cost (5 labour for 3hr @Rs 40/ hr)]* | 642/- |
| | *Forging cost [Coal cost (1bag @ Rs. 60/bag) + Labour & overhead cost (5 labour for 3hr @Rs 40/ hr)]* | 660/- |
| | *Water quenching cost [Coal cost (30% bag @ Rs. 60/bag) + Labour & overhead cost (2 labour for 0.5hr @Rs 40/ hr)]* | 58/- |
| | *Cleaning and artwork cost (5 labour for 3hr @Rs 40/ hr)* | 600/- |
| **Total Running Cost** | | **11,920/-** |
| **Fixed cost**<br>(Assume 300 working day per year and 10 year average life span of each tools/ machines) | | |
| Crucible (6 crucible/ year @Rs 500/ crucible for 10 year) | | 10/- |
| Mould (20 mould/ year @Rs 200/ crucible for 10 year) | | 13.33/- |
| Casting tong (5 tong @Rs 200/tong) | | 1.33/- |
| Anvil ( 2 anvil @Rs 10000/anvil) | | 6.67/- |
| Forging hammer (10 hammer @Rs 1000/ hammer) | | 33.33/- |
| Forging tong (10 tong @200/tong) | | 0.67/- |
| Quenching bath (2 bath @ Rs 2000/ bath) | | 1.33/- |
| Other tools (Rs 10000 aprox) | | 3.33/- |
| **Total Fixed Cost** | | **70/-** |
| **Total production cost (** Running cost + Fixed Cost) | | **11990/-** |
| **Sell value** (8.5kg @ Rs. 1500/kg) (assume 0.5kg surface oxide loss and 1 kg production waste during forging and casting) | | **12750/-** |
| **Gross profit** (sell value - production cost) | | **760/-** |
| **Health expenses** (approx. Rs. 50,000/yr per person for 5 person) | | **685/-** |
| **Net profit** (gross profit - health expensess) | | **75/-** |

# Annexure H

## Cost-benefit analysis of the production system after the modifications

| **Running cost** | | **Cost in Rs. per day per unit** |
|---|---|---|
| Raw material cost | *Bell metal cost (10kg per day @ Rs 980/ kg )* | 9,800/- |
| Transportation and holding cost | *Cost of transportation of raw material (2 times per month @ Rs 750/time)* | 50/- |
| | *Cost of transportation of finish product (2 times per month @ Rs 750/time)* | 50/- |
| | *Cost of holding (@Rs 1500/month)* | 50/- |
| Manufacturing cost | *Casting cost [*Power cost (1.5 kW for 2 hr @ Rs. 10/kWhr) + Labour & overhead cost (5 labour for 3hr @Rs 40/ hr)] | 630/- |
| | *Forging cost [*Power cost (5 kW for 3 hr @ Rs. 10/kWhr) + *Labour & overhead cost (5 labour for 3hr @Rs 40/ hr)]* | 750/- |
| | *Water quenching cost [*Power cost (5 kW for 0.5 hr @ Rs. 10/kWhr) + *Labour & overhead cost (2 labour for 0.5hr @Rs 40/ hr)]* | 65/- |
| | *Cleaning cost (5 labour for 3hr @Rs 40/ hr)* | 600/- |
| | **Total Running Cost** | **12,005/-** |
| **Fixed cost**<br>(Assume 300 working day per year and 10 year average life span of each tools/ machines) | | |
| Workplace modification cost (Rs 500000 approx.) | | 166.67/- |
| Casting vertical furnace (2 furnace @Rs 30,000/furnace) | | 20/- |
| Crucible (6 crucible/ year @Rs 500/ crucible for 10 year) | | 10/- |
| Casting table (2 table @Rs 15,000/table) | | 10/- |
| Mould (20 mould/ year @Rs 200/ crucible for 10 year) | | 13.33/- |
| Casting tong (5 tong @Rs 200/tong) | | 1.33/- |
| Heating furnace (Rs 500000/-) | | 166.67/- |
| Anvil ( 2 anvil @Rs 10000/anvil) | | 6.67/- |
| Forging table (2 table @Rs 40,000/table) | | 26.67 |
| Forging hammer (10 hammer @Rs 1000/ hammer) | | 33.33/- |
| Forging tong (10 tong @200/tong) | | 0.67/- |
| Quenching bath (2 bath @ Rs 2000/ bath) | | 1.33/- |
| Working table (2 table @Rs 20000/table) | | 13.33/- |
| Other tools (Rs 10000 approx.) | | 3.33/- |
| Safety equipment (Rs 200000 approx.) | | 66.67/- |
| | **Total Fixed Cost** | **535.67/-** |
| **Total production cost (** Running cost + Fixed Cost) | | **12540.67/-** |
| **Sell value** (9 kg @ Rs. 1500/kg) (assume 0.5kg surface oxide loss and 0.5 kg production waste during forging and casting) | | **13500/-** |
| **Net profit** (sell value - production cost) | | **959.33/-** |

*Highlighted parts are the added cost due to modifications

# List of Publications

## Peer Reviewed Journals

1 **P K Sarkar** and S K Kakoty, "**Bell Metal Product Manufacturing Techniques: A Technical Report from Sarthebari, Assam**", *Journal of The Institution of Engineers (India): Series C*, https://doi.org/10.1007/s40032-021-00673-z

2 **P K Sarkar** and S K Kakoty, "**Effect of quenching parameters on mechanical properties of bell metal",** *Materials Today Proceedings,* https://doi.org/10.1016/j.matpr.2020.10.529

3 **P K Sarkar**, J J Kalita and S K Kakoty, "**Copper leaching in drinking water from bell metal utensils**", (Under review, submitted to *Sadhana* on 12th December, 2020).

4 **P K Sarkar** and S K Kakoty, "**User-centric drudgery free workstation design for the bell metal industry"**, (Under review, submitted to International Journal on Interactive Design and Manufacturing on 3rd September, 2021).

5 **P K Sarkar** and S K Kakoty, "**Multi-objective optimization of TIG welding process for joining the bell metal**", (Under review, submitted to Materials and Manufacturing Process on 9th September, 2021).

## Patent

1 **P K Sarkar** and S K Kakoty, "**Bell metal welding process**", Application no: 202031011398 (FER replied on 27th July, 2021).

## Conferences

1 **P K Sarkar** and S K Kakoty, "**Engineering properties of cast bell metal**", at Institution of Engineers (Assam state Center) on March 25-27, 2019.

2 **P K Sarkar** and S K Kakoty, "**Mechanical properties of bell metal**", at Indian Institute of Technology Delhi on March 25-27, 2018. http://rutag.iitd.ac.in/rutag/sites/default/files/images/user38/Souvenir-website.pdf