# SUSTAINABLE HARD MACHINING USING MECHANICAL MICRO-TEXTURED CUTTING TOOLS WITH MINIMUM QUANTITY NANO-GREEN CUTTING FLUIDS

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## Introduction and need of sustainable machining

Machining is one of the oldest basic manufacturing processes. Before the industrial revolution of 18$^{th}$ century, hand tools were used for machining. Since the advent of steam power, power driven machine tools became common in industries. Some of the popular machining processes are turning, milling, drilling and grinding. Among these, turning is most widely used machining process.

Turning is a traditional machining process for obtaining cylindrical, conical or tapered parts. In this process a single point turning tool of relatively harder material compared to workpiece and having a sharp cutting edge is fed against the rotating workpiece. The cutting action takes place due to fracture of the workpiece material at shear zone so as to remove the unwanted part for producing the desired geometry.

In the turning operation, the main process parameters are cutting speed, feed and depth of cut, whose optimum value depends upon the cutting tool and workpiece material. The major performance parameters are tool-chip interface temperature, cutting force, feed force, coefficient of friction, workpiece surface roughness and tool wear. Other important parameters are cutting fluid, cutting fluid application technique, cutting tool material, work material, tool geometry, motor power, workpiece dimension, machine stability, etc. that have a direct influence on the turning process. Tool geometry affect chip formation, tool strength, cutting force, feed force and workpiece surface roughness. The cutting force, feed force, cutting fluid and cutting fluid application technique have a direct influence towards the workpiece surface roughness and tool wear. It is always important to work with optimum process parameters to obtain better surface finish, minimize tool wear and to make machining more sustainable.

## Environmental aspects in turning processes

Environmental concerns call for the reduction of cutting fluid in metal cutting practice and nowadays it has become an important objective in industry. Efficient utilization of cutting tool in machining is an important focus of researchers. The performance of cutting tool depends on the process parameters and the cutting environment. Many a times, a cutting fluid is used to enhance the tool life and to improve the surface integrity. The fluids that are used to lubricate in machining contains environmentally harmful or potentially damaging chemicals constituents. The airborne particle of cutting fluids can be inhaled by operators and causes respiratory irritation, asthma, pneumonia, dermatitis and several types of cancers (oesophagus, skin, lung, pancreas, colon etc.) [1, 2]. The concept of dry machining has the advantages of non-pollution of the atmosphere and water, no residue on the swarf resulting in the reduction of the disposal and cleaning cost and no danger to health such as skin rupture and allergy etc. As such, dry machining has become popular with regards to safety of the environment as well as low production cost [3]. However, sometimes the surface integrity of finished product in dry turning is not superior as compared to wet turning. The concept of surface textures, environmental friendly cutting fluids, minimal quantity cutting fluid and nanofluids in turning seems to be a better alternative to conventional dry and wet turning.

**Surface textured cutting tools**

Surface texturing refers to the modification in topography of surface to improve tribological performance between sliding pairs. It has been reported that friction and wear results in an economic cost of 5% of GDP of developed countries. Researchers have found that surface texturing can help to improve load carrying capacity and better lubrication. Moreover, the surface modifications have been found to decrease wear and friction in piston rings, piston pins and hydrodynamic bearings. Recently, surface texturing has also been used in cutting tools [4]. In order to provide lubrication to inaccessible area of tool chip contact zone and to decrease contact length of chip on tool, the research has been focused on development of micro and nano textured cutting inserts to have cleaner production with less carbon footprints [5].

**Environmental friendly cutting fluids**

Availability of mineral based oils is limited as they are finite source and decreasing steadily, whereas vegetable based cutting fluids are sustainable. Literature studies about machining using vegetable based cutting fluids are limited. Vegetable oils are evolving as metal cutting fluids due to its higher biodegradability and ability to minimize the waste treatment costs. It also reduces the health risks to operators, which are quiet common with petroleum based mineral oils due to their lower toxicity [6]. Cleaner and healthier work environment having less mist in the air is main point. For above mentioned reasons, vegetable oils as cutting fluids are environmentally friendly. Furthermore, they are also better lubricant as compared to others. Above all, they are extracted from renewable sources and thus unlimited and sustainable.

All these factors have pushed the industries, research centers and universities for studying the process in detail and come up with better optimal solution. Several of them have proposed various methods for reducing the exposures of cutting fluids while some have advised in changing its composition [7, 8]. Huge quantities of cutting fluids are still in use in the industries releasing harmful gases into the atmosphere, causing numerous skin and respiratory diseases in the workers and increasing disposal costs [9]. Thus, a research study has been conducted to analyze the vegetable oils that act as an environment friendly cutting fluid, so that the industries can find alternative answers and use protective measures.

**Minimum quantity cutting fluids**

Near-dry machining (NDM) or minimum quantity lubrication (MQL), also known as minimum quantity cutting fluid (MQCF), is an alternative solution for reducing detrimental environmental effects and improving machining performance [10]. In MQCF applications, a minute amount of cutting fluid is used at a flow rate of 5–500 mL/h. A cutting fluid with a high convective heat transfer coefficient is mixed with compressed air to form a uniform atomised mist. This generated mist is injected directly into the tool-chip interface in the machining region [11]. MQCF reduces occupational hazards, addresses environmental issues and produces economic benefits by reducing cutting fluid costs. MQCF is an accepted environment friendly machining method that can improve workpiece surface finish and reduce tool wear as well as cutting forces relative to dry machining [12].

**Nano-cutting fluids**

Minimum quantity cutting fluids (MQCF) is an alternative for dry machining and flood cooling. However, use of MQCF is limited to mild machining conditions due to high heat generation during machining of hard materials. The applicability of MQCF can be extended in aggressive machining conditions by using vegetable-based cutting fluids with nanoparticles as potential additives. A colloidal mixture of nanometer-sized metallic and non-metallic particles in conventional cutting fluid is called nanofluid. Nanofluids are considered to be potential heat transfer fluids because of their superior thermal and tribological properties [13].

A new class of cutting fluids can be synthesized by mixing metallic, non-metallic, ceramics, or carbon nanoparticles in a conventional cutting fluid because as compared with suspended milli- or micro-sized particles, nanofluids show better stability, rheological properties, extremely good thermal conductivity and no negative effect on pressure drop [14].

Moreover, the combination of above processes make machining more sustainable by reducing negative environmental affects, associated costs and enhancing operators safety. Furthermore, it also enhances machining performance and final workpiece surface finish.

**Gaps in the literature**

Based on the literature survey on dry machining, environmental friendly cutting fluids, minimum quantity cutting fluids and nano-cutting fluids in various fields, major research gaps are as follows:

1. Almost in all previous studies, surface textures are fabricated using thermal based texturing methods. However, thermal-based texturing methods have various drawbacks such as heat affected zone of textures, recast layers, inferior qualities of textures that causes more abrasive wear.
2. Not much attention is paid on optimizing area density of textures (number of textures per unit area) between sliding surfaces.
3. The researchers have followed trial and discovery approach in the development of textured pattern, but the effectiveness of such pattern may be increased by ensuring less contact area between chip and tool rake surface. Detailed comparison between micro-indent and micro-channel textures needs to be studied in depth.
4. The focus on cutting fluids has shifted from only machining performance to environmental friendliness and its biodegradability over the years in order to protect our precious environment. Extensive comparative analysis of thermal, rheological, biodegradation, storage stability and anti-corrosion property of mineral oil, bio-cutting fluid and vegetable-based green cutting fluids still needs to be done.
5. MQCF techniques have existed since the past decade; however, the effectiveness of its input parameters has not been discussed. The efficiency of an MQCF system depends upon mist (mixture of pressurised air and cutting fluid) formation and quality, which are controlled by the MQCF input parameters namely, emulsion composition, stand-off distance between the nozzle and machining zone, nozzle spraying angle, and air pressure.

No clear guidelines have been proposed by researchers for selecting or optimising these parameters.

6. Nanofluids have existed since the past decade; however, most of the research is carried out with metallic or ceramic nanoparticles, which are too costly. Solid lubricants based nano cutting fluids are not given much attention. Due to low cost and outstanding properties of solid lubricants, they have enormous potential to be an innovative, effective alternative to metallic or ceramic nanoparticles for nano cutting fluid applications.
7. Hybridization of surface textured cutting tool, environmental friendly cutting fluid and minimum quantity nano cutting fluid has not been attempted till now.

**Motivation and objectives of the present work**

As per the literature it is known that mineral oil based cutting fluids have various disadvantages. The main motivation of this thesis is to make machining more sustainable for the environment, economic and social benefits. It can be achieved by elimination or minimization of cutting fluid usage, shifting towards highly biodegradable and environmental friendly cutting fluids and optimized use of nano cutting fluids. Furthermore, hybridization of all above process makes machining more sustainable. The main objectives of the present work are as follows:

1. Fabricating micro-textures using mechanical conventional method such as Vickers hardness tester and scratch tester to avoid various disadvantages of thermal based surface texturing.
2. To optimize the area density of textures (number of textures per unit area) between sliding surfaces.
3. To compare machining performance of micro-indent and micro-channel textured cutting tool.
4. To compare thermal, rheological, biodegradation, storage stability and anti-corrosion property of mineral oil, bio-cutting fluid and in-house developed vegetable based green cutting fluids.
5. To optimize the MQCF input parameters such as emulsion composition, stand-off distance between the nozzle and machining zone, nozzle spraying angle as well as to compare hard machining performance using MO, BCF and GCF.

6. To develop the solid lubricant based nano cutting fluids and to study its dispersion, dynamic viscosity, thermal conductivity, volumetric specific heat, wettability and hard machining performance.
7. To combine four different individual sustainable machining techniques to create hybrid and advanced sustainable process for making machining more sustainable:

- Textured tools (economical and conserve energy)
- Green cutting fluids (minimize negative environmental impact and ensure safety to employees and consumers)
- Minimum quantity cutting fluids (minimize cutting fluid usage and minimize negative environmental impact)
- Nano cutting fluids (to enhance hard machining performance and conserve energy)

**Work carried out in the thesis**

To achieve the above stated objectives, mechanical micro-textures were fabricated on the surface of plasma nitride high speed steel (HSS) cylindrical pins using Vicker hardness tester with varying texture area density. Afterwards, these mechanical micro-textured HSS pins were coated with molybdenum disulphide ($MoS_2$). Friction and wear tests were carried out with the help of pin-on-disc tribometer (Make: Ducom®, Model: TR-201) and texture area density were optimized experimentally. Result shows that $MoS_2$ coated 10% texture area density pin perform best among all in terms of coefficient of friction, surface temperature, wear and wear rate.

Optimized area density mechanical micro-textures were fabricated on the HSS cutting tool rake face. Afterwards, textured cutting tools rake faces were coated with $MoS_2$. Effect of micro-textures on the strenght of the tool were investigated using static structural finite element analysis with the help of Ansys® workbench. Plan of experiments were designed using central composite rotatable design (CCRD) method. Machining experiments were carried out with the help of lathe (Make: HMT®, Model: NH 26) for machining of AISI 1040 steel. Machining performance of untextured (UT), mechanical micro-textured (MμT) and $MoS_2$ coated mechanical micro-textured (C-MμT) cutting tools were compared in terms of cutting force, feed force, tool-chip interface coefficient of friction and workpiece surface roughness. Analysis of variance (ANOVA) was done for finding the percentage contribution of each input parameter on the output response. Finite element analysis shows that stresses generation for MμT cutting tools are higher as compared to UT tools, however, stresses are well within the bearing capacity of cutting tool. Experimental result shows that C-MµT performance best among all in terms of tool-chip interface temperature, cutting force, feed force, tool-chip interface coefficient of friction and workpiece surface roughness.

Three different geometric MµT were fabricated on the tungsten carbide cutting tool rake face using Vicker hardness tester and scratch tester (Make: Ducom®, Model: TR-101). Afterwards, these cutting tools were coated with $MoS_2$. Comparative hard machining studies of six different types of cutting tool were carried out with the help of lathe for machining of AISI H-13 steel. For reference, experiments were also carried out using UT cutting tools. Surface morphology of cutting tools rake faces were investigated with the help of optical microscope (Make: Zeiss®, Model: AxioCAM MRc) and field emission scanning electron microscope (Make: Zeiss®, Model: Sigma). Result shows that $MoS_2$ coated perpendicular mechanical micro-textured cutting tool performs best among all.

Environmental friendly green cutting fluid (GCF) was synthesized with mixtures of various vegetable oils and emulsifiers using magnetic stirrer (Make: Abdos®, Model: MS-H280-Pro). Cutting fluids thermal stability and rheological properties were tested using thermal gravimetric analyzer (Make: NETZCH instruments®, Model: STA F4913) and rheometer (Make: Anton Paar®, Model: MCR-101). Cutting fluids biodegradation, anti-corrosion and storage stability tests were performed in accordance with *Standard Method 2005*, ASTM D 4627 and ASTM D 3707, respectively. For comparison, all tests were also carried out with commercial petroleum based mineral oil (MO) and commercial eco-friendly bio-cutting fluid (BCF). Result shows that GCF shows better biodegradability, thermally stability, high viscosity, anti-corrosion property and storage stability as compared to BCF and MO.

Minimum quantity cutting fluid (MQCF) setup was fabricated. Input parameters such as cutting fluid emulsion concentration was optimized using thermal property analyzer (Make: KD2 Pro thermal property analyzer). MQCF input parameters such as nozzle stand-off distance, area coverage of spray and nozzle angle position were experimentally optimized using in-house fabricated MQCF setup. Afterwards, hard machining experiments were carried out during machining of AISI H-13 steel using MO, BCF and GCF with MQCF setup and their machining performance was compared. 1:16 emulsion concentration, 30 mm nozzle stand-off distance and 45° nozzle angular position was selected as optimized MQCF parameters.

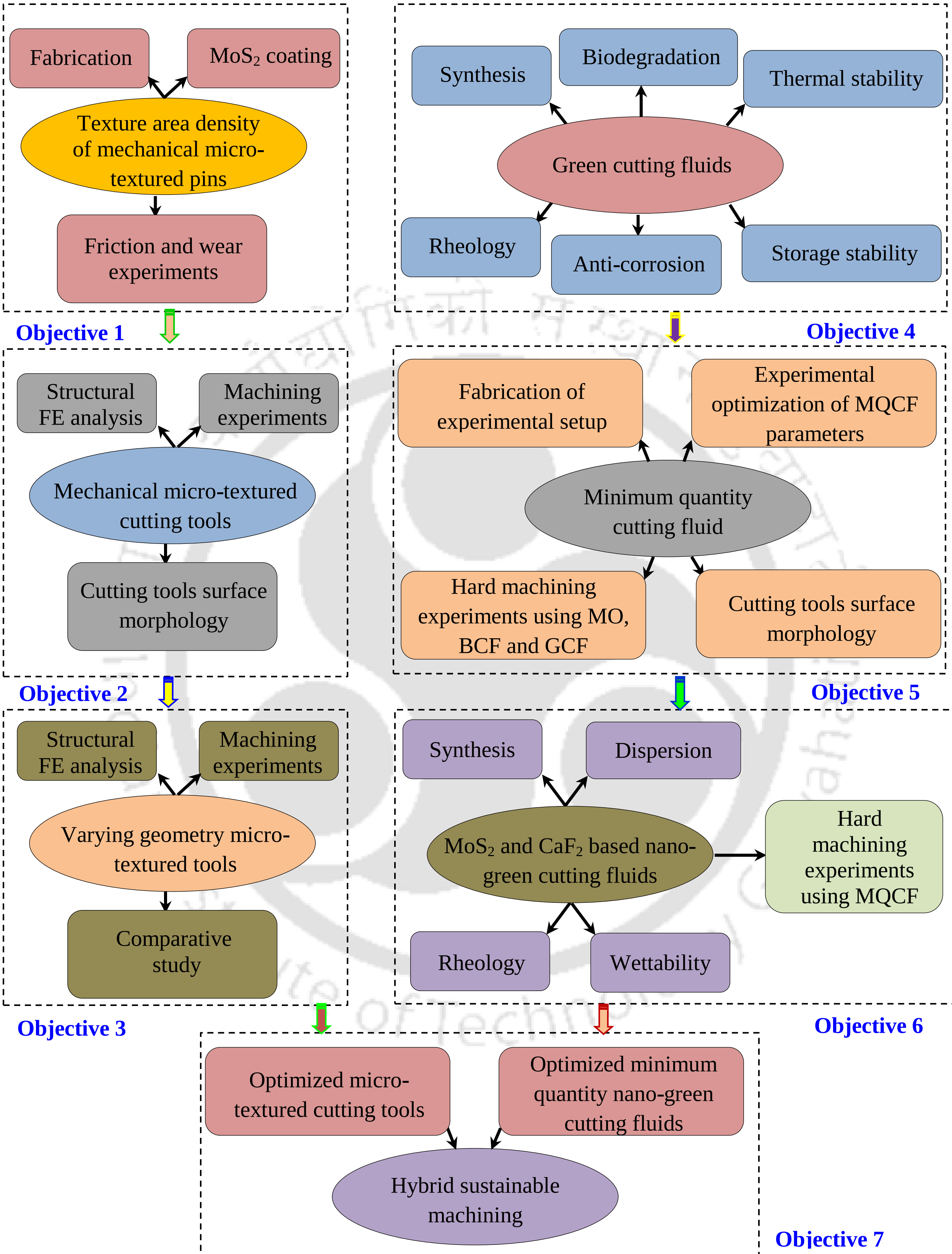


**Figure 1.** Plan of work carried out in this thesis

Five varying concentration of each calcium fluoride ($CaF_2$) and $MoS_2$ based nano-green cutting fluids (nano-GCF) were developed using ultra sonication (Make: Buehler®, Model: 75-2003-220) and magnetic stirrer. Thermal and rheological of $CaF_2$ and $MoS_2$ nano-GCF (5 varying concentration each) were carried out and compared with MO and BCF. Contact angle of cutting various nano-GCF were measured using goniometer (Make: Holmarc®, India, Model: HO-IAD-CAM-01B) for wettability test. Afterwards, hard machining experiments were carried out during machining of AISI H-13 steel using MO, BCF and optimized concentration of both $CaF_2$ and $MoS_2$ based nano-GCF with in-house fabricated MQCF setup and their machining performance was compared. Result shows that 0.3% concentration of $MoS_2$ based nano-GCF reduces the tool-chip interface coefficient of friction by 11.01 % as compared with MO.

At last, hard machining experiments were carried out using combination of MμT cutting tool with environment friendly nano-GCF using MQCF technique during machining of AISI H-13 steel to make hard machining more sustainable by reducing detrimental environmental impact and improving machining performance. Result shows that hybridization of mechanical micro-textured cutting tools with minimum quantity nano-GCF reduces the tool-chip interface coefficient of friction by 39.61% as compared with DM. Figure 1 show the plan of work carried out in this thesis.

**Organization of the thesis**

Current thesis is organized into 9 chapters with references and appendices at the end.

- **Chapter 1** discusses the need of elimination or minimization of conventional cutting fluids in machining processes. A brief literature review of the dry machining, environmental friendly cutting fluids, near dry machining and nano cutting fluids are also discussed. Finally, gaps in the literature, different challenging issues, scope and detailed objectives of the present thesis are described.
- **Chapter 2** includes discussion about fabrication of mechanical micro-textures on the surface of the high speed steel pin with varying area density. Tribological performance of $MoS_2$ coated mechanical micro-textured cutting tools during dry sliding test are investigated. Area density of textures (number of textures per unit area) between sliding surfaces are also optimized.

- **Chapter 3** presents preliminary experimentation to find area for texturing on the rake face of the tool. Afterwards, mechanical micro-textures are fabricated on the rake face of the tool. In order to check the effect of micro-textures on the strength of the tool, static structural finite element analysis is done in the Ansys® workbench. Later, comparative study of machining performance with un-textured, mechanical micro-textured and $MoS_2$ coated mechanical micro-textured high speed steel cutting tools are carried out.
- **Chapter 4** deals with the comparative study of hard machining with various mechanical micro-textured and $MoS_2$ coated mechanical micro-textured tungsten carbide cutting tools. Six different uncoated and $MoS_2$ coated mechanical micro-textures are fabricated and their hard machining performance is compared. For comparision, machining is also carried out using conventional cutting tool.
- In **Chapter 5**, environmental friendly green cutting fluid was developed using mixture of various vegetable oils and emulsifiers. Afterwards, biodegradation, thermal, rheological, storage stability and anti-corrosion properties of in-house developed green cutting fluids are compared with commercial bio cutting fluid and mineral oil.
- **Chapter 6** discusses the development of minimum quantity cutting fluid setup. The MQCF input parameters such as emulsion composition, stand-off distance between the nozzle and machining zone as well as nozzle spraying angle are optimized experimentally. Afterwards, using optimized input parameters, hard machining performance of MO, BCF and GCF with MQCF technique are compared.
- In **Chapter 7**, $MoS_2$ and $CaF_2$ based nano-green cutting fluids with varying concentration are developed. The effect of the nano-solid lubricant ($MoS_2$ nanoplatelet and $CaF_2$ nanoparticles) enhanced cutting fluids are studied by conducting absorbance tests, dynamic viscosity test, thermal conductivity test, volumetric specific heat test and wettability test. Afterwards, hard machining experiments are carried out to evaluate the performance of nano-solid lubricant enhanced GCF using MQCF technique.
- **Chapter 8** deals with the hybridization of above four individual sustainable machining processes. For hard machining, combination of mechanical-micro-textured cutting tool with in-house fabricated minimum quantity cutting fluid using in-house developed nano-green cutting fluid is used.

- **Chapter 9** represents the main findings of the present work, important conclusions and future scope in the field of sustainable machining. The outcome of the present work in the form of various journal papers, book chapter and conferences is reported.

  References and appendices are included at the last.

**Major outcomes**

In the present work, sustainable machining experiments using mechanical micro-textured cutting tools, environmental friendly cutting fluids, minimum quantity cutting fluids and nano-green cutting fluids were carried out. The major contribution and findings of current work are summarized as follows:

1. Coefficient of friction between $MoS_2$ coated textured pins with 10% texture area density was reduced by 51.37% and 53.33% as compared to UT pins under 19.6 N and 49 N loads, respectively.
2. $MoS_2$ filled pins with 10% texture area density showed the best tribological performance amongst all investigated samples.
3. Finite element analysis show that von-Mises stress generation at the cutting edge of UT and MμT cutting tool are in safe limits. Also, the presence of the mechanical micro-textures on the tool rake face had very less influence on the mechanical strength of the cutting tool.
4. Tool-chip interface temperature, machining forces and tool-chip interface coefficient of friction were reduced significantly for MμT and C-MμT as compared to UT cutting tools.
5. $MoS_2$ coated perpendicular mechanical mirco-textured cutting tool (PDT-M) perform best in terms of reducing tool-chip interface temperature, machining forces and tool-chip interface COF.
6. The improvements in machining performance of uncoated MμT cutting tools are due to reduced contact length and during machining with $MoS_2$ coated MμT cutting tools, the formation of a self-lubricating film of $MoS_2$ reduces friction, thus enhancing its machining performance.
7. As per *Standard methods 2005*, ultimate biodegradability of GCF, BCF and MO is found to be 98.27%, 96.67% and 18.32%, respectively.
8. GCF showed corrosion breakpoint of 4; whereas BCF and MO exhibit corrosion breakpoint of 8 and 9 as per ASTM D 4627 standard.

9. As per ASTM D 3707 standard, GCF shows more remaining emulsion as compared to BCF and MO after storage stability test.
10. The BCF emulsion performed better than MO and GCF, in terms of its higher thermal conductivity, high specific heat, and better ability to penetrate the chip-tool interface.
11. Sticking and sliding zones were reduced in the case of MQCF machining. The BCF emulsion performed better than the MO and GCF emulsion in this regard.
12. Nano-green cutting fluid with 0.3% concentration of $MoS_2$ nanoplatelets (GCF-0.3M) reduced the tool-chip interface coefficient of friction by 11.01 %, 4.36 % and 2.38 % as compared with MO, GCF and nano-green cutting fluid with 0.3% concentration of $CaF_2$ (GCF-0.3C), respectively.
13. Hard machining using hybrid mechanical micro-textured cutting tools and minimum quantity nano-green cutting fluids reduced the tool-chip interface coefficient of friction by 39.61% as compared with DM.

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**List of publications from thesis work**

**International Journals: Published and Accepted**

1. **Kishor Kumar Gajrani,** Somapalli Suresh, Mamilla Ravi Sankar, 2018, **"Environmental friendly hard machining performance of uncoated and $MoS_2$ coated mechanical micro-textured tungsten carbide cutting tools",** Tribology International, Vol. 125, pp. 141−155. (**DOI**: 10.1016/j.triboint.2018.04.031**).**
2. **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, Uday Shanker Dixit, 2018, "**Tribological performance of $MoS_2$-filled microtextured cutting tools during dry sliding test",** ASME Journal of Tribology, Vol. 140(2), pp. 021301 (1−11). (**DOI**: 10.15/1.4037354).
3. **Kishor Kumar Gajrani**, Rokkham Pavan Kumar Reddy, Mamilla Ravi Sankar, 2018, **"Tribo-mechanical, surface morphological comparison of un-textured, mechanical micro-textured (MµT) and coated-MµT cutting tools during machining",** Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, **(DOI:** 10.1177/1350650118764975).
4. **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, Uday Shanker Dixit, 2018, "**Environmentally friendly machining with $MOS_2$ filled mechanically micro-textured cutting tools",** Journal of Mechanical Science and Technology, Vol. 32(8), pp. 3797−3805. (**DOI:** 10.1007/s12206-018-0732-5).
5. **Kishor Kumar Gajrani**, Dhanna Ram, Mamilla Ravi Sankar, 2017, "**Biodegradation and hard machining performance comparison of eco-friendly cutting fluid and mineral oil using flood cooling and minimum quantity cutting fluid techniques",** Journal of Cleaner Production, Vol. 165(C), pp. 1420−1435. (**DOI**: 10.1016/j.jclepro.2017.07.217).
6. **Kishor Kumar Gajrani**, Dhanna Ram, Mamilla Ravi Sankar, Uday Shanker Dixit, P. S. Suvin, Satish Vasu Kailas, 2017, **"Machining of hardened AISI H-13 steel using minimum quantity eco-friendly cutting fluid",** International Journal of Additive and Subtractive Materials Manufacturing, Vol. 1 (3/4), pp. 240−256. (**DOI**: 10.1504/IJASMM.2017.10010905).
7. **Kishor Kumar Gajrani**, Rokkham Pavan Kumar Reddy, Mamilla Ravi Sankar, 2016, **"Experimental comparative study of conventional, micro-textured and coated micro-textured tools during machining of hardened AISI 1040 alloy steel",** International Journal of Machining and Machinability of Materials, Vol. 18(5/6), pp. 522−539. (**DOI**: 10.1504/IJMMM.2016.078982).

## International Journals: Under review/Under preperation

**8.** **Kishor Kumar Gajrani**, P. S. Suvin, Satish Vasu Kailas, Mamilla Ravi Sankar, 2018, **"Hard machining performance of indigenously developed green cutting fluid using flood cooling and minimum quantity cutting fluid",** Journal of Cleaner Production, (2nd minor revision submitted on 10th September 2018).

9. **Kishor Kumar Gajrani**, P. S. Suvin, Satish Vasu Kailas, Mamilla Ravi Sankar, 2018, **"Thermal, rheological, wettability and hard machining performance of $MoS_2$ and $CaF_2$ based minimum quantity hybrid nano-green cutting fluids",** ASME Journal of Manufacturing Science and Engineering (Under review).

10. **Kishor Kumar Gajrani**, P. S. Suvin, Satish Vasu Kailas, Mamilla Ravi Sankar, 2018, **"Environmentally friendly hard machining performance using hybridization of mechanical micro-textured cutting tool with minimum quantity nano-green cutting fluids "** (Under preparation).

## International Procedia Journals: Published

**11.** **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, 2017, **"State of the art on micro to nano textured cutting tools",** Materials Today: Proceedings, Vol. 4(2A), pp. 3776−3785. (**DOI**: 10.1016/j.matpr.2017.02.274).

**12.** **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, 2017, **"Past and current status of eco-friendly vegetable oil based metal cutting fluids",** Materials Today: Proceedings, Vol. 4(2A), pp. 3786−3795. (**DOI**: 10.1016/j.matpr.2017.02.275).

## Book Chapters: Published

13. **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, 2018, **"Sustainable cutting fluids: Thermal, Rheological, Biodegradation, Anti-corrosion, Storage Stability Studies and its Machining Performance",** Reference Module in Materials Science and Materials Engineering, Elsevier. (**DOI:** 10.1016/B978-0-12-813195-4.11152-X).

14. **Kishor Kumar Gajrani**, Mamilla Ravi Sankar, 2018, **"Sustainable Machining with Self-Lubricating Coated Mechanical Micro-Textured Cutting Tools",** Reference Module in Materials Science and Materials Engineering, Elsevier. (**DOI:** 10.1016/B978-0-12-803581-8.11325-6).

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2. **Kishor Kumar Gajrani,** Mamilla Ravi Sankar **"Cutting Fluid Emissions in Mechanical Machining and its Adverse Effects on Biodiversity"** 21ST ADNAT Convention and International Symposium on Biodiversity and Biobanking (BIODIVERSE 2018), 27−29 January, 2018, IIT Guwahati, India.

3. **Kishor Kumar Gajrani**, Subrat Kumar Mallick, Mamilla Ravi Sankar, **"Comparative Studies on Mineral Oil, Eco Friendly Bio-Cutting Fluids Treatment and their Machining Performance"** Proceedings of the National Conference on Sustainable

Mechanical Engineering: Today and Beyond (SMETB), March 25−26, 2017 at Tezpur University, India, pp. 111−116, 2017 (**BEST PAPER AWARD**).

4. Mamilla Ravi Sankar, **Kishor Kumar Gajrani**, **"Cutting Fluid Emissions and Eco-Friendly Cutting Fluid for Sustainable Machining"** Proceedings of the National Conference on Sustainable Mechanical Engineering: Today and Beyond (SMETB), March 25−26, 2017 at Tezpur University, India, pp. 157−162, 2017.
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