

**FABRICATION OF A BORING BAR WITH AN INBUILT
MQL SYSTEM FOR SUSTAINABLE AND CHATTER FREE
BORING**

Thesis Submitted For the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Mechanical engineering

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2022**

DECLARATION

I, hereby declared that the presented work in the thesis entitled “**Fabrication of a boring bar with an inbuilt MQL system for sustainable and chatter free boring**” in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of Dr. Amardeep Singh Kang, working as Associate Professor, in the School of Mechanical engineering, Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.



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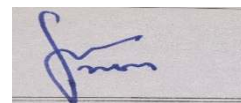
CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled “**Fabrication of a boring bar with an inbuilt MQL system for sustainable and chatter free boring**” submitted in fulfillment of the requirement for the reward of degree of **Doctor of Philosophy (Ph.D.)** in the mechanical engineering, is a research work carried out by Kamal Hassan, 41700227, is bonafide record of his/her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.



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LIST OF ABBREVIATIONS & SYMBOLS

BHN	Brinell hardness number
SAE	Society of automotive engineers
PCD	Polycrystalline diamond
TiN	Titanium nitride
TiCN	Titanium carbo-nitride
CVD	Chemical vapor deposition
EP	Extreme pressure additives
MQL	Minimum quantity lubrication
MRF	Magnetorheological fluid
DC	Direct current
L/D	Length to diameter
PID	Particle impact damping
AISI	American iron and steel institute
SMA	Shape memory alloys
CNC	Computer numeric control
VSVDA	Variable stiffness dynamic vibration absorber
ERF	Electrorheological fluid
MWF	Metal working fluid
EDAX	Energy dispersive analysis through X-ray
SEM	Scanning electron microscope
XRD	X-ray diffraction
GHG	Greenhouse gas emission
PZT	Piezoelectric transducer
IEPE	Integrated electronics piezoelectric
RLC	Resistor inductor capacitor
S/N ratio	Signal-to-noise ratio
OA	Orthogonal array

RoW	Rest of world
GLO	Global
LICA	Life cycle inventory analysis
WCAE	Water consumption, Aquatic ecosystems
GWFE	Global warming, Freshwater ecosystems
MEPH	Marine eutrophication
TET	Terrestrial ecotoxicity
MEET	Marine ecotoxicity
WCTE	Water consumption, Terrestrial ecosystem
FET	Freshwater ecotoxicity
SOD	Stratospheric ozone depletion
LU	Land use
IR	Ionizing radiation
FEP	Freshwater eutrophication
OFTE	Ozone formation, Terrestrial ecosystems
TAD	Terrestrial acidification
OFHH	Ozone formation, Human health
GWTE	Global warming, Terrestrial ecosystems
WCHH	Water consumption, Human health
HNCI	Human non-carcinogenic toxicity
HCCT	Human carcinogenic toxicity
GWHH	Global warming, Human health
FPMF	Fine particulate matter formation
MRS	Mineral resource scarcity
FRS	Fossil resource scarcity
°C	Degree centigrade
m/min	meters per minute
mm/rev	millimeters per revolution
ml/h	milliliters per hour

μm	Microns
R_a	Average surface roughness
V_b	Tool wear
C_m	Coolant medium

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ABSTRACT

Machining is one of the primary operations in production, and because long and narrow boring bars are typically required to undertake inside machining of workpieces, vibration is a significant issue in internal turning operations. Internal turning tool vibration regularly degrades surface quality, tool life, and production efficiency while also causing severe environmental concerns such as excessive noise levels. A lathe machine was equipped with all the essential components to perform the internal turning operations required to measure the requisite output characteristics such as surface roughness and vibrational amplitude.

Cutting tests were performed by selecting vibration amplitude and average surface roughness as response parameters, and machining characteristics were evaluated by piezoelectric shunt dynamic response. It was experimentally concluded that, compared to the no damping condition, mean vibrational amplitude and surface roughness decreases considerably using piezoelectric damping. Grey relational methodology has been utilized for multi-attribute decision-making to depict the optimal boring parameters.

The growing demands for high machining productivity require high cutting velocity and feed rate. Such machining inherently produces a high cutting temperature, which not only reduces tool life but also impairs the product quality. Metal cutting fluids change the performance of machining operations because of their lubrication, cooling, and chip flushing functions, but the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. The minimization of cutting fluid also leads to economic benefits by saving lubricant costs and workpiece/tool/machine cleaning cycle time. The concept of minimum quantity lubrication (MQL) was suggested a decade ago to address the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors.

This novel work also investigates the internal turning of aluminium alloy using three cutting environments, i.e. dry, flood, and minimum quantity lubrication. The effect of variable machining parameters and cooling media drives the surface quality and tool

effectiveness. The in-house fabricated experimental setup was used for the machining trials. A specially designed mist nozzle produces an aerosol used for sustainable machining. Shiny chips and improved surface finish are achieved during near-dry machining, even at higher feeds. The presented method's usefulness is attributed to high levels of association among conceptual, empirical, and literature survey results. The mist produced by supplying aerosol internally through a boring bar proved an effective technique for better surface integrity than conventional and flood lubrication. Machining productivity increases significantly with an improved surface characteristic and less tool wear.

One of the issues confronting manufacturers is the requirement for establishing sustainable production methods, which poise between economic feasibility and ecological preservation. Alternative sustainable cutting fluid methods must be developed since the traditional lubricants employed in machining operations are unsustainable from the environmental impact point of view.

This work deals with the sustainable assessment of machining performance under different cutting conditions through life cycle assessment. The inventories used during the experimentation are given as input for life cycle inventory analysis (LCIA) and its environmental impacts studied by the assessment techniques on SimaPro 8.0.1 software. Gate-to-gate approach methodology adopted for life cycle assessment of selected functional unit to investigate the ecological impact using ReCipe 2016, Endpoint (H) method. Life cycle analysis results depict that dry machining outperforms flood and MQL machining in terms of sustainability in terms of global warming, freshwater ecosystems, water usage, and human health. Flood machining contributes more toward ecosystem and resources than dry and MQL machining. And in water consumption, aquatic ecosystems, marine ecotoxicity, stratospheric ozone depletion and land use, flood machining dominates more than dry and MQL cutting conditions.

CHAPTER 1

INTRODUCTION

Current engineering and technical applications require lightweight materials with increased strength and toughness, good machinability, and excellent component surface finishes. It is challenging to obtain such a rare combination of qualities in metallic alloys. Aluminium alloys can offer a high strength-to-weight ratio and better machinability. When compared to pure metal, combining alloying elements, including iron, copper, magnesium, silicon, and zinc, improves strength, formability, and good electric conductivity. Various aluminium alloys have fabricated numerous technical components with enhanced physical, chemical, mechanical, thermal, and electrical properties. This material holds vast applications in multiple industries, including automotive, marine and aerospace, electrical and electronics, sports, and entertainment. With recent advancements in aerospace and marine applications, lightweight materials are an obvious choice ([Yerokhin and Khan, 2010](#)). Aluminium alloys offer better corrosion and moisture resistance than other metals and composites. Due to this, these are used frequently in automotive applications for weight reduction and fuel economy.

Industrial application requires precise dimensional accuracy, low operating cost, and good surface quality. Many production techniques have been utilized for the last decades to generate quality surfaces; machining is one of the basic operations. Aluminium alloys have an excellent machinability rating due to alloying elements such as silicon and magnesium. However, the generation of a good surface depends on the composition of the workpiece, cutting tool signature, cutting environment, and machine tool accuracy. Their optimum combination gives good surface quality, high tool life, and more product life cycle ([Kah et al., 2016](#)). In low and moderate-speed machining, aluminium alloy gives excellent machinability, higher surface finish, and reduced tool wear than other key engineering materials such as steel, cast iron, titanium, etc. Due to less strength, it is not suitable for high-speed machining

The machining process involves using various rotary and reciprocating parts for product manufacturing. Misalignments and faulty operations can decrease surface quality and severely damage the cutting tool or machine components. It generally arises due to the lack of dynamic stiffness in the machine tool, cutting tool, and workpiece in almost every machining operation. Free, forced, and self-excited vibrations in the machining process should be less to achieve higher productivity, good dimensional accuracy, and long tool life. Over the last four decades, various researchers have done extensive work on reducing vibration for better production output. Continuous monitoring and recording of the signals from the machining or use of specific particle dampers and electric field-driven fluid boring bars are the main techniques for chatter reduction in a machining process ([Quintana and Ciurana, 2011](#)).

From the pertinent literature review, active vibration control is an effective technique for continuous chatter detection in a machining process which helps in rapid changes in the tuning process for an unstable operation without altering the configurations of the tool, tool holder, and machining system ([Gyebrószki et al., 2018](#)). In the present research, the active vibration control technique has continuously monitored chatter detection and damping through a damping device. An RLC circuit with a piezoelectric transducer was attached to a boring bar to dampen the vibration-induced during machining at selected cutting conditions. Machining trials revealed that vibration and surface roughness decrease significantly under the effect of piezoelectric shunt damping.

Adequate tool geometry, cutting conditions, and effective lubrication can significantly decrease vibrations in machining. Numerous techniques for machining a surface are developed and widely explored by many researchers. Dry machining is the oldest method, where material removal takes place with a cutting tool without using coolant/lubricant. Less utilization of resources and energy reduces the overall production cost and is favorable for environmental protection ([Goindi and Sarkar, 2017](#)). However, the machining productivity is slightly lower than lubricant machining due to limitations in heat removal, tool damage, and high production time ([Brinksmeier et al., 2015](#); [Grzesik](#)

and Zalisz, 2008; Gupta et al., 2018; Olufayo et al., 2021; Xu et al., 2009). These limitations lead to a shift to lubricant machining for improved machining productivity

Machining performance increases with the use of cutting fluids. Cutting fluids can lower temperatures on the workpiece, chip, and cutting tool surface by reducing gathered heat across cutting regimes. Appropriate cutting fluid selection is crucial as it greatly affects the machining performance. The choice of lubricant depends upon the machining process types, tool-work material, and cutting conditions (Brinksmeier et al., 1999). Cutting fluids cover almost all engineering materials, such as carbon steel, alloy steel, stainless steel, aluminium, titanium, composites, etc. The effectiveness of cutting fluids depends upon the mode of delivery in the machining zone. Conventional cooling utilizes a large amount of continuous lubricant supply during machining for cutting temperature decrement and less machining energy (Isik, 2016). Cryogenic cooling uses liquid nitrogen or carbon dioxide gases for machining a surface at low temperatures. Also, it gives promising texture and tool quality results during the machining of hard materials. However, complex nozzle design and intricate delivery channels sometimes make fluid unreachable in the machining zone.

Industrial wastes in these lubrication techniques enhance air-water contamination and exposure to operators to various respiratory diseases and hazardous working conditions. Air and near-dry machining offer better outcomes and less energy consumption. Air cooling requires a heat transfer mechanism to lower the workpiece's initial temperature or supply of chilled air into the cutting regime. Higher initial cost and more component usage limit its application. Near dry gives substantial machining performance (Gupta et al., 2017), covers almost each engineering material and has been more widely explored in the last decades than rest techniques. Due to less resource consumption, it offers clean machining. Less coolant usage reduces the production cost and avoids the operator's exposure to fatal diseases. It utilizes a mist for cooling and lubrication and considerably reduces cutting forces, stresses, and temperature. Due to these, specific organizations/industries emphasize green and clean production for sustainable development. The detailed literature review shows that three different lubrication

conditions, dry, flood, and minimum quantity lubrication, are employed for machining trials on AA 6061 with an in-house fabricated setup. The outcome gives the best machining performance with MQL, followed by flood and dry machining.

In recent years, sustainable development has replaced conventional development, which is much more stimulating and recognized mainly by many nations worldwide. Proposals for clean technologies and continuous improvement for sustainable aspects will decide the future of every manufacturing industry. It must include ecological indicators, social footprint, and cost-effective production. For machining, the consequences of energy, equipment usage like tool-workpiece production, cutting fluids and machine tools, etc., require focus for sustainability purposes. Sustainable consumption and production is a holistic approach for managing wastes throughout the life cycles of products [Fig 1.1](#) by using fewer natural resources.

Life cycle analysis is a promising assessment model that uses Ecoinvent ([Kurukulasuriya et al., 2020](#)) databases to review the environmental impact of various industrial applications. It is a sustainable method for assessing environmental factors based on raw materials utilization, power consumption, and tool-workpiece usage. Its scope also includes the social and economic effects on numerous critical variables controlled by different methodologies.

For a variety of industrial applications, including energy systems ([Hertwich et al., 2015](#); [Laurent and Espinosa, 2015](#)), electric vehicles ([de Souza et al., 2018](#); [Wang et al., 2006](#)), production ([Khan et al., 2020](#)), sustainable building design building ([Ramesh et al., 2010](#)), agriculture and wastewater treatment, etc. life cycle analysis has gained widespread acceptance in recent years.

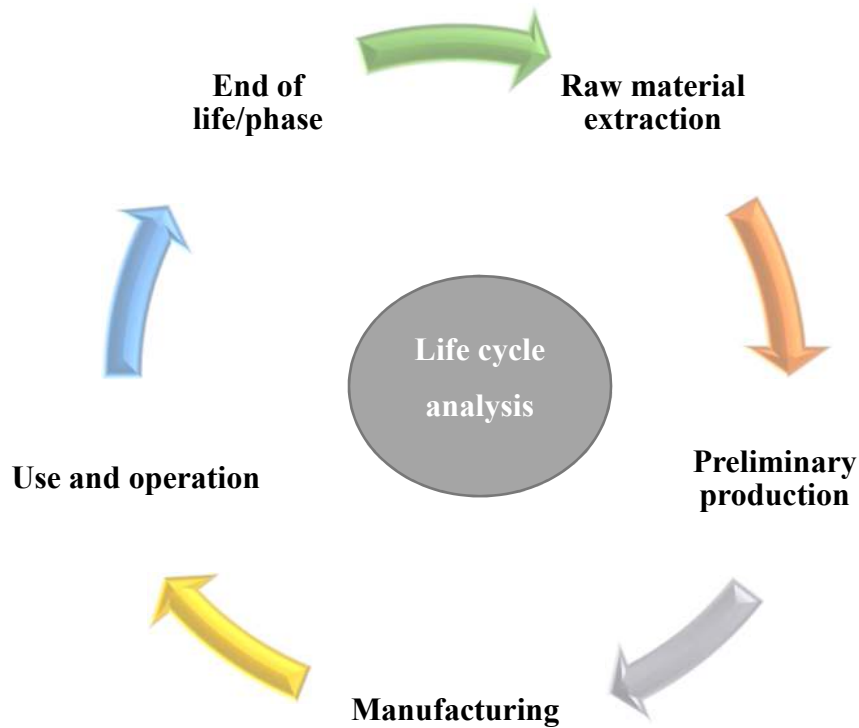


Fig 1.1 LCA components for sustainable production

The key aspects of the manufacturing and services sectors are machining processes, which further substantially promote the development of the world economy. Improved tool-workpiece materials strengthen machining performance, and eco-friendly manufacturing methods are quickly gaining popularity. Some materials, such as stainless steels, superalloys, Inconel and titanium grades, etc., will not produce the same temperature during machining. Cutting fluids can lessen it, but they are expensive and directly affect the environment. Certain cutting fluids may be carcinogenic and expose the machine operator to cancer and other skin conditions. The machining data was recorded based on cutting parameters selected from the detailed analysis of available literature under three lubricating conditions. The results showed that dry and near-dry machining was more sustainable than flood machining based upon the sustainable key indicators covering health, environment, and ecological aspects.

2.1 Introduction to the material

Aluminium is a lightweight material and exhibits good anti-corrosion properties. Adding alloying elements such as iron, copper, magnesium, silicon, and zinc improve strength, formability, and good electric conductivity compared with pure metal. Wrought, cast, and aluminium-lithium alloys are the three major classifications of aluminium alloy. Wrought alloys' property refinement depends on work hardening techniques with various annealing procedures (Davis, 2001). Their designation is 4-digit, where the first digit represents the alloy series. For example; 1xxx, 2xxx, 4xxx..... 8xxx. Class of alloy represents the percentage of the alloying element with iron as a chief constituent. Silicon and magnesium are the chief alloying constituents in the 6xxx series (Edwards and Crouch, 2017). These possess good welding, forming, and heat treatment properties. Widely used for automobile, marine, and construction applications.

Cast alloys are designated by a 3-digit number and a decimal value; placed after numbers. For example, 1xx.x, 2xx.x, 3xx.x 8xx.x is the family of cast alloys. The decimal represents the limits of cast alloys. Decimals .1 and .2 showcase ingots' compositions per the conformance of casting requirements. The initial series is pure form constituents, adding alloying elements such as copper, silicon, magnesium, and zinc. 8xx.x is the only tin alloy that may contain a small amount of tin (Vasu and Reddy, 2012).

The other aluminium alloy family contains mainly aluminium and lithium as alloying elements. It contains 0.7-3% of lithium content. It reduces the alloy density and provides a significant strength-to-weight ratio. Due to the cost constraints of lithium, it is used explicitly for aerospace applications.

Due to good mechanical properties and excellent machinability, aluminium 6061 alloy is selected for the experimental work. However, its mechanical properties depend upon heat treatment or tempering type, making it anti-corrosion even at the abraded surface. Due to heat treatment and corrosion resistance properties, it is the most widely

explored material and is suitable for almost every lightweight application, e.g., car body parts and piston sleeves ([Santos et al., 2016](#)).

2.2 Industrial applications of aluminium alloy

Careful weight optimization requires the top and side of an aeroplane during flight to encounter compressive loads. It necessitates a lightweight material, which offers a suitable strength-to-weight ratio. Due to less chemical affinity and adequate strength, aluminium alloy seems a viable option ([Starke and Staley, 2011](#)). Also, due to its lightweight properties, it can sustain high loads during loading an aircraft. With recent advancements in aerospace material application, composite decreases the use of aluminium in airframe design. However, composite offers less impact resistance, moisture captivation, and recycling constraints. Thus, for an aircraft structural design ([Aamir et al., 2020a](#)), aluminium alloys are preferred due to their established production techniques, corrosion resistance, lightweight, and reduced cost compared to other metals and composites. Al-7056 alloy is widely used for aircraft applications as they offer the highest strength among all series alloys ([Campbell, 2008](#)). 2xxx series alloys offer sound resistance against damage and crack propagation. Al-2024 alloy is suitable for fuselage construction and Al-6061 for landing mates and frames ([Verma et al., 2001](#)).

Also, Aluminium alloys are used for various automotive applications due to their higher thermal conductivity, anti-corrosion, and lightweight properties. It decreases the overall weight of an automobile, improves emissions, and gives good fuel economy ([Ramesh and Nataraj, 2020](#)). Aluminium alloys have outclassed cast iron components due to the improvement in the latest techniques in casting work-hardening procedures ([Hirsch, 2004](#)). The addition of magnesium and silicon in the aluminium gives a significant improvement in welding and joining properties. For adhesive bonding, aluminium alloys are used widely to fabricate car body structures and other vital closures. ([Cavezza et al., 2020](#)) It offers durability and moisture resistance for mechanical fastening due to good cold working ability. ([Österreicher et al., 2018](#)) investigated the paint-baked applications for Al7075 and Al 7021 alloys and experimentally proved that the former promises better

performance for automotive applications. To run the marines (Garg et al., 2019) at a higher speed, aluminium alloys are widely explored to fabricate marine components.

Recently aluminium alloy has been competing with composites as the latter has high initial and maintenance costs (Kah et al., 2016). It extends to high-strength applications such as bridge decks, seismic protection (Dokšanović et al., 2017), large roof spans, and intricate structures. Aluminium alloys exhibit excellent recycling characteristics, making them low-cost raw materials for various manufacturing processes.

The drawbacks of low strength of various high-end applications get improved with the addition of nano-particles. Recycling aluminium alloys is less expensive due to less production cost manufactured through low-energy electrolysis (Kuchariková et al., 2016) and environmental effects depend upon the level of alloy composition (Paraskevas et al., 2015). Scrap selection is controlled by molten metal's chemical composition, which evaluates different melting outcomes to assess the desired recyclability. Salt slag restoration with ambient air generates pleasant odours (Xiao et al., 2005) and less production of toxic ammonia resulting in a high-quality product, environment protection, and good human health.

Generally, aluminium alloys are used for various structural and non-structural applications, like armaments, cladding, door window fittings, and electronic components (Mazzolani, 2004). 6xxx alloys are preferred for manufacturing defence vehicles and the fabrication of artillery (Gopi and Mohan, 2021). Al 5052 produces high-strength micro-welds with the addition of silica carbide particles in the explosive cladding (Saravanan et al., 2019). Due to the lightweight applications of aluminium alloys, it is more suitable for rehabilitating ancient buildings and bridges as it helps in the variable transfer of loads.

Pure aluminium can benefit from passive seismic protection due to its lower-yielding and high ductility. Due to plastic deformation, it can dissipate seismic energy. Aluminium alloys give significant results in shear panels compared to other metal panels (Mazzolani, 2004). This alloy is most favorable for structures in chemically active environment or exposure to extreme temperature situations. It offers less brittleness in such cases in comparison to steel (Dokšanović et al., 2017).

2.3 Benefits of aluminium alloy in comparison with other lightweight metals

Lightweight materials reduce fuel consumption, but other costs are associated with manufacturing and recycling these materials. Some lightweight materials (Fig 2.1) are already used for various industrial applications as they offer a higher strength-to-weight ratio (Luis and Moncayo, 2012). Steel is significantly used in multiple automotive applications, but due to various regulations on fuel economy, environmental protection, and sustainability, aluminium alloys are becoming an obvious choice. These have one-third density in comparison to steel. They offer corrosion resistance properties and high stiffness requirements for auto-making. However, due to more initial costs than steel, certain car manufacturers are devising various strategies in collaboration with governments for cost reduction. Thus, aluminium alloys are gradually replacing steel in automotive applications (Tisza and Czinege, 2018).

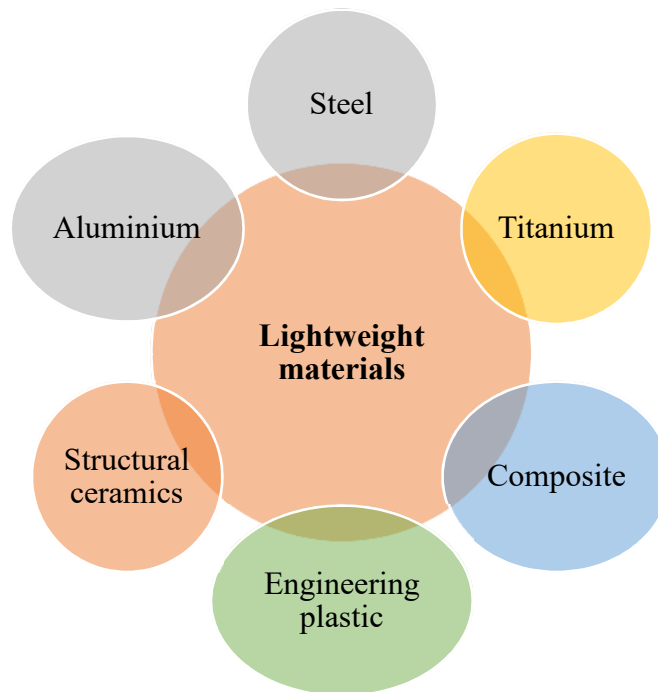


Fig 2.1 Lightweight materials for industrial applications

Few automotive companies have shifted the material from steel to aluminium for space-frame design fabricated by extrusion and stamping process (Edwards and Crouch, 2017). These designs are affected by production volume and car segments. The cost of

aluminium-based automotive bodies is more than steel; however, the overall manufacturing cost is less. It increases the net profits of car production ([Budai et al., 2017](#)).

Another lightweight material is titanium having 60% of the density of iron. It is widely used in petrochemical, marine, and biomedical applications as it promises anti-corrosion and high-strength properties. Capital investment for titanium and its alloys is generally higher than for aluminium alloys for corrosion-resistant applications ([Luis and Moncayo, 2012](#)). Titanium requires an intricate casting for the surveillance system in aerospace components.

Titanium is a difficult-to-machine material and has very low machinability compared to steel. It maintains high strength and hardness at elevated temperatures, increasing tool wear. Also, the relatively lower modulus causes an excessive deflection in the workpiece during thin sheets machining leading to chatter. For an intermittent cutting operation, the metal removal rate of titanium alloys is 60% greater than steel but less than aluminium alloys ([Singh and Sharma, 2017](#)). Another issue when drilling titanium alloy is the elevated cutting zone temperature and causing the adhesion of the chips on the tool rake surface ([Zeilmann and Weingaertner, 2006](#)).

Aluminium alloys have good recyclability and less recycling cost. Due to this, they are more favorable than engineering plastics. An inefficient database of engineering plastics alters a designer's decision from a mechanical properties point of view as they are much younger than engineering metals and alloys. As they are viscoelastic, they exhibit non-competence performance in long-term loading applications. The plastics' mechanical behavior (Stress-strain curve) is non-linear and has no proportional limit compared with aluminium alloys. ([Campos Rubio et al., 2015](#)).

Compared to aluminium, plastic has a hardness of 5-50 BHN, making it unsuitable for various engineering applications. Ductile plastic offers more resistance in loading up to a specific limit but fails in fatigue loading. Engineering plastic is non-degradable and insensitive to the environment. Also, thermal cracking is a significant challenge in plastics but can be controlled with crystalline material. Polyvinyl chloride (PVC) is known for its

good rigidity, but its processing is complex due to less impact strength (Lakhdar et al., 2022).

Polymer composites are more corrosion resistant than aluminium alloys, but the main drawback is the high unit and fabrication cost. The assembly cost contributes to nearly 70% of the total cost. Delamination of polymer composites is another reason for its less susceptibility in various high-loading conditions (Thakur et al., 2022). Although aluminium alloys require high maintenance, composites are always tough to repair. These are flimsy in out-of-plane directions as the matrix holds initial loads and is unsuitable for complex applications such as wall fitting (Lakhdar et al., 2022).

Ceramics are formed by the covalent bonding of metals and non-metals, mostly of crystalline nature. Their applications range from heating elements of a heat exchanger, bearings, sensors, implants, etc. growing demand for ceramics is structural ceramics (Wang et al., 2020). Conventional machining is inappropriate for ceramic manufacturing as it involves high temperature and high tool wear (Fernández-Valdivielso et al., 2016). With abrasive machining, ceramics tend to form surface cracks and the generation of residual stresses (Kirchner, 1984).

2.4 Machining of aluminium alloy

Machining is a process of material removal from the surface of a workpiece with a cutting tool in the form of chips. Metal removal occurs when the cutting tool advances through the workpiece with a specific cutting parameter (Singh and Sharma, 2017). Machining is characterized by machinability. The ease with which a material can be removed by a sharp cutting tool is termed machinability. A good machinable material consumes small power in less time to produce a good surface finish.

Machinability depends upon a material's physical properties like thermal conductivity, tensile strength, and work hardening. Simultaneously it also depends upon the chemical compositions of tool-workpiece material, cutting conditions, and machine rigidity (Habrat et al., 2018). Machinability is directly dependent upon the state and physical properties of the workpiece. Strength of the material changes due to the change in

grain size. Grain size is largely reliant on heat treatment and processing techniques. Solution treatment occurs at a temperature range of 516-579°C. Precipitation strengthening is achieved in an 8-hour quenching time of Mg₂Si. This increases the formability and workability of the material for industrial applications (Lee et al., 2002). Due to the low hardness value of 95 BHN, this alloy can be easily machined; generates fewer cutting forces. The contact pressure in the primary shear zone (Mark Benjamin et al., 2018) is lower, and heat generation is lower than in other metal grades.

With an increase in carbon content, strength increases, and the material will be difficult to machine material. Machinability can be calculated relative to the results gained on steel SAE 1112 on a hardness value of 160 BHN. Machinability of aluminium alloy generally ranges from 100-300 % for cast and wrought alloys. The machinability of 6061 alloy is 270 % due to the addition of silicon and magnesium Table 2.1. Aluminium alloy has non-heat-treatable properties, and it can be cold-worked easily to impart strength at low ductility. Also, it possesses good corrosion resistance properties, thus offering a good surface finish (Songmene et al., 2011).

Table 2.1 Comparison of machinability rating of various aluminium wrought alloys

Aluminium wrought alloy	Machinability rating (%)
2011	280
5052	260
6061	270
7075	170

Cutting tool material and its geometry also affect the machined surface characteristics. During machining of material, cutting inserts causes deformation in the primary zone along the feed direction. The contact pressure increases, and rupture occurs in the form of chips. For aluminium alloy machining, cutting tools range from speed steels to diamond-based tools. Carbide tools are suitable at low to moderate cutting speeds; due

to less affinity with aluminium cemented, carbide tools are also used. Positive and negative rake signatures are mostly used in the machining process. A positive rake gives low tool life, less cutting force generation, and less tendency of built-up-edges formation ([Zaman and Dhar, 2019](#)). In contrast, a negative rake increases the tool life and is best suited for high-speed machining.

During ductile machining materials such as aluminium, the contact area between chip and tool and the chip-thickness ratio are high. The shear strength is relatively low in chip-tool areas, but machining aluminium is comparatively easy. To understand better the machining of aluminium, the following aspects must be considered; Cutting forces and stresses, power, cutting temperature, surface characteristics, tool wear, and cutting fluids.

2.4.1 Cutting forces and stresses in aluminium alloy

Low cutting forces are utilized while machining aluminium alloy compared with other ferrous alloys. This is due to low mechanical strength accounting for most of the cutting pressure ([Campatelli and Scippa, 2012](#)). Upon the addition of chemical agents or by some thermal or heat treatment, strength increases and consequently decreases the contact pressure in the chip-tool interface. This decreases the cutting force requirement and net power utilization ([Fang and Wu, 2005](#)). In some cases, by the addition of hard particles in 10-15% volume, precipitation increases, and 15-20% fewer cutting forces are produced. An increase in the cutting speed generally reduces the cutting forces despite the high strength of aluminium alloy. This occurs due to the decrease in the shear zone resulting in an increased machining temperature ([Sreejith, 2008](#)). However, high-speed machining can decrease the machining forces at a nominal deformation rate.

Higher cutting speed increases the wear at the flank surface in the presence of hard material in aluminium alloy due to abrasion of tool material with the workpiece ([S. Kannan and Kishawy, 2008](#)). The same work is correlated with ([Lahres et al., 1997](#)), where sticking of the workpiece is overcome with the presence of lubricant between the tool-work interface. Feed or depth of cut increases the cutting forces as the area of primary and

secondary shear zone increases. 35% fewer stresses were observed in the secondary shear plane zone, as the cutting takes place initially in the primary deformation zone.

Other aspects of increased machining forces are revealed by the selection of different cutting geometries, different rake angles, and nose radii. The presence of built-up edges and increased rake angle reduces machining forces significantly (Gómez-Parra et al., 2013). In another study, reported by (Ravi Shankar et al., 2005), substantial strain hardening was observed on reduced rake angle usage in the cutting of aluminium alloy 6061. This might be due to the less resistance offered by the low rake angle. Work-tool interfacial contact area increases with the flank wear, consequently increasing the machining forces, as reported by (Tang et al., 2009).

Cutting forces, tool wear, and surface roughness can be minimized by using sharp cutting edges or by suitable tool material coatings. The coating on the tool, either chemically or vapor-deposited, prevents the direct contact of the tool with the workpiece. Diamond cutting tools give the least force magnitude due to less affinity with the aluminium alloy (Shen et al., 2008).

2.4.2 Power consumption in aluminium alloy

During high-speed machining of aluminium alloys, high energy is required. But the specific cutting energy is less because more material removal takes place at a higher cutting speed and feeds for higher productivity. The forces generated while machining aluminium alloy are 30% less than machining steel (Nur et al., 2015). An increase in the hardness and strength of the workpiece increases specific machining energy but decreases at higher cutting speed and feed rates.

Machining power relies on shear plane loads, which are consequently further dependent on the strength and presence of free alloys in the cutting process. Softening of alloy and prevention of sticking action takes place at high-speed machining. Machining power reduces with the use of coolant, optimum hardness, and balanced cutting conditions. Also, free-cutting elements like lead, tin, and bismuth with a weight percentage of 0.2-0.10% amalgamate with cutting speed, resulting in less power generation as they insist on

less sticking ([Çakır et al., 2016](#)) and promote the easy removal of the chips from the chip-tool area. Machining power increases when feed and cutting length increase because of the increase in cutting forces in both cases.

2.4.3 Cutting zone temperature aspects in aluminium alloy

In aluminium alloy machining, cutting temperature is vital due to its low melting point. Lower melting does not allow for a change in the mechanical properties of the tool. ([Kishawy et al., 2005](#)). But the life of the tool is greatly influenced by the machining temperature. Up to a certain limit of machining temperature, an increased cutting temperature can alter the microstructural behavior, formation of residual stresses on the workpiece, and decrease tool life. Adherence of the chip on the tool is another consequence of increased temperature ([Ramana et al., 2021](#)). High temperature increases the ductility of the workpiece and produces longer chips which may clog the cutting regimes. This also increases the chemical affinity between coated tools and aluminium work-piece to endorse atomic diffusion. Addition of silicon content in 5-12% wt. achieved a temperature range of 360-750°C in some machining processes ([Dasch et al., 2006](#)). [Tang et al., \(2009\)](#) validate the residual stress formation on the machined surface due to increased temperature at the distant cutting edges.

Shear plane deformation increases while working at high cutting speed and feed in aluminium machining. With an increase in feed rate, the chip contact area does not increase significantly thereby, decreased temperature is observed in machining ([Fukui et al., 2004](#)). The flow of chips along the rake surface is convenient due to the increased temperature, which can be achieved by making some arrangements in the tool geometries (rake and clearance angles) ([Dasch et al., 2009](#)). Another source of heat dissipation can be explored along the clearance surface and machined part with some alteration to the tool signature ([Santos et al., 2016](#)). Generally, adding hard materials, increased cutting speed, feed, and increased strength allows for working at high machining temperatures.

Compared with nickel alloy, steel alloy, and titanium, aluminium possesses high thermal conductivity. Due to this, heat covers up the cutting zone, making chip disposal

difficult. To overcome this, lubricant supply at high discharge is the solution for various industrial applications.

2.4.4 Surface characteristics of aluminium alloy

Microstructural characteristics and hardness of alloy directly impact the surface characteristics of aluminium alloy (Jeong-Du Kim, 1997). While machining, the metal removal rate limits the surface finish (Szablewski and Sokolowski, 2004) due to variable cutting parameters. Increased hardness of the material leads to poor surface quality and abrupt microstructural changes. It can be reduced to a certain extent by adding hard particles with controlled weight percentages. As stated earlier, a high chemical affinity for various aluminium-based oxides and nitrides promotes the impingement of particles in machining areas. The negative impact of ductility and formation of built-up edges can be negated by the proper selection of cutting parameters and low affinity to aluminium material.

For better surface characteristics, high-speed aluminium machining is not preferred as more extended chip formation is observed, and these chips can clog the drilling groove (Ciftci et al., 2004). The addition of silicon carbide filler material in the aluminium cannot sustain deterioration in the surface due to flank wear. It depends upon the circulation and size of hard particles.

Tin or bismuth addition (0.6 wt.%) as a free element in aluminium alloys gives a good surface finish even at a higher cutting speed (Biermann and Heilmann, 2010). It makes the chip brittle and facilitates sliding from the tool's surface. However, this method is costly compared to wet machining of aluminium alloy, which necessitates opting for lubricants (Dasch et al., 2009). Warping is another setback while machining aluminium alloy; this occurs due to increased temperature, as discussed in the previous section. This might be due to the thin section machining of the workpiece. The main reason could be the simultaneous loading and elevated temperature. Warping is further influenced by the cutting parameters, tool material, and loading state.

2.4.5 Selection of tool material for aluminium alloy machining

Cutting tool selection is vital in achieving the desired output in aluminium alloy machining. High-speed steels and diamond-based and cemented carbide tools are mainly used for the machining of different grades. The sticking of chips on the tool surface can be reduced with fine-graded diamond-based tools ([Campatelli and Scippa, 2012](#)). Cemented carbide tools have a dense grain structure that provides wear resistance and longer tool life. Also, these can counter the effect of chemical affinity with aluminium which improves surface finish and helps in the reduction of tool wear accumulated on the cutting edges ([Toropov et al., 2005](#)). Coated carbide tools are generally used at moderate speed and low machining length. N10 coated carbide cutting tools find application in silicon carbide-based material in the turning, boring, milling, and drilling process. In case of abrupt changes in the cutting temperature and grinding process, the N20 coated carbide cutting tool is frequently used ([Hartig et al., 2022](#)).

In the drilling process, the selection of point angles, helix angles, and proper tool geometries derive the circularity and quality of drilled holes ([Nouari et al., 2003](#)). While drilling aluminium alloys, positive tool geometry and deep grooves prevent the adhesion of the chip on the tool surface. But helix angles of 30-40° give improved results for drilling of low-strength alloy. As stated earlier, diamond-based tools can achieve a high cutting speed for aluminium alloy machining ([Toropov et al., 2005](#)).

Polycrystalline tools (PCD) containing hard particle constituents of silica carbide and ceramic in 15-20% of volume can resist wear propelled by thermal actions. The main reason is the increase in hardness due to the presence of ceramic particles. Also, cemented carbide tools have one-third thermal conductivity than PCD tools, generating less cutting temperatures and is a good option ([Coelho et al., 1995](#)). To improve the machining characteristics of aluminium alloys, diamond-based tools are proved to be a suitable viable option due to their low coefficient of friction, higher thermal conductivity, ability to withstand high cutting temperature, and low chemical affinity ([Beranoagirre and López De Lacalle, 2011](#)).

For dry turning operation ([Chattopadhyay et al., 2009](#)) used multilayered coated cutting tools and proved that chemically vapor deposited diamond tools offer low wear of aluminium stock. It validates the earlier mentioned point that diamond-based tools have low chemical affinity and proved effective for high-quality machining. Another similar research reported that nanoparticles embedded in diamond-based cutting tools give comparatively more minor surface roughness and less crack propagation ([Liang et al., 2008](#)). TiN/TiCN (titanium nitride, titanium carbon nitride) coatings also reduce cutting temperature and flank wear, thus giving excellent machinability ([Heaney et al., 2008](#)).

2.4.6 Tool wear during aluminium alloy machining

Wear problem occurs mainly due to cutting conditions, the material of the tool, and workpiece properties in the aluminium alloy machining. The low melting point of aluminium alloy results in less machining temperature. This leads to the generation of minor flank wear and superficial plastic deformation in shearing at elevated temperatures under the action of high compressive stresses ([Bezerra et al., 2001](#)). The same research outcome is also observed by ([Sreejith, 2008](#)).

The second reason is the high concentration of hard particles (abrasive wear) and increased cutting temperature, causing adhesiveness of the chip-tool interface. Adhesive and abrasive wear increases when hard particles (Al_2O_3 , SiC_p , and Si) abraded the contact surfaces, increasing the machining temperature ([Kelly and Cotterell, 2002](#)). It can be controlled by the presence of 12-20% silicon carbide in an aluminium alloy workpiece. The higher proportion of hard particles gives more flank wear and vice-versa ([Beranoagirre and López De Lacalle, 2011](#)). The combination of hard particles and elevated cutting speed may enhance the magnitude of flank wear when machined by cemented carbide tools. The possible solution to this problem is using diamond-based or coated tools to make clean surfaces, reducing adhesiveness ([Roy et al., 2009](#)).

Improper use of cutting tool geometry and machining characteristics in the aluminium alloy can cause lateral flow of material. High frictional coefficients generated at high cutting speeds can cause the undesirable delamination of coating materials which

fails the tool material (Liang et al., 2008). Delamination occurs due to low adhesion evident between the coating and substrate. This can be reduced by diamond coating or fine-grain diamond-based tools (Dasch et al., 2006). This effect also prevents the reuse of the cutting even after the sharpening process.

Another possible solution to reduce the wear is the addition of free elements (copper, tin, lead, and bismuth) in the aluminium alloy, which consequently increases the machining quality. Suitable cutting conditions, cooling strategies, and tool material also help in wear reduction. (Dasch et al., 2009) employed Pb and Sn constituents of 0.08%-0.02% wt. in aluminium alloy machining to increase drill productivity. Low cutting speed is suitable for silicon-aluminium alloy machining. Flank wear reduces significantly at low cutting parameters (Manna and Bhattacharyya, 2002). During the turning of aluminium alloy (A356 with 20% silicon precipitates), about one-half flank wear was reported when the cutting speed was reduced from 250 m/min to 60 m/min (S. Kannan and Kishawy, 2008). Liang et al., (2008) compared three different cutting tools (uncoated carbide, tungsten-based carbide tool, and nanostructure diamond-based tools) performance when milling silicon-aluminium-based alloys and the results revealed that the latter two tools give improved tool wear characteristics. (Karakaş et al., 2006) investigated triple-coated ($\text{TiCN} + \text{Al}_2\text{O}_3 + \text{TiN}$), double-coated ($\text{TiN} + \text{TiAlN}$, titanium aluminium nitride) chemical vapor deposition (CVD) tools, and uncoated tools at 0° rake angle and showcased that triple coated tools give the most negligible value of flank wear.

2.4.7 Cutting fluid in the machining of aluminium alloy

Cutting fluids increases machining productivity by lowering tool wear, machining temperature, cutting forces, etc. It also helps in chip removal from the tool-work interface, lowering the friction coefficient. The problem of heat accumulation in the cutting zone is reduced with the use of coolant.

Cutting fluid does not allow overheating and adherence of chip on machined surface and tool in aluminium alloy machining. It also reduces flank wear and surface roughness. Machining accuracy increases due to oxidation prevention and releasing of

chips from the tool rake face (Kelly and Cotterell, 2002; Roy et al., 2009; Sreejith, 2008). Easy removal of chip reduces machining temperature, as proved by (Kurgin et al., 2012). (Kannan et al., 2020) investigated that flank wear reduces, reducing the cutting temperature with the use of cutting fluid.

For aluminium alloy machining, ductility is a significant factor, and it should be machined in dry conditions to encounter the issue of chemical affinity (List et al., 2005). Soluble oil at a low discharge rate improves machining results for Al-Si alloys. Accumulation of materials during cutting can be reduced significantly by cooling, and lubrication as the former helps reduce material's softening and decreases friction in the cutting regime (Saglam et al., 2006).

Drawbacks of dry machining can be overcome by wet or near-dry machining. The cutting fluids may be extreme pressure additives (EP), vegetable oil, nanofluids, and oil-based (Sarıkaya et al., 2021). High machining accuracy, less surface roughness, and decreased cutting temperature are achieved with minimum quantity lubrication (MQL) machining of aluminium alloy (Arora et al., 2015). This process is economical compared to flood lubrication as it utilizes a much less cutting fluid (5-100ml/h). It increases dimensional accuracy, and sound heat exchange can be achieved with mist aerosol (Gupta et al., 2018) presented a brief review on sustainable indicators and heat transfer enhancement using near-dry machining. (Kelly and Cotterell, 2002) The reduced feed force was revealed using minimum quantity lubrication and low cutting conditions. MQL can machine an economically, environmentally friendly aluminium component and is more thermally stable. The temperature difference between the drill centers due to heat accumulation is reduced significantly, and the formation of built-up edges is not visible during MQL machining compared with dry machining (Zhu et al., 2020).

Liquid nitrogen and cryogenic machining are other viable options for a sustainable approach for aluminium alloy machining. (Gupta et al., 2015) demonstrated that crater wear and tool life reduced expressively at liquid nitrogen cooling compared to dry and flood lubrication. (Park et al., 2015) conducted end milling trials in flood, nano-MQL, and

cryogenic conditions and achieved a 35% increase in tool life in combination cooling(nano-MQL and cryogenic).

In contrast with the base fluids, nanoparticles offer higher thermal conductivity and better chemical mixing to overcome machining temperature and reduce significant tool wear. Heat transfer increases with the concentration of nanoparticles in circular cross-sections observed by computational studies ([Azwadi et al., 2017](#)). A similar study (Park et al., 2017) proved that MQL and liquid nitrogen produce less cutting forces and tool wear compared to dry and wet conditions.

Usually, the machining of aluminium is not a significant concern. The presence of hard particles offers major drawbacks of cutting temperature enhancement, gradual wear increment, etc. The challenges include the warping of aluminium due to shear deformation, forces, and stress accumulation during machining. The above discussions provide a better solution to these problems by selecting proper cutting conditions, cutting geometries, and cutting tool materials. The usage of cutting fluid facilitates the chip removal, prevents clogging, and adequate heat management during the machining of aluminium alloy.

2.5 Vibrations in machining

Despite all the issues mentioned above and their solution in the upper portion, machine vibrations that occur due to the tool or workpiece or even by the machine can cause a significant amount of alteration in surface finish, wear, and machining productivity ([Fig 2.2](#)). Machining processes sometimes lead to three basic types of vibrations, which occur due to the scant stiffness of both machines and the tool holder, in addition to the tool and workpiece material. These are intensified by the improper selection of cutting parameters and chip thickness variations. The first type of vibration, i.e., free vibrations, generally appears due to displacement from serenity when a system is allowed freely for rotation. It can be generated from the rapid involvement of machine tables or initial contact with the cutting tool. Forced vibrations emanate from unbalanced forces in a rotating element, such as faulty gear arrangement, imbalance in heavy components, and lack of proper alignment of motors and pumps. The frequency of chatter can predict forced

vibration to the frequency of possible obliging functions. Such identification can lead to the reduction of chatter marks during the cutting operation.

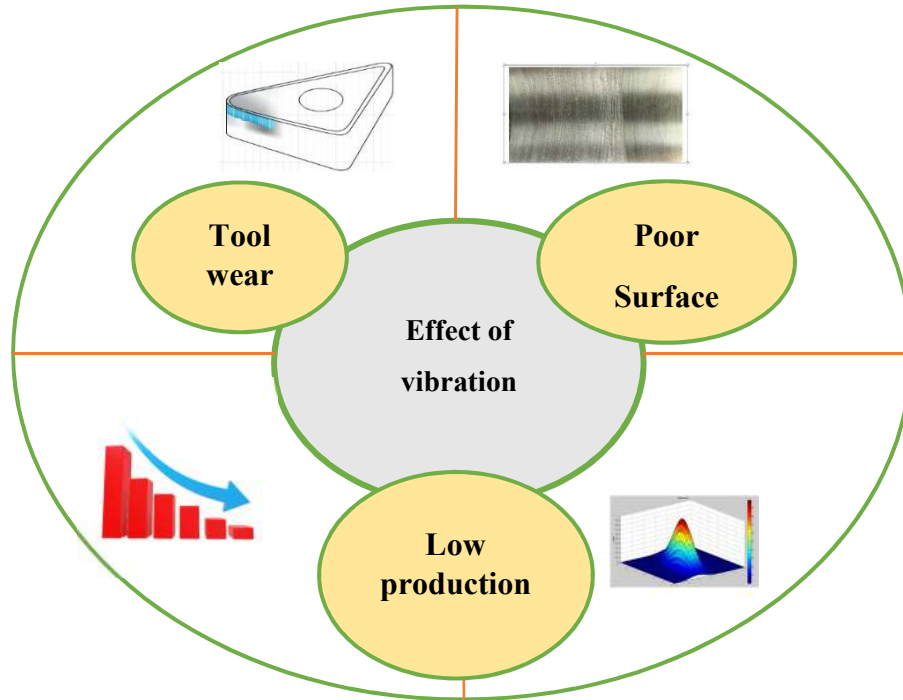


Fig 2.2 Severe effect of vibration

Waves in the surface finish are chatter or chatter marks, and various parameters such as velocity disparities in slide motion, servo instability, and stick-slip friction contribute toward episodic variations. Self-excited vibrations arise due to variations in chip thickness. (Quintana and Ciurana, 2011). Self-excited vibrations are the most influencing factor in the progress of cutting conditions, speed, and machining of thermal-resilient alloys. For chatter resistance, the cutting tool must have minimum dynamic stiffness. The researchers have tested the above approaches to select an optimal length-to-diameter ratio, resulting in a product of high surface quality, improved dynamic stability, and avoiding chatter (Munoa et al., 2016).

The primary reason for this vibration is mainly due to the mode coupling. Mode coupling is due to interactions among cutting forces and the irregularities on the surface as

a result of the previous tool passes. These facts conclude the relationship between chatter and damping, which further decides the shape of the chip and is dependent upon the spindle speed.

Machining involved in vibratory motion in a chip-tool interface decreases machining performance. A cutting tool will be subjected to variable cutting parameters upon chatter involvement.

2.6 Vibration reduction techniques

Decreased output of the product diminishing the profit of any organization imposes a decline in chatter or occurrence up to tolerance limit set by governing standards. By any means, if not possible to undergo any reduction, the material removal rate is to be lowered. Consequently, increased machining time due to chatter results in increased production costs (Ulrich et al., 2008). It concludes that chatter must be reduced by any means in machining. In boring operation, vibrations occur not only in the boring bar, which is the most flexible member but can be visualized due to other machine tool components such as the tool holder, tail center, and chuck (Altintas and Ber, 2001). Frequent vibration reduction techniques are based on chatter detection, continuous control, and fluid-based damping (Fig 2.3).

Active vibration control utilizes continuous feedback signals of dynamically adjustable parameters. This technique combines observation of chatter, diagnosis, and control processes. It generally uses piezoelectric actuators, magnetic actuators (Lu et al., 2014), and advanced sensors for chatter detection and corrective actions regarding variable cutting parameters. Passive vibration control improves the design to alter performance against vibration by adding components that absorb energy like dampers (friction damper, mass, or tuned damper) and particles of various materials having better damping capability (particle impact damping). The operating cost of passive damping is more petite than active damping, but this method cannot control dynamic characteristics.

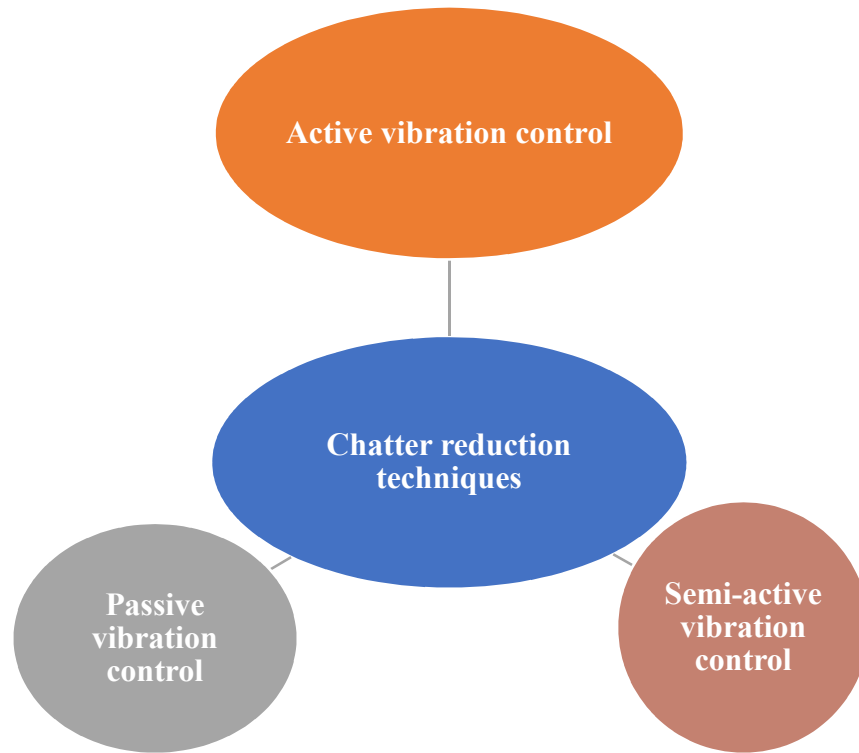


Fig 2.3 Chatter reduction techniques

Semi-active vibration control utilizes smart materials to alter damping and natural frequency. Magnetorheological fluid (MRF) performs these functions as they exhibit material to flow under external loading conditions. Apparent viscosity increases under the application of a magnetic field. These fluids form particle chain movement, which limits the movement of fluid.

Like MR fluid, electrorheological fluid exhibits viscosity change upon application of electric fields and is reversible. They can change from liquid to solid or vice-versa within a fraction of a second. These fluids can alter the damping and stiffness of vibratory components with the application of an electric field (Lel, 2012). The boring bar is filled with electrorheological fluid coupled with a DC supply. Dynamic characteristics can be controlled by sensing the signal for viscosity variation under an electric field.

2.6.1 Active vibration control technique

A non-contact linear magnetic actuator is utilized for boring on an aluminium 6061 T6 cylinder with an active damped boring bar. Dynamic stiffness of boring bar increases, which further increases stiffness, achieving chatter reduction at higher depth. A linear relationship between the parameters associated with boring bars and magnetic actuators having displacement sensors is recommended. A very large boring bar can be used to bore large components to increase the cylinder of large diesel engines, power turbines, and castings. Tuning against vibration is essential to achieve precision and the required surface finish. This paper deals with chatter suppression in the turning process while machining 6061 Aluminium using a computer numeric control (CNC) turret lathe and a vibrant combination of accelerometers and a data acquisition system. This piezoelectric inertia actuator has a preliminary mass operated as a tuned vibration absorber. Experimental results proved that a higher damping ratio of vibration absorber chatter could be significantly reduced; thus, cutting stability is observed ([Tarng et al., 2000](#)).

([Rubio et al., 2013](#)) Different types of clamping conditions can also be used to study the dynamic characteristics of the boring bar. Standard (AISI 4330) boring bar and modified boring bar comprising accelerometer and embedded piezoelectric actuator are used for model analysis. Results revealed that the dynamic properties of a bar depend upon clamping conditions, physical dimensions, and material.

([Pratt and Nayfeh, 2001](#)) studied the active damping system effect by establishing a correlation between the chip shape and system damping. The shape of the chip is studied in terms of spindle speed to increase the system's stability. Presented as stability lobe diagram to showcase stability analysis in terms of spindle speed and chatter frequency. Also, root locus is developed for chatter frequency as an open and closed-loop system. It can be concluded that a relationship between chatter and damping along with the shape of the chip, depends upon spindle speed. As validated by root locus analysis, active damping accounts for chatter reduction at variable speeds. The difficulty in measuring tool usage demands tool conditioning monitoring, which is currently explored by the machining community across the globe. A conditional probability distribution is used to calculate

optimal speed and other substitutions. Proposed a model for optimal speed and replacement time for conditions to alter tool and optimal parameters. But cutting speed could be reduced if the tool is about to wear out immensely (Zhou and Wysk, 1992).

Driving tip of the frequency response function of modified tool holder connected with different circuits and by comparing roughness values of two components bored with modified tool-holder. It can be concluded that there is a significant increment in damping when the system is excited in the piezoelectric layer causing dissipation of energy. As cutting forces mostly rely on geometrical features of the machining process, dissipative shunt circuits can be utilized in two directions for vibration reduction. Results revealed that surface roughness could be reduced significantly by around 31%, 15%, and 33% for three profile measurements with a shunt circuit (Fig 2.4) (Martins et al., 2015).

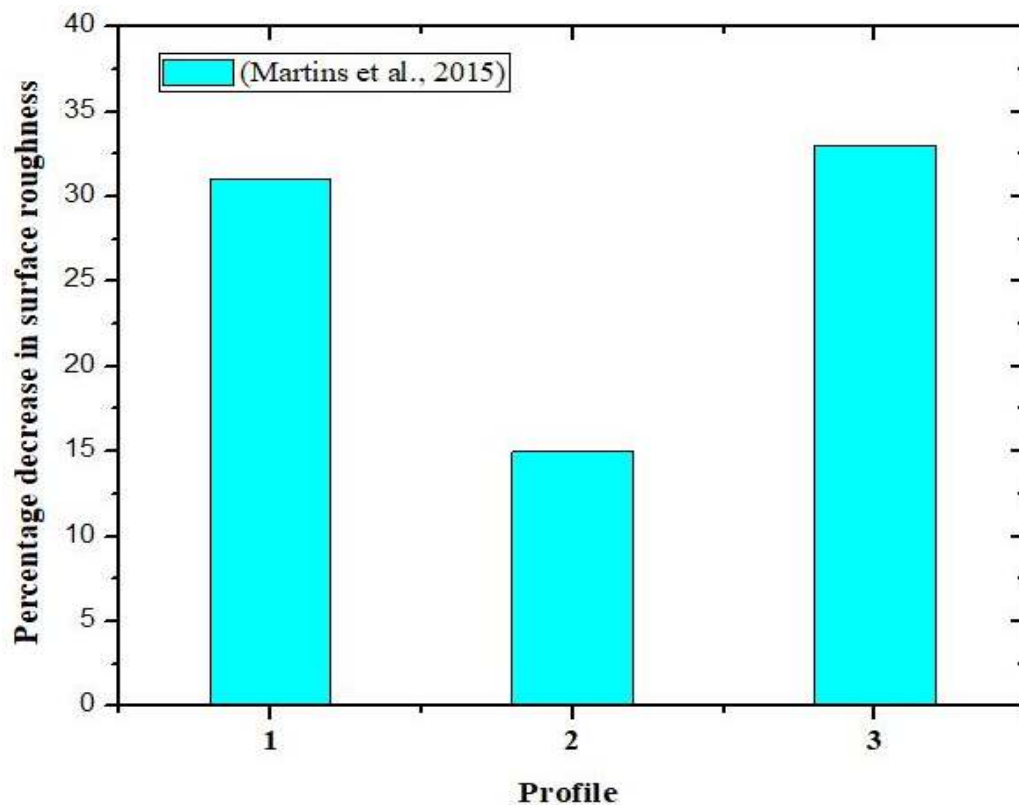


Fig 2.4 Percentage reduction in surface roughness with piezoelectric shunt damping (Martins et al., 2015).

Critical piezoelectric shunt damping can increase cutting process stability as validated by hypothetical and experimental trials (Yigit et al., 2017). An alternative approach for conventional actuators by shape memory alloys (SMA) exhibits properties to recall its original position under deformation. SMA is generally made up of alloying elements such as Cu-Zn, Cu-Al-Ni, and Ni-Ti employed as a damper. SMA of copper and zinc in 60-40 ratio was used as a passive damper for chatter suppression. SMA was prepared by the vacuum arc melting process. Boring bar made up of EN-31 steel used for tool wear optimization by selecting stable cutting conditions for damper position, cutting velocity, and depth of cut. Optimization was done by using regression modelling and response surface methods. Results predicted that tool wear could be reduced expressively by selecting shape memory alloys on the boring toolbar at the proper position and process conditions. Damper position is the most significant factor, followed by cutting velocity (Chockalingam et al., 2016).

There are various hurdles involved in active control strategies like an optimal selection of actuator size, complex analysis of a generated model for machining parameters, and chatter frequency suppression in workpiece material. To overcome all these complications robust active damping design is required.

2.6.2 Passive vibration control technique

Reduction through active damping generally requires actuators and the control system is much more complicated. Due to the large size of the actuators, certain obstacles ascend in the machining process. Passive damping reduction employs a simple structure and does not offer flexibility to various cutting parameters.

Another critical aspect of particle impact damping is using shots of different materials such as copper, brass, lead, chromium, lead, and steel of variable size inserted in the hollow boring bar for chatter suppression. Constant cutting parameters and the cantilever beam's overhang length were used as machining parameters. Surface roughness was analyzed using particle density, size, and hardness as process parameters. Experiments

conclude that small size balls give more surface finish than large size balls as they provide more collision force and the frequency of striking the walls is more. Collision force decreases with an increase in size. Also, the density of the particles does not produce a significant picture in terms of surface roughness as low and dense material also produces a high surface finish compared to high-density balls. Steel and chromium have high hardness, resulting in a good surface finish (Sathishkumar et al., 2014).

(Phanse and Jadhav, 2015) The effect of vibration and surface roughness was studied using the damped and undamped boring bars. Six cutting parameters were taken to analyze the amplitude of acceleration and surface roughness, such as cutting speed, feed rate, depth of cut, length-to-diameter ratio, packing ratio, and particle size. A damped boring bar accounts for the reduction in surface roughness and amplitude acceleration compared to a non-damped boring bar. Furthermore, optimal parameters were predicted by Taguchi's robust design and grey relational analysis.

(Altintas, 2010) produced a model that obtains chatter-free depth of cut in the axial direction while turning AISI1045 steel on a CNC lathe with specially designed tuned mass dampers. The outcome confirms the decrease in chatter by using tuned mass dampers. VSVDA (Variable Stiffness Dynamic Vibration Absorber) is a better technique for deep-hole boring, considering the high L/D ratio.

(Chockalingam et al., 2017) used particle damping technique (PID) in boring operation wherein the metal particles such as copper and zinc are inserted in the cavity created in the boring bar. Due to the high resonance gap generated by the colliding actions of particles inside the boring bar, the surface roughness of the machined surface decreases by 79% with Cu-Zn particles, 71% by Cu particles, and 54% by Zn particles (Fig 2.5). (Liu et al., 2017) compared the vibration characteristics with variable stiffness dynamic vibration absorber boring bar (VSVDA) to study vibrational characteristics on both standard and new modified boring bars. VSVDA inserted at the obverse of the boring bar. Trials were conducted on a C45E4 workpiece of the length of 350 mm, overhang length of 600 mm, and L/D ratio of 15 on the lathe turning center. The size of the damped and regular boring bar is kept constant with variable spindle speed. VSDVA is equipped with

an adjusting unit and an accelerometer for acceleration measurement. A tuned vibrational absorber affects the cutting parameters. Through various experiments like excitation and impact tests, damped VSDVA can diminish vibration.

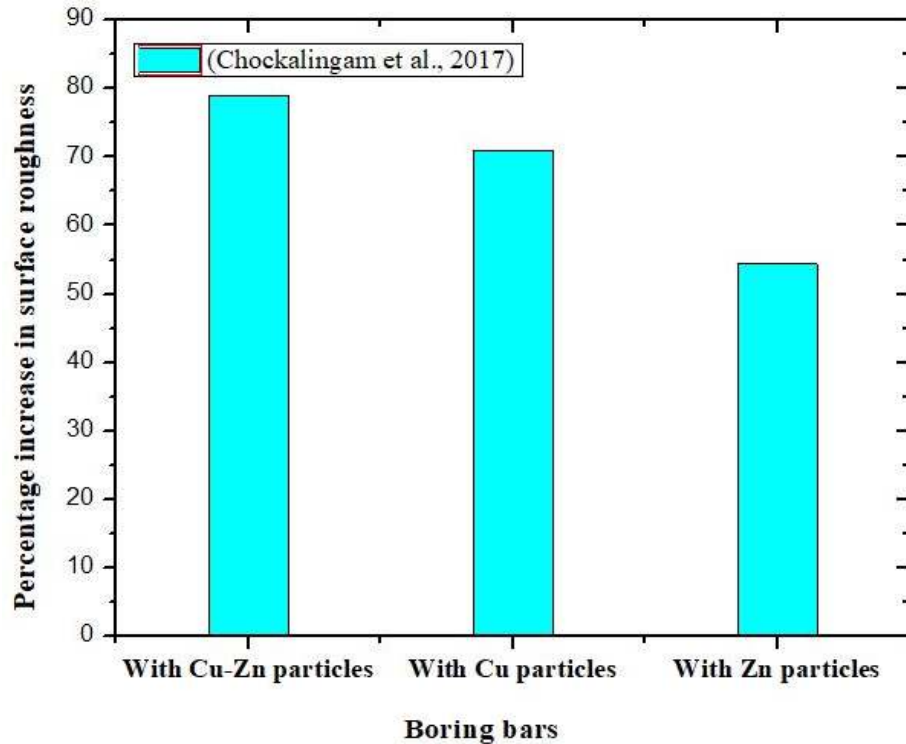


Fig 2.5 Percentage increase in surface roughness with unmodified boring bar w.r.t PID boring bar (Chockalingam et al., 2017)

(Bai et al., 2009) Developed a particle-assisted thrust damper with a mass sliding on the bearing (ensures piston oscillation inside the container). Four different types of particles diameter and different quantities of the same mass flowing in the enclosure were employed to investigate the damping act. Input parameters were friction coefficient, normal restitution, material density, Young's moduli, particle size, piston depth, and vibration amplitude for transient vibrations. Simulation findings with steel and glass particles validated that piston-based particle damper gives high damping capacity. More extended particle immersion depth gives better damping performance.

(Leon et al., 2009) Used specially designed particle dampers of box and piston based to investigate damping coefficients for transient vibration system. In box-based, steel particles are filled with metallic particles in an enclosure that requires damping. When vibration induces kinetic energy is shifted from vibrating assembly to particles, and dissipation starts through particle-particle, particle-wall frictions, and inelastic collisions. Contributing parameters of particle damping mechanism are primary mass ratio, level of excitation, metallurgical characteristics of particles, and geometry of dampers. Transfer of energy from vibrating structure to steel particle was analyzed in both damper types. Steel particles prompt vibrating structure in terms of time, and collision with damping structure determines energy transfer. Concluded that both energy transfer and dissipations affect damping performance. However, in both the dampers, 13% of total energy dissipation was achieved through exchanges between particle and wall.

(Salueña et al., 1999) Examined dissipative properties of vibrated granular materials using molecular dynamic simulations. These simulations spectacles show that different damping regimes occur during the analysis of energy-loss rate in the amplitude-frequency plane of external forcing, i.e., solid, convective, and gas-like phases. (Ramesh et al., 2015) Piloted trials on mild steel workpiece using EN31 steel boring bar. Nine experiments were conducted using cutting speed, feed rate, depth of cut, and overhang length as controlled parameters. Natural frequency calculated for boring bar using the impact-hammer test. A brass damper was used to check the effect on the chatter employed at various lengths from the cutting edge. Type K thermocouple employed for displacement measurement of the tool. Relationships among controlled parameters were proposed by an artificial neural network. Results proved that predicted observations using the backpropagation method were near to experimental results.

(Rivin et al., 2000) Studied performance using a tuned dynamic vibration absorber with a boring bar up to an L/D ratio of 15. The system under sinusoidal excitation gives a better damping ratio than cutting force excitation and random excitation. Illustrated different types of boring bars used in that machining, such as a smart boring bar concerning process stability and emphasizes productivity and quality enhancement by optimal

utilization of the cutting tool, structure, machining setup, and interactions among machine tools and workpiece.

Passive control improves damping in critical mode and improves the system's dynamic characteristics with a positive solution by utilizing the stability lobe diagram (if the machinability of the workpiece is low, spindle speed variations produce promised results). However, a passive damper can be used for a slender bar, which does not allow an increase in stiffness.

2.6.3 Semi-active vibration control technique

The boring bar's dynamics can also be improved by altering the fluid phase under an active magnetic field. (Mei et al., 2009) An experiment was conducted on an AISI low-carbon steel workpiece of 120 mm external and 100 mm internal diameters on a conventional lathe machine, boring bar with 6 L/D ratios. The experimental setup consists of MR controlled boring bar, accelerometer, and amplifier roughness with or without using an MR-controlled boring bar. Results validate that surface roughness decreases along with a reduction in chatter. ERF (Electrorheological fluids) under an applied electric field gives significant results similar to MR fluids.

(Alammari et al., 2015) Carried investigation to scrutinize static stiffness and damping characteristics with different filler materials. Steel and grease balls are packed in a hollow bar to improve dynamic characteristics by force interactions and friction. The tuning process is attained by variation in reservoir fluid level and mass. Using such materials increases the static stiffness of the boring bar by 32 and 38%, respectively. Due to this, the damping ratio increased by 22% and 4% when steel balls and grease were packed in the vicinity of the boring bar (Fig 2.6). Embedding ER fluids in tool structure can alleviate vibration to a certain extent. ER fluid utilizes polarizable solid particles spread in non-conducting oil. ER fluids are reversible in nature and exhibit phase change from liquid to solid upon application of an electric field. Like MR fluids, their viscosity can also be converted instantly under the application of an electric field. Vibration reduction could

be attained by alteration of viscosity under the action of an electric field. Utilizes ER fluids in a variation of the magnitude of electric field and through ERF squeeze film damper.

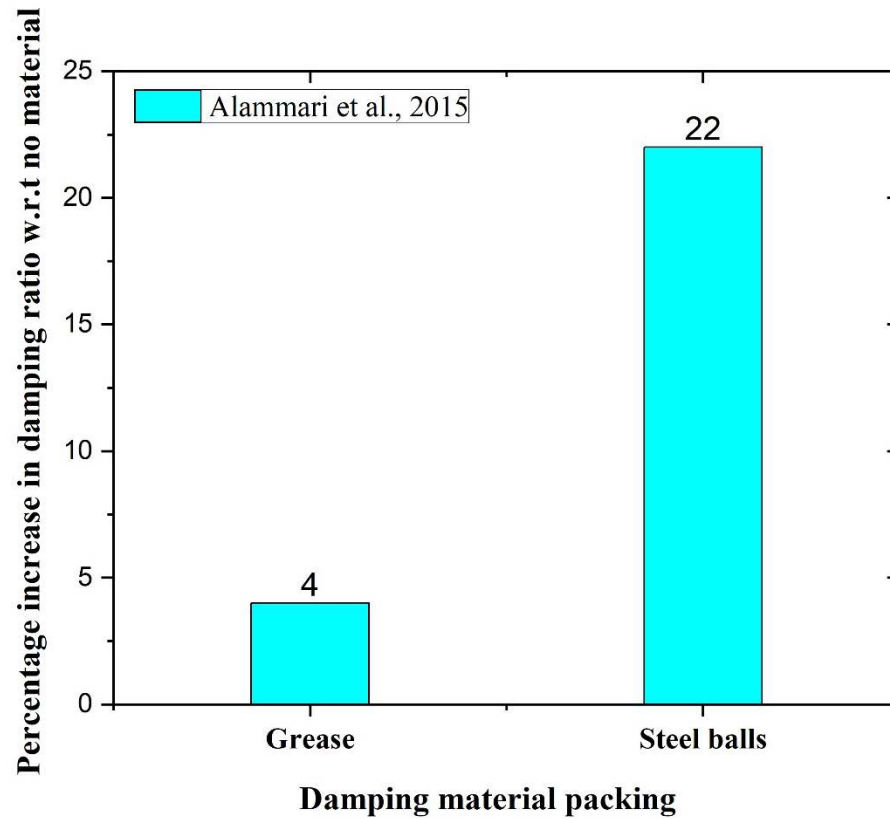


Fig 2.6 Percentage increase in damping ratio w.r.t no material packing (Alammari et al., 2015)

In impact loading, ER and MR fluids are used in various devices, and results confirmed that both the fluids could reduce impact load. Further, in these conditions' ER fluids are more capable of delivering fixing relaxation under applying a magnetic field.

2.7 Types of cooling/lubrication used for machining

2.7.1 Dry machining benefits and its challenges

The standard approach to a clean environment without using coolant in machining is called dry machining. The advantage of the dry approach is the non-pollutant machining

and less production cost. The lubrication cost comprised nearly 17% of the total production cost. (Olufayo et al., 2021) analyzed the overall production in dry and flood conditions with MICO (machining inventory and cost optimization) and found that dry machining is more favorable than wet machining. For ecological protection laws, most industries are striving toward dry machining. Moreover, it offers resistance to respiratory diseases, cancer, and skin diseases of the operator by avoiding prolonged exposure to coolants (Brinksmeier et al., 2015). Cutting parameters and workpiece properties decide the selection of the dry technique. If the machinability of the workpiece is more for low-speed machining, then dry machining is more favorable. But high-speed machining encounters some problems of high tool wear, low surface quality, reduced tool life, etc. (Sristi et al., 2022).

But it comes with the drawbacks of low machining performance. An excessive increase in temperature is a common phenomenon during dry machining, as much heat accumulates during cutting and more energy requirement for plastic deformation (Goindi and Sarkar, 2017). Another consequence of elevated temperature is the dimensional inaccuracy of the workpiece and less surface integrity. It arises due to frictional forces generated in the cutting regime, which increases the temperature of the tool-workpiece and generated chips. Due to this, chip adhesion is typical behavior during dry cutting. The absence of cutting fluids decreases the desirable tool life. (Xu et al., 2009) investigated the tool wear during machining cast iron and steel and revealed that cutting temperature in a dry environment is higher than in fluid-based machining. The elevated temperature at the tool leads to softening of the tooltip as the material loses hardness.

Moreover, the geometry of cutting edges transformed, resulting in crack propagation and sudden failure of the tool. A similar study was done by (Grzesik and Zalisz, 2008) on tool wear and examined that diffusion occurring at elevated temperatures causes the tool material to diffuse from tool to chip, leading to fail prematurely. This chemical process between tool and chip increases by increased machining temperature, generating crater wear at the cutting edge. Also, the abrasive action of hard particles decreases the hardness of the tool.

When machining a component in dry conditions, significant heat accumulation in the cutting zone can cause undesirable geometrical dimensions. During the machining of Inconel 718 (Subhas et al., 2000) studied that accumulated heat was causing thermal deformation in the workpiece. Upon cooling, it can cause geometrical indistinctness. The temperature at the cutting edge is more than the rest of the vicinity of the workpiece resulting in non-uniform deformation and thus resulting in dimensional inaccuracy. (Rakesh and Datta, 2019) stated that adhesion and chip welding is primarily responsible for tool wear. Consequently, decreasing surface finish. The microstructural analysis of the surface revealed that dry machining promotes the oxidation of work material.

Dry machining also deteriorates the surface property. The main reason is phase transformation and alteration in the workpiece's microstructure due to high machining temperature (Novovic et al., 2004). By microscopic examination, the formation of a white layer appeared on the surface due to alteration in surface characteristics. Dry machining also accounted for the formation of residual stresses in the workpiece, making the workpiece incapable of fatigue and corrosion resistance. Also, an increase in feed-in end milling increases the surface roughness due to the presence of more chatter marks (Fig 2.7) (Sun and Guo, 2009).

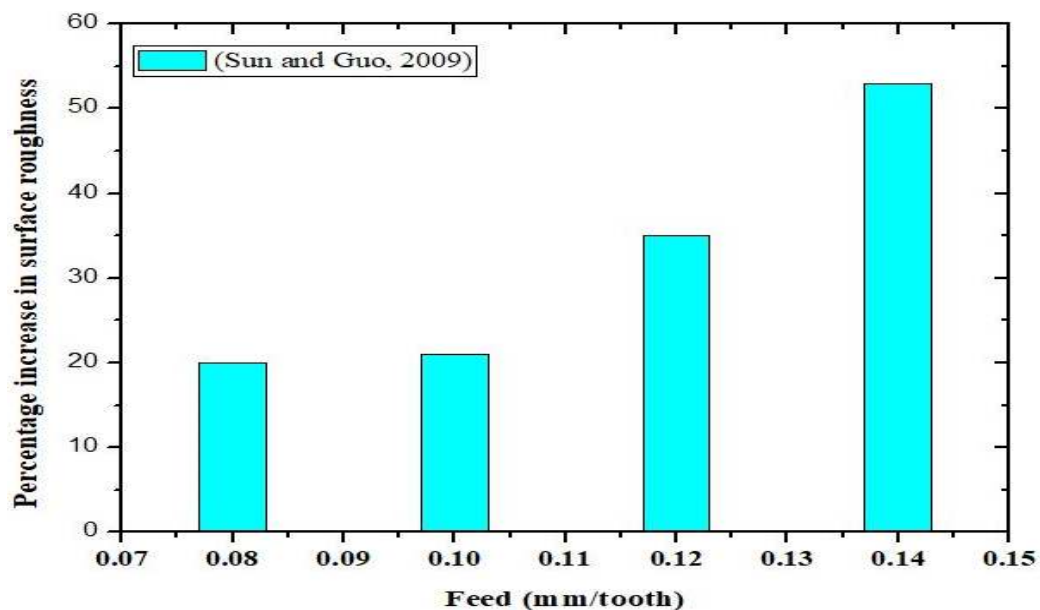


Fig 2.7 Percentage increase in surface roughness at increased feed (Sun and Guo, 2009)

(Cagan et al., 2020a) performed turning experiments on aluminium 7075 alloy and compared the surface roughness of the workpiece in dry and MQL conditions and attained a significant gain of 14%, 11%, and 10% at a cutting speed of 400, 450, and 500 m/min in mist lubrication than in dry conditions. This is due to removing heat from the cutting zone under mist lubrication. Moreover, chip length was more in mist conditions (Fig 2.8). A similar study was done by (Aamir et al., 2020) under dry conditions on three different workpieces (Al2024, Al6061, and Al5083) with non-coated carbide tools. Al 6061 alloy possesses a good surface finish than other grades. This happens due to the ability to sustain hardness at higher cutting forces and temperatures. Feed rate was identified as the most significant parameter from the statistical analysis.

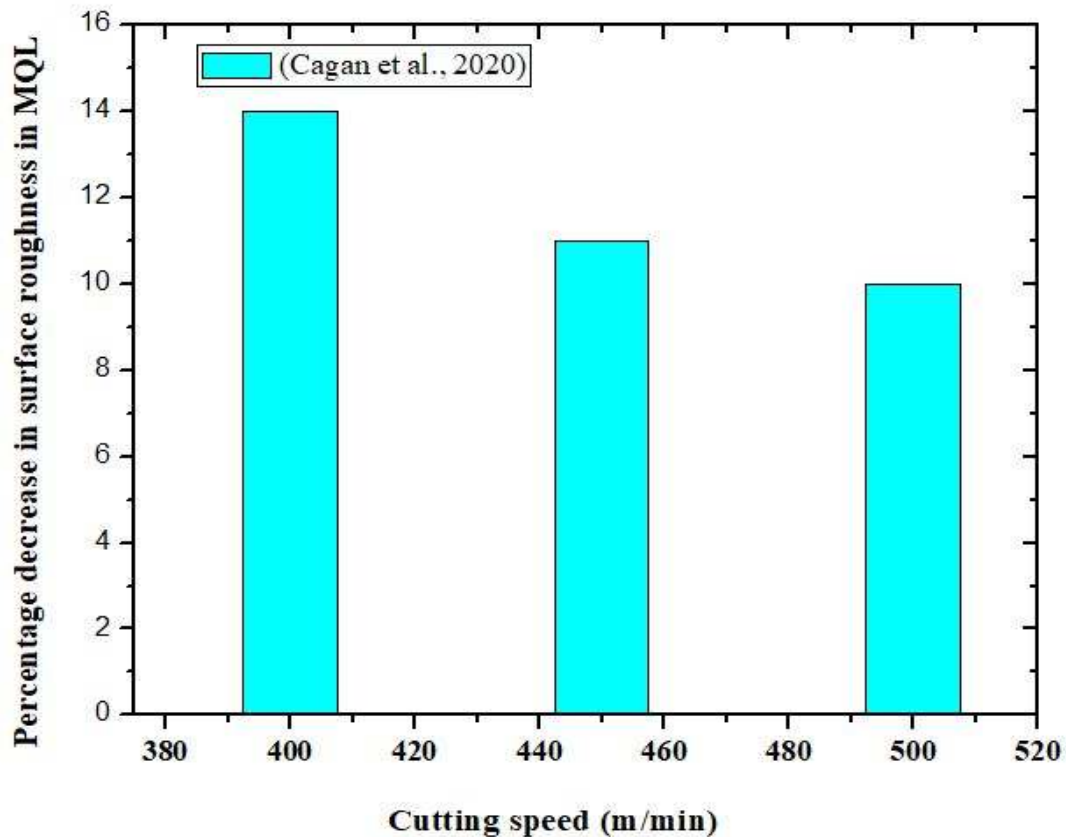


Fig 2.8 Percentage degradation in surface roughness in MQL machining w.r.t dry machining (Cagan et al., 2020a).

(Bhowmick et al., 2010) concluded that dry drilling of an AM60 magnesium alloy using a high-speed steel drill led to abrupt drill failure before drilling 80 holes, and the maximum temperature generated in the dry condition is more than in wet and MQL drilling conditions. Surface roughness is measured using three values at different locations of the machined surface. Due to a thick solid layer in fatty acid lubrication, sticking the unwanted material during hole drilling is relatively less than in other lubricating conditions. As per (Fig 2.9), a considerable decrease in surface roughness is observed in all lubricating conditions than in dry machining.

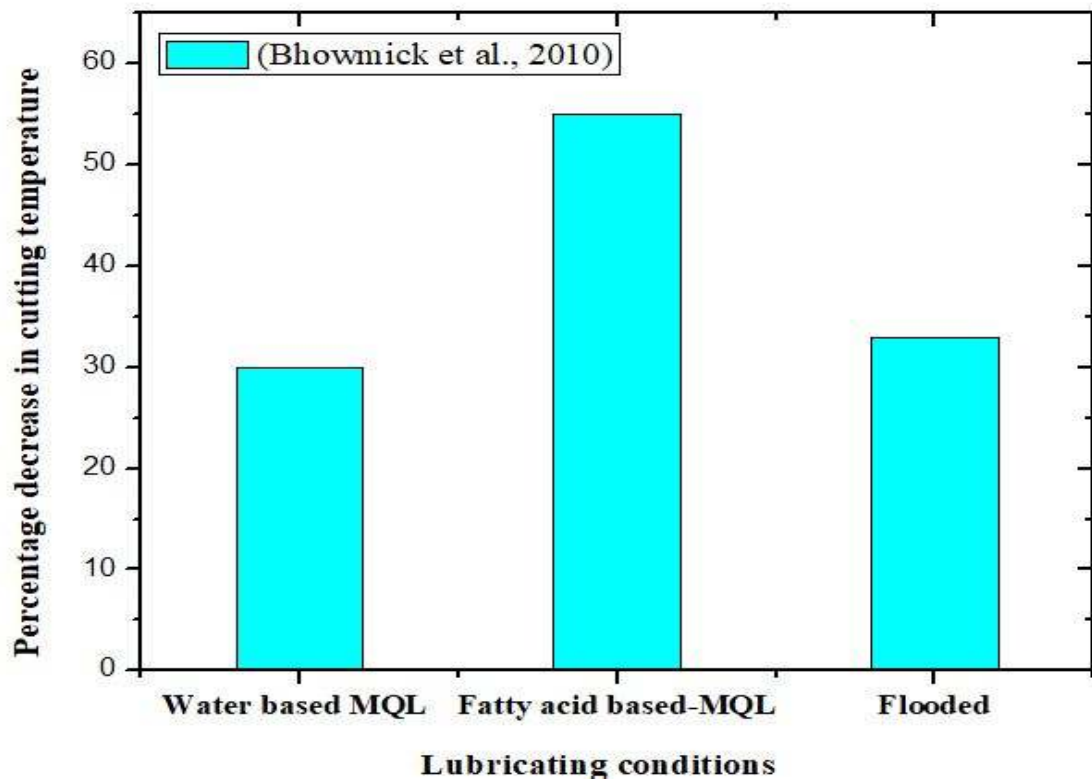


Fig 2.9 Percentage decrease in surface roughness w.r.t dry machining in different lubricating conditions (Bhowmick et al., 2010).

For high-speed machining, the width of the cut influences the tool wear in the milling of aluminium alloy 6061 (Okokpujie et al., 2017). Tool life shortens in dry machining in comparison with wet conditions. (Marksberry and Jawahir, 2008) Developed

a model for tool life calculation and observed less tool wear in near dry machining than in dry machining. Dry machining also enhances the oxidation of some elements in the workpiece. The selection of suitable work material could prevent this phenomenon. (Rakesh and Datta, 2019) performed machining trials on Inconel 718 and identified the presence of white layers of iron oxides on the top of the machined surface.

From the above discussion, it is clear that dry machining is a cost-effective and sustainable approach but not suitable for enhanced machining performance. This leads to a shift to wet machining for improved machining productivity.

2.7.2 Wet machining benefits and its challenges

During the metal cutting process, a variety of obstacles arise. Heat is mainly produced on the primary shear plane and at the tool-workpiece interface in a cutting process, particularly in the flow zone on the tool rake face (Trent and Wright, 2000). Most of the heat created in most cutting procedures is eliminated in the chip, with just a tiny amount being carried into the workpiece. Although coolants cannot directly contact the principal heat source zones, they can effectively lower temperatures on the workpiece, chip, and cutting tool surfaces.

Machining performance increases with the use of cutting fluids. It is indeed interesting to note that the performance of the coolant depends a lot on how it's supplied or how it's distributed. The cutting fluid should be routed toward the cutting tool's accessible surfaces, the areas of highest temperatures (Nageswara Rao et al., 2007). It serves the purpose of cooling exposed surfaces prone to high cutting temperature in high-speed machining. They have minimal time to penetrate the tool-chip regime for lubrication. Coolant's main objective is to reduce the friction between the chip tool and the work interface. It also increases tool life, reduces surface disparities, and facilitates chip removal. Despite this, the machinist should care for the rusting, operator's health, and disposal of the cutting fluids (Kopac, 2009).

Cutting fluids are primarily used in operations that involve separating metal from the part in the chip (milling, turning, drilling, threading, broaching, etc.), rubbing

operations (grinding, lapping, etc.), and metal forming operations. Depending upon functionality, metalworking fluids are used for ailing machineable alloys such as stainless steel and high-speed machineable alloys. The tool-work material and machining conditions influence the selection of cutting fluids. The extensive historical development of metalworking fluids was presented by ([Brinksmeier et al., 1999](#)). Chemical compositions and tribological actions derive the machining performance.

Mineral oil-based coolants with no water content give irrelevant lubrication, but they could be enhanced by adding extra-pressure additives like sulfur, chlorine, and phosphorus. These additives certainly create toxicity in an environment that could affect the operator's health. Emulsifiable oils are mineral-based but have a good mixture of emulsifiers, additives, and extreme pressure agents. Emulsifiers decrease interfacial tension among water (2-10% concentration level) and oil droplets but are vulnerable to hard water resulting in the formation of insoluble precipitates ([Sharma et al., 2009](#)).

Synthetic metalworking fluids (MWF) containing soapy and other wetting agents are supplied in the form of concentrates to provide stability against hard water and safeguard against corrosion. These are mainly used for abrasive operations and high-speed machining operations. Above mentioned pros and cons are taken care of by semi-synthetic fluids, which are solutions and emulsions of synthetic lubricants, emulsifiers, and additives with mineral oils ([Clark and Pilehvari, 1993](#)). They also deliver protection against corrosion over synthetic coolants and improve mineral oil's cooling and moistening ability. The precautionary measure is contamination by foreign particles and less stability in hard water.

MWF results in improved surface finish, enhanced tool life, less energy consumption, and closer tolerance of workpiece dimension. It ensures clean cutting regimes along with rust-free machining. Increased demand for high-quality product necessities optimal combination of cutting parameters, low tool and machine tool wear, low coefficient of friction, and less scrap from every machining unit ([Marksberry, 2007](#)). While comparing the machining parameters in dry and wet conditions observed that surface finish and wear rate were better in wet conditions. Moreover, in the absence of coolant,

chip thickness was more under dry conditions (Sankar and Choudhury, 2015). In internal turning operation under dry and wet lubrication during drilling of Inconel 718 (Peng et al., 2019) identified that wet machining produces minor wear and surface roughness compared to dry machining. A similar investigation by (Wang et al., 2014) revealed that the less drilling forces were generated in flood colling rather than in dry environments.

The delivery of MWF in the cutting area is accomplished by a nozzle jet. Generally, the discharge rate of fluids (5-230 L/min) is high to isolate the tool-work boundaries. The high volume of the coolant is primarily responsible for considerable heat reduction and flushing of chips from the tool rake surface in various machining operations (S Kannan and Kishawy, 2008). At low cutting speed, tool wear is not depending on thermal effects. But with an increase in cutting speed from 60 to 240 m/min, flank wear increases rapidly in dry machining. In wet machining, a significant decrease in the flank wear is observed due to the presence of lubricant, which reduces cutting temperature and avoids surface adhesion (Fig 2.10).

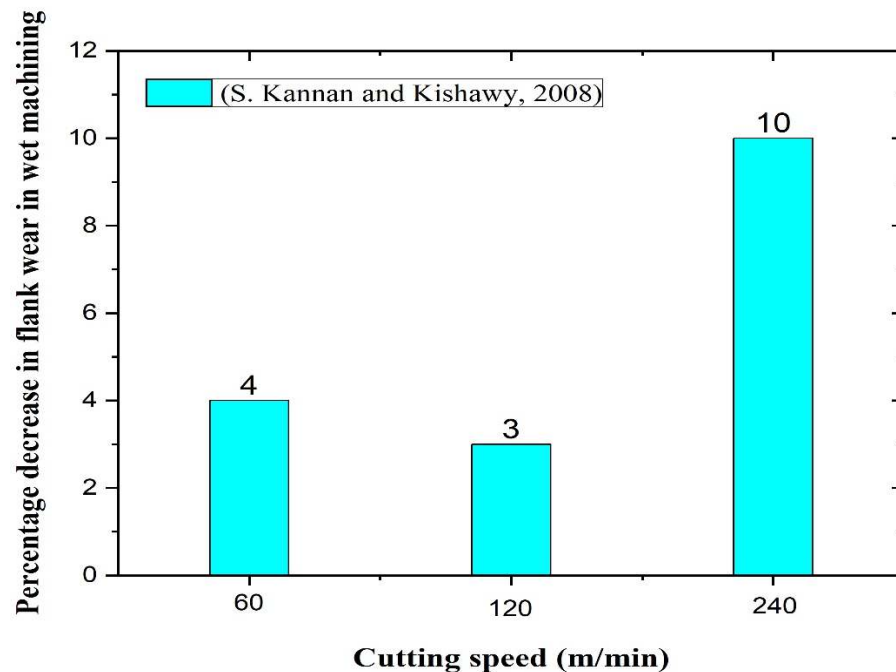


Fig 2.10 Percentage decrease in flank wear in wet machining w.r.t dry machining (S Kannan and Kishawy, 2008)

That is why wet machining is superior to dry machining, as it also promises good surface quality and less flank wear (Surya et al., 2017). Although wet machining gives superior results, the main drawbacks are the disposal of polluted fluid and adverse effects on the operator's health. Heat dissipation is the main characteristic of coolant, but it takes only about 50% of the total accumulated heat in high-speed machining. Reduction in the temperature occurs due to suitable thermal stability of coolant. To achieve more heat reduction, wettability is a crucial factor. With increased wettability, better splashing action was performed, reducing the generated heat (Shokoohi et al., 2015b). While machining AISI 1040 steel with an uncoated carbide tool in flood conditions (Dhar et al., 2006) investigated the effect of cutting temperature and chip reduction coefficient. Results revealed an improved dimensional accuracy and less machining temperature than dry machining. Reduction in the chip size enhances the tool life and specific energy requirements. Chip reduction coefficient can be abridged by operating at higher cutting velocity and feed rates.

The use of lubricant plays a vital role in defining the chip geometry. Discontinuous, continuous with built-up edges (BUE), and continuous without BUE were observed during machining in dry and wet conditions. Furthermore, flank wear increases with increased cutting conditions such as speed, feed rate, and depth of cut. Experiment results revealed a decrease of 8 and 10% in flank wear when machining was performed under a Cryogenic and MQL environment at a high cutting speed of 1200rpm (Fig 2.11). This is due to the reduced cutting temperature under the action of the lubricating medium (Sivaiah and Chakradhar, 2019).

So, it will be helpful to summarize the implementation of wet machining as it increases the machining performance by reducing the machining temperature, cutting forces, etc., through lubricating action. But its disposal after machining is a significant concern. Due to this, various countries and industries have many regulations to maintain the ecological balance. It necessitates the shift from conventional machining to sustainable machining wherein bio-degradable oils, nano-fluids, etc., help overcome the above drawbacks for moderate to high-speed machining.

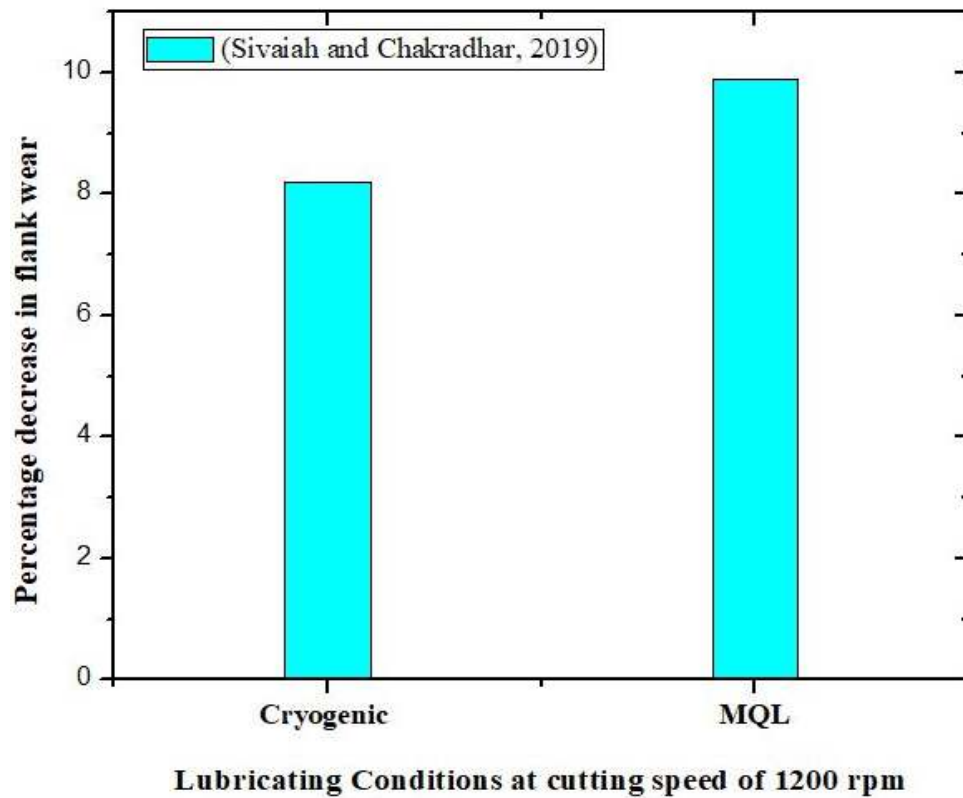


Fig 2.11 Percentage decrease in flank wear w.r.t dry machining (Sivaiah and Chakradhar, 2019)

2.7.3 Near dry machining benefits and its challenges

In conventional wet machining, large quantities of lubricant is applied to the cutting zone through bulky jets. Abundant use of lubricant leads to costly machining and generates harmful fumes during machining, which harms the operator's health. The alternate technique of minimum quantity lubrication has proven to be a good substitution, exploiting a mixture of compressed air and lubricants. Moreover, it prevents the excessive splashing of lubricant and promises better reachability due to the high-pressure supply. The lubricant requirement is only about 40ml/h flow rate and a compressed air supply of 3-6 bar (Sharma et al., 2009). The setup of near-dry machining comprises an atomizer, lubricants, and nozzle. High-pressure air is used to atomize the lubricant. The lubricant is then supplied

through a distribution system at relatively low pressure in the machining zone. Atomization occurs in the mixing chamber by compressed air, where coolant particles get converted into an aerosol of mixing particles. Proper mixing ensures the spraying operation as mist, which serves as a coolant and lubricant for deep penetration. Delivery of cutting fluids can be done internally as well as externally. In an internal system, fluid-air mixing takes place inside the nozzle and is supplied through an inbuilt channel in the tool. In an external system, aerosol preparation is accomplished by an atomizer, and its delivery is ensured by the external nozzle equipped with the machine tool. Cooling action is performed by compressed air, and the cutting fluid provides lubrication.

(Kamata and Obikawa, 2007) investigated surface roughness and tool life during turning of Inconel 718 under mist conditions with different carbide tools. Machining results revealed that mist lubrication gives better surface quality and low tool wear than dry and wet machining. (Simunovic et al., 2015) assessed the role of machining parameters and different cooling environments during milling of structural steel and obtained significant improvement in surface finish and a more negligible vibration effect. (Hadad and Sadeghi, 2013) presented a mathematical model to depict the cutting temperature and observed that oil mist on the rake surface was able to prevent the chip adhesion. Consequently, improvement in the surface finish was attained along with minimal tool wear.

(Shokoohi et al., 2015) observed an increase in machining performance by pre-cooling of the workpiece. Due to pre-cooling of the workpiece, longer chips are not observed, resulting in breaking into small parts. Also, it decreases the temperature of the tool and workpiece, consequently decreasing the surface roughness. The total variation in surface roughness is around 8%, 6%, and 5% during the machining of the pre-cooled workpiece and in MQL and flood conditions. Under MQL and flood medium, cutting forces reduce significantly, decreasing the heat accumulation at the cutting zone (Fig 2.12). Several other effects of health and ecological issues were investigated.

As discussed earlier, mist lubrication utilizes aerosol through various channel systems, offering a reduction in environmental pollution. Fluids should be biodegradable and offer stability for a more extended period due to less quantity usage. The near-dry

machining is superior to dry and wet machining while turning AISI 4340 steel with an uncoated carbide insert on flank wear and surface roughness (Kalyan Chakaravarthy et al., 2020). Cutting enactment with MQL is far better than the dry turning process as it offers lower temperature reduction (Parikh et al., 2021). Machining with MQL proved better than dry and wet cooling, increasing cutting performance by reducing tool wear, cutting temperature, and forces between chip-tool interactions (Kayihan et al., 2020).

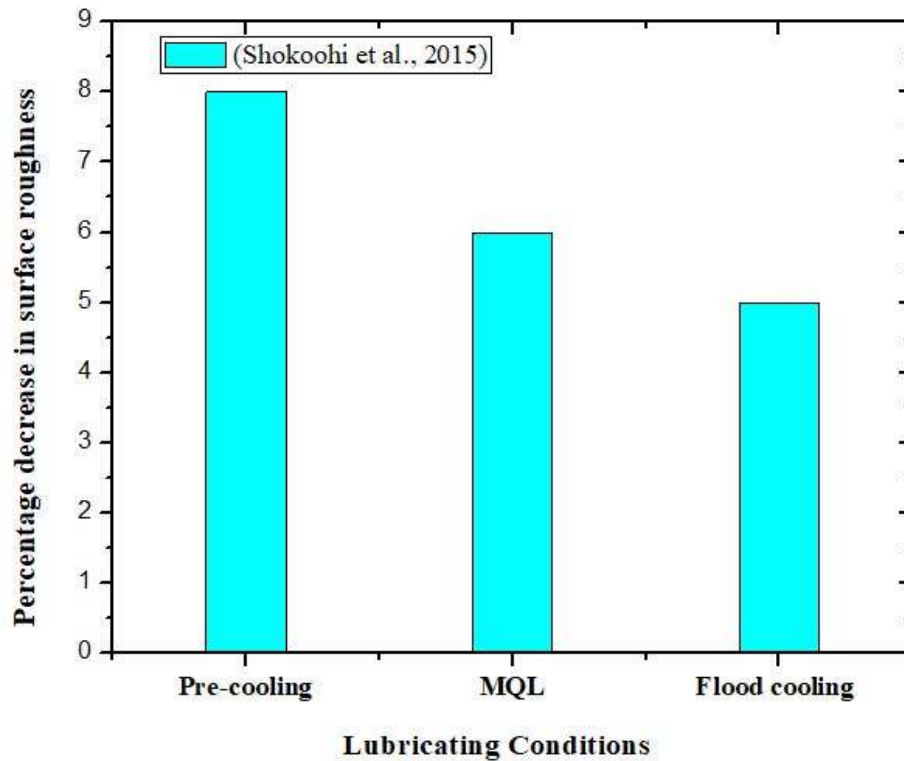


Fig 2.12 Percentage variations in surface roughness in different lubricating conditions (Shokoohi et al., 2015)

Development of innovative cooling techniques arises rapidly due to the requirement for improved cutting performance. The usage of vortex tubes in machining under an MQL environment can divide an entering compressed gas flow of identical heat into two streams. It consists of a vortex chamber, a cold air exit, a hot air outlet with a control valve, and an intake nozzle. An absurd behavior of a decrease of 35% in surface roughness was observed in dry machining (Fig 2.13). It is due to the decrease in vibration amplitude and the

machining trials conducted at low speed and feed rate. In contrast, to dry machining, surface roughness increases surprisingly in cryogenic and RHVT+MQL lubricating conditions as the cutting conditions are relatively higher than in dry machining. Moreover, the cutting temperature between the tool and workpiece decreases significantly with the Ranque-Hilsch vortex tube (RHVT) (Gupta et al., 2021).

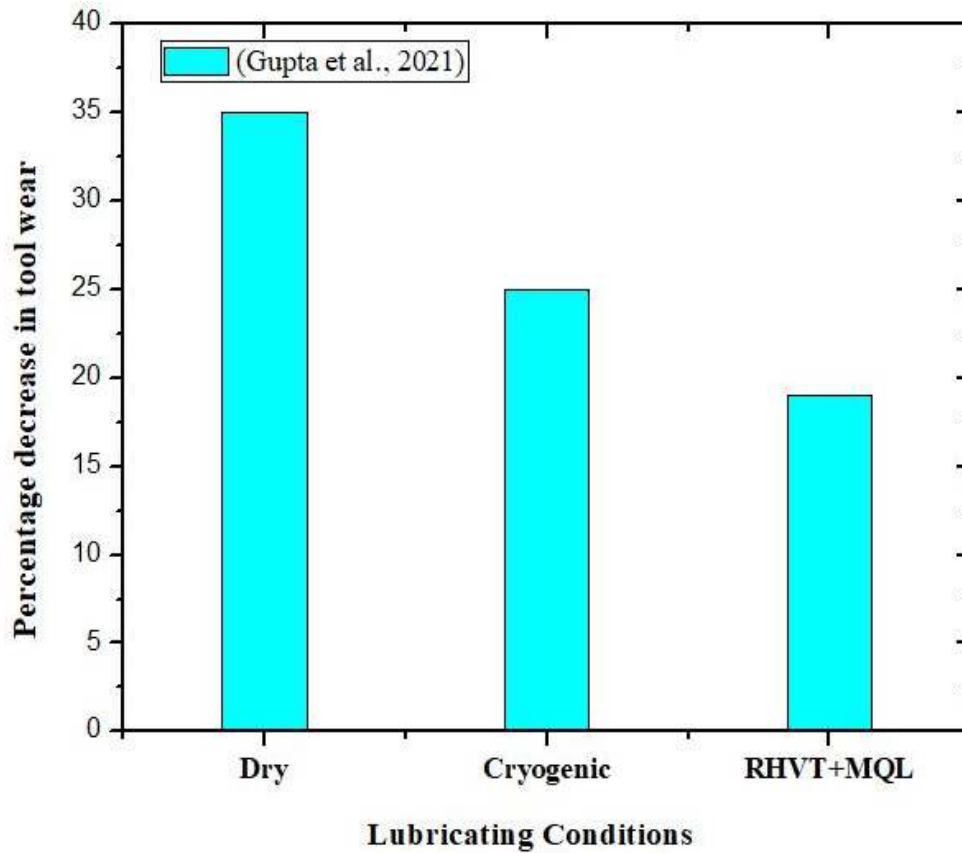


Fig 2.13 Percentage decrease in flank wear w.r.t cryogenic and MQL lubrication (Gupta et al., 2021).

Cutting performance by using emulsion mist in the MQL process can have significant improvement in cutting characteristics achieved due to optimal heat change and the introduction of extreme pressure (EP) and antiwear (AW) additives (Khanna et al., 2020). Renewable vegetable oil demand is growing considering health concerns and biodegradability in machining than mineral oil. Palm oil performed much better machining

regarding microhardness, surface imperfections, sub-surface deformity, and surface harshness (Dennison et al., 2020). Reduced forces, temperature, surface roughness, and tool wear are the highlights of nano-fluids machining compared to dry machining (Zhang et al., 2020). Base cutting fluids increase nano-particle concentration resulting in higher conductivity, viscosity, density, and more significant heat withdrawal (Sharma et al., 2016). Nano-fluids MQL produces better holes than compressed air and other base oil. Air and oil flow rate significantly reduce tool wear in MQL conditions during micro-milling steel specimens (Yıldırım et al., 2019).

Near dry or MQL machining offers a substantial improvement in the machining performance. But its implementation has some limitations in almost every machining operation. Firstly, due to less coolant, evacuation of chips is not proper in MQL machining as in flood machining. The design of this system is sometimes very complex and requires changes in the geometry of the tool, tool-holder, etc. The penetration rate of mist is relatively less than high-pressure fluids, creating instability in the deep-hole drilling and grinding process (Fratila, 2013).

2.8 Lubrication techniques used in aluminium alloys machining

Table 2.2 illustrates the importance of process parameters on machining characteristics and optimization and prediction using statistical design methods based on a review of recently cited articles on aluminium alloys. Optimization approaches are frequently used in machining studies to employ the appropriate measures and effectively present the statistically evaluated findings. The literature findings show that dry, wet, and MQL are widely explored in aluminium alloy machining, but at least for internal turning.

Table 2.2 Progress in the aluminium alloy machining

Material tested	Tool used	Machining parameters	Cooling/ Lubricants	Response Parameter s	Results/Inferences	References
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on technique					
6061 Aluminium Alloy	Diamond Coated Carbide	C_s :50-400 m/min f_o : 0.15 mm/rev w: 1.0 mm	Dry, Flood, MQL	Flank Wear, Cutting Forces, Surface Roughness	The speed directly affects flank wear, while the forces and roughness values are higher under dry conditions but fall under flood cooling.
Aluminium-Silicon Alloy SAE 323	Diamond Coated Carbide, Uncoated Carbide K10	V_c : 300 m/min, f : 0.1, 0.2 mm/rev, No. of Holes: 612, 408	MQL, Flood	Tool Wear, Cutting Forces, Cutting Power	Wear Decreases when using an uncoated drill in an MQL environment
1038 Steel, Cast 308 TiAlN- coated Aluminium	Solid carbide, TiAlN- coated drills	N;4130rpm, F_r : 0.13 mm/rev, P_r : 537 mm/min	MQL	Tool Wear	MQL gives a much higher drill life compared to dry drilling
Aluminium Alloy (A2017)	Uncoated carbide,	Speed: 100 m/min,	MQL	Flank wear,	DLC Coated tools give improved

(Sreejith,
2008)

(Braga et
al., 2001)

(Tai et al.,
2014)

(Saikawa et
al., 2004)

	DLC coated	S ₀ : 0.10 mm/rev, t: 15mm		Surface roughness	results than carbide in drilling tests	
Aluminium AA1050 Discs	Uncoated carbide	V _c : 60, 75, 90 m/min, S ₀ : 0.15, 0.20, 0.25 mm/rev	Dry, MQL, Flood	Cutting Forces, Surface Roughness	MQL and flood techniques result in a lowered cutting force and eventually the power.	(Davim et al., 2006)
6061 Aluminium Alloy	Uncoated Cemented Carbide	Feed rate: 0.01mm/rev, N: 5000-7000 rpm	MQL	Absorption behavior, Cutting Forces	Synthetic polyol ester and carrier gases enhance cutting performance	(Wakabayashi et al., 2007)
319 Aluminium Alloy	HSS, DLC	V _c : 50m/min, f: 0.25mm/rev, Depth: 15 mm	Dry, MQL, Flood	Thrust force, Torque	Reduced the drilling torque in H ₂ O-MQL cutting.	(Bhowmick and Alpas, 2008)
EN AC-46000 Aluminium alloy	Solid Carbide	Variable cutting speed, Drilling depth 250mm	MQL	Heat and Work Load	Significant heat reduction was achieved in MQL machining.	(Biermann et al., 2012)
EN AC-46000	Solid carbide	V _c : 100-170 m/min, f: 0.1-0.3mm	MQL	Heat Input	The lowered temperature was simply due	(Biermann and Iovkov, 2013)

Aluminum alloy				to the reduced machining times.	
Al7075-T6 alloy	Coated Carbide	V _c :	Dry, MQL	Surface texture and Chip morphology	Longer chip formation was observed in MQL cutting conditions.
		400,450,450 m/min; w: 1mm, F _r : 0.1mm/rev			

(Cagan et al., 2020a)

2.9 Optimization techniques in machining

Optimization is useful for obtaining the desired design parameters and suitable operating conditions. It also determines the corresponding decision value variables for the maxima and minima of one or more desired objectives. Formulation of objective functions and selection of suitable optimization methods define the accuracy of optimum solutions. Some of the commonly employed optimization techniques are:

- Grey relational analysis
- Genetic algorithm
- Artificial neural network
- Particle swarm optimization, etc.

Grey relational analysis presents an alternative method to the traditional single optimization for processes involving multiple optimizations. Deng (1989) suggested using the Grey Relational Grade to evaluate the degree of approximation between sequences. Recently, several investigators have explored adopting Taguchi-based grey relational analysis to optimize process parameters.

(Tzeng et al., 2009) studied the Taguchi technique and GRA optimization of turning operations with numerous performance criteria. The Taguchi approach and the GRA were used by (Kuram and Ozelik, 2013) to multi-optimize with multiple responses in the micro-milling. (Yan and Li, 2013) used the grey relational analysis to optimize the

milling parameters for energy, output rate, and cutting quality. (Tripathy and Tripathy, 2016) employed grey relational analysis to optimise wear ratio, surface roughness, tool wear and metal removal rate. (Angappan et al., 2017) Performed the modelling of optimization of turning parameters in dry-cutting conditions. The effect of the input parameters on the surface roughness and cutting forces were analyzed by grey relational analysis, and the optimal set of combinations was calculated. To determine the ideal process parameters for machining carbon nanotube-reinforced carbon fibre nanocomposite, the grey relational analysis (GRA) is utilised as an optimization method (Mausam et al., 2019).

(Younas et al., 2019) determined the optimal parameters with grey relational analysis in combination with an analytical hierarchy process for cutting energy and wear rate in sustainable machining of titanium alloy. (Pekşen and Kalyon, 2021) The machinability of stainless steel was experimentally and statistically evaluated using two types of different coated tool inserts and three levels of C_s and f_r . The effect of machining parameters and best optimum parameters were calculated with GRA analysis (Pekşen and Kalyon, 2021). Statistical analysis revealed an improved grey relational grade upon the confirmation test, consequently improving aluminium alloy's surface quality and chatter reduction (Hassan et al., 2021).

Another computer-based optimization which is mostly used in the machining process is the genetic algorithm. A genetic algorithm (GA) is a model that seeks to imitate a species' genetic progression. In particular, GA mimics the biological mechanisms that let successive generations of a population adapt to their surroundings. GA is a population-based search approach result. It began with a randomly generated population of individuals, each representing a collection of points covering the search space and made up of strings of the design variables. Each individual is appropriately coded into a chromosome composed of a long series of genes, where each gene uses a series of bits, a real number, or other alphabets to encode one of the design parameters. The fitness function is created to gauge how excellent a solution is. Better solutions should have a higher fitness function

value than inferior ones in the design. The selection method heavily relies on the fitness function.

(Hazir and Ozcan, 2019) Depicted the optimal parameter for surface roughness with GA and desirability function approach in CNC wood machining, considering various input parameters. Optimization findings were in line with machining results for the surface finish of the wood. (Kumar, 2018) An empirical model was created using experimental data and regression techniques to frame the fitness function. Genetic algorithms have optimised parameters for the excellent surface finish with little machining time (GA). Confirmation studies were conducted to ensure that the GA result was accurate and microchannels were successfully constructed. (Świć et al., 2020). For a high level of control process automation, algorithmic machine learning techniques were applied. We managed the turning process's dependability by training the network on data from actual measurements, accounting for several elements that are typically ignored during mathematical modelling. The trials' successful outcomes support the usefulness of the suggested approach for regulating low-rigidity shaft turning.

(Butt et al., 2021) the original and updated GA algorithms are discussed in a case study. The single-point optimised placement demonstrates contact loss when the machining force is applied at other sites. The workpiece's isostatic is shown to be unaltered in the placement optimised by the updated method, despite all four positioning errors converging to the same value. The outcomes of the suggested and updated algorithm are confirmed by utilising simulation.

When modelling nonlinear issues like machining operations, an artificial neural network (ANN) is one of the key artificial intelligence techniques. Artificial neural networks can precisely predict and optimise machining operations more than conventional techniques.

(Ozcelik et al., 2005) for end milling of Inconel 718 alloy with the best cutting conditions and the least surface roughness, an artificial neural network and genetic algorithm were merged. Three-level complete factorial designs were utilised in the statistical method of research. The approach mentioned above performed well and showed

good agreement. (Palanisamy et al., 2008) used ANN modelling and regression to estimate tool wear during end milling AISI 1020 steel with carbide cutters. The experiment's design included three complete factorials with five levels. Cutting speed, feed rate, and depth of cut were used as inputs in the models, while flank wear was the output response. The authors discovered that the ANN model outperformed the regression model regarding flank wear prediction.

(Guo et al., 2008) Combined two trained and tested subnetworks, achieved multisensor tool wear and breakage detection. The outputs of the three different sensors used for the multisensor detection were fed into two separate neural networks, and the outputs of those networks were then used as inputs in a combined neural network.

(Kant and Sangwan, 2015) examined how well an artificial neural network model can forecast the cost of energy use. According to the results, the research's suggested model can anticipate energy usage. Such models are necessary for the current environment so that prediction models' acceptance may be increased, and they can be used in sustainable process planning during the manufacturing stage of a machine tool's life cycle.

Kennedy and Eberhart (1995) established particle swarm optimization (PSO) to address issues with continuous optimization. Volumeless particles with stochastic velocities that make up the swarm individually stand for a workable solution. The algorithm moves the particles in the solution space until it finds the best answer. PSO is incredibly easy to implement and requires a little computer code. It just needs simple mathematical operators, which makes it computationally efficient in performance and memory use. PSO combines elements of GA and evolution techniques.

(Župerl et al., 2007) PSO was used to improve the milling machining process parameters. A predictive model was created using ANN to forecast the cutting forces during machining for the best process parameters for milling machining, such as cutting speed and feed rates. The findings showed that the suggested approach increased the quality of the solution while accelerating the convergence process compared to existing evolutionary strategies like GA and SA. (Babbar et al., 2020) For mono- and bi-objective constrained optimization, the effects of individual and combination process parameters

were studied using conventional PSO, FA, and hybrid HPSO-FA. By using an inventive method to process the brass plate, it was discovered that machining time was the most important factor that contributed most to the variation in the determined response variables.

2.10 Sustainability indicator model: Life Cycle Analysis

Environmental degradation and decreased availability of resources crop an idea of life cycle analysis in 1960. Life cycle analysis concentrates upon energy usage, carbon emission, and other ecological pointers. Various research groups and technical committees, particularly in Europe and the United States of America, started developing a database (Ecoinvent) for analysis and policies for sustainable development in 1970. Afterwards, certain governments apply various policies for sustainability, environmental protection, and the harmful emission of toxins from production. Nowadays, life cycle assessment (LCA) widened its approach from different products commissioned by industries and governments of major countries. Environmental concern, energy, and material depletion are the main focus of life cycle assessment. It is a tool to evaluate the ecological impact and resource utilization throughout the product's life cycle. Management of waste products (solid, chemical, etc.) for environmental protection is done by the analysis of input-output parameters ([Guinée et al., 1993](#)).

LCA utilizes various standards and databases governed by the ISO 14040-14044 (1997-2006), Environment management- life cycle assessment, and European Commission (2010). The prominent role of life cycle analysis is cataloguing the environment and regulations on the product life cycle and its waste management. The future of LCA is promising as most countries are dedicated to working on sustainable development, the ecosystem, cleaner production, and high energy efficiencies ([Michael Z. Hauschild, Ralph K. Rosenbaum, 2018](#)). Over the recent years, a transition has been made to sustainable development from conventional, which is far more encouraging and widely accepted by many nations globally. The year 2015 is known as the year of sustainability, including the sustainable development goals (SDGs) and the United Nations framework on climate change. Effective use of natural resources, less energy consumption, and technological

advancements necessitate shifting to sustainable production. Sustainable consumption and production is a comprehensive method for minimum use of natural resources and waste management across product life cycles. Sustainable product analysis deals with environmental concerns and social and cost assessment (Narita and Fujimoto, 2009). In the LCA analysis, there are four major factors-

- goal definition and scope assessment
- inventory handling
- impact assessment
- improvement analysis.

Goal definition deals with identifying purpose and creating system boundaries and various assumptions. The inventory analysis, termed life-cycle inventory analysis (LCIA), addresses material, energy consumption, and environmental emissions during each manufacturing stage (Finnveden et al., 2009). Upon quantifying environmental emission, LCIA impact analysis focuses on human health impact by energy and raw material contribution. At last various prospects were evaluated for energy reduction, material requirement, and ecological impact assessment at each phase of the product life cycle.

2.10.1 Applications of life cycle analysis

Over the past decades, life cycle analysis has been widely accepted for various industrial applications such as energy systems, electric vehicles, production, biofuels, sustainable design of buildings, agriculture, chemicals, nanomaterials, drinking water supply, solid waste management, wastewater treatment, etc.

The energy requirement is expected to rise rapidly across the globe, thus putting pressure on the supply of conventional fossils. Therefore, alternative resources are in demand, which can significantly replace conventional resources. Thus for a sustainable environment, depletion of fossil resources, energy security, and abrupt climate change focus upon sustainability. (Hertwich et al., 2015) Climate change indicators include particulate matter exposure, freshwater toxicity, and eutrophication under the baseline scenario. They developed a novel hybrid life cycle analysis model and compared the results

with international energy agency standards by collecting inventories for solar, photovoltaic, and wind power. Emissions through this process were critically analyzed by life cycle analysis. A similar study on a macro-scale conducted by (Laurent and Espinosa, 2015) showcased the importance of environmental impacts in energy system requirements by comparing different energy across multiple nations and recommended the applications of life cycle assessment on a global scale.

(Turconi et al., 2014) assessed the environmental impact of wind power by collecting data on the electricity supply from 2010. They emphasize greenhouse gas reduction, which increases other impact categories. The life cycle analysis was done by using electricity, biomass, and generated power in cogeneration plants. A comparison is drawn between Denmark's low-carbon and conventional electricity systems. Furthermore, concluded that Denmark may expressively reduce global warming impacts and abundant consumption of fossil resources with wind energy generation as a replacement for coal-based electricity.

The evolution of electric vehicles is an excellent alternative to conventional petroleum oil-based vehicles. Electric vehicles can considerably reduce CO₂ emissions compared to conventional internal combustion vehicles. The emission of greenhouse gases is responsible for climate change. Electric vehicles emerged as a sustainable alternative fuel technology and significantly reduced greenhouse gas emissions.

Life cycle analysis of the automobile industry is dependent upon data collection with GREET Model (Greenhouse gases, regulated emissions, and energy use in transportation model). The GREET model is open-source interactive software for evaluating electric vehicles. It contains vital information about various vehicle components' manufacturing and life stages (Wang et al., 2006). (de Souza et al., 2018) conducted life cycle analysis on fuel consumption and powertrain configurations of vehicles. Various fuel consumption scenarios and functional units of 1-kilometre distance covered were taken for life cycle inventory analysis. The results revealed that ethanol has a higher impact on the environmental assessment for acidification, and gasoline has a higher impact on fossil fuel depletion.

Moreover, the electric vehicles operated through batteries have the least ecological impacts, followed by ethanol-operated vehicle. (Sen et al., 2019) established a unique life cycle assessment method for calculating the material footprint of vehicles across local and global supply chains. Battery production of vehicles leads the life-cycle material footprints and accounts for more than 65% direct impact on material footprints.

Moreover, to have a sustainable future in the automotive sector source of raw materials is vital in developing alternative fuel vehicles. (Shafique et al., 2022) The life cycle assessment approach addressed the societal concerns on the environmental advantages of electric vehicles and included the future scenario of vehicles from 2024 to 2050 in Hong Kong. They employed the future electricity mix situation for petrol and diesel-fueled vehicles and compared it with electric vehicles. LCA results revealed that electric vehicles with a 2050 electricity mix are an optimum choice and the environmental impact was least in most sustainability indicators compared to gasoline and diesel-driven vehicles.

Oil depletion, global warming, and the scarcity of fossil fuels are global concerns. Biofuels are one of the viable alternatives for economic reasons and an alternative to fossil fuels. Biofuels reduce greenhouse gas emissions and diversify fuel production in most areas. For the life cycle analysis of all biofuels, global warming is a standard sustainability indicator (Van Der Voet et al., 2010). Biofuels can replace fossil fuels and can have a significant decrease in energy in the transport sector. The blending of bioethanol with wheat is an alternative to fossil fuels by which a considerable decrease in GHG is achieved by the inventory analysis from the well-to-tank and well-to-wheel approach (Gnansounou et al., 2009). In a study conducted by (Liu et al., 2018) on the life cycle assessment of bioethanol and biodiesel fuels as alternative fossil fuels across China. Inventory analysis evaluated GHG emissions and energy consumption, revealing a significant variation for bioethanol.

Furthermore, the production of bioethanol from corn, sugarcane, etc., is proven to be more sensitive to energy and cost-effective. (Mayer et al., 2020) presented a comparative study on energy analysis with LCA on energy ratio calculation for the

efficiency and sustainability of biofuel production. Energy is evaluated by the mathematical equations governed by case studies of sugarcane ethanol and biodiesel production. Inventory allocation and its analysis revealed significant results for ethanol in terms of various sustainable parameters.

Life cycle analysis of energy usage in the building considerably decreases energy consumption and controls emissions. It is an approach for entire energy inputs to a building throughout its life cycle. The LCA system's boundary conditions comprise the building's manufacturing, use, and end phase. The primary energy use in building results in 40-50% greenhouse gas emissions. Distribution of life cycle energy consisting mainly of operating energy of the building. Due to this, it is the most critical parameter for the design of a building (Ramesh et al., 2010). To suppress the demand for energy in the building, there are many alternatives like; insulation of walls, the low emissivity of coatings, solar thermal power collector, and heat pump coupling with air/water. (Mithraratne and Vale, 2004) used higher insulation for energy saving in a timber house and presented a comparison with different measures.

Energy reduction can be attained with soil, cow dung bricks as the replacement of burnt clay bricks, cement, etc. Energy can also be reduced by using recycled material in construction. This can attain more than 50% more energy savings and is cost-effective (Thormark, 2000). (Hegeir et al., 2022) implemented life cycle assessment to compare the environmental impact on an industrial building made of timber, concrete, and steel. Three different materials produce frames to sustain the building load. The LCA results revealed that timber has a good sustainable impact compared to steel and concrete.

2.10.2 Life cycle analysis in machining

Machining processes are the main components in the production industry and contribute a lot to the growth of the global economy. Machining performance increases with improved tool-workpiece materials, and eco-friendly environment techniques are becoming extremely popular for cleaner production. The temperature generated during machining is not the same for some materials such as stainless steel, superalloy, Inconel,

and Titanium grades. It can be reduced with the use of cutting fluids but have a direct impact on the environment and cost. Certain cutting fluids are carcinogenic and expose the operator to various skin diseases, cancer, etc. Thus, sustainable lubrication (dry machining, MQL, cryogenic machining, etc.) in manufacturing becomes an obvious choice. For sustainable analysis, LCA is a valuable tool for assessing the environmental impact and providing a comparison between different cooling strategies.

(Abbas et al., 2019) investigated the impact on the environment concerning surface roughness and power generated during the machining of AISI 1045 steel. The sustainable assessment is also carried out for machining cost, waste management, and the worker's health. Results presented a 23% increase in sustainability index during nano-fluid minimum quantity lubrication. Better performance is due to less resource utilization, low lubricant usage, and less energy consumption. Dry machining gives the best results in sustainability indicators due to the absence of lubricant and no requirement for power to run the air compressor. Thus, in all three lubricating conditions, dry machining is the most sustainable process as it gives an increase of 35% in the sustainable index (Fig 2.14).

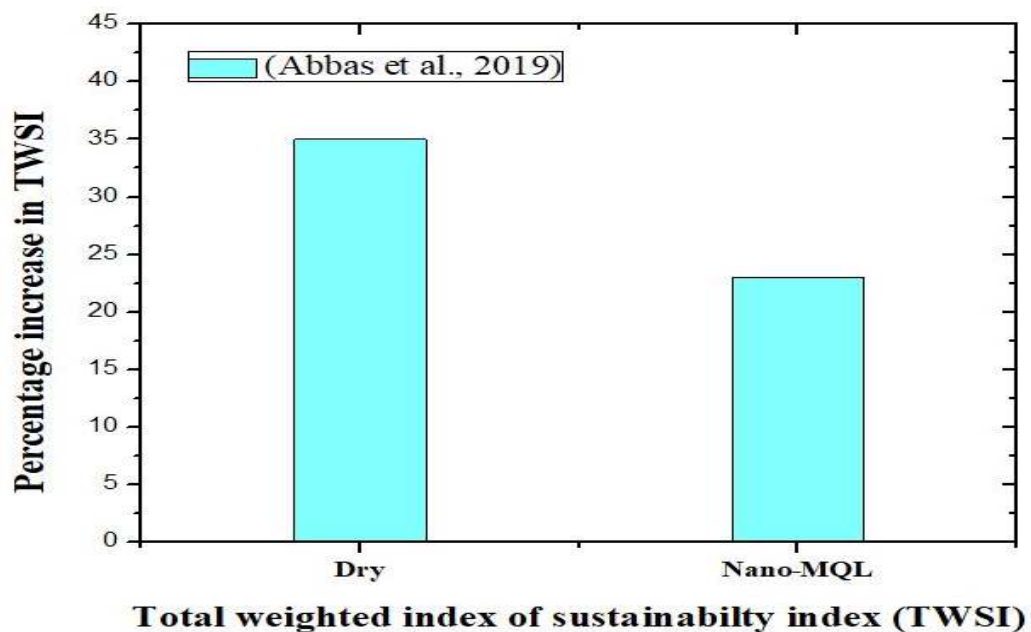


Fig 2.14 Percentage increase sustainability index w.r.t flood machining (Abbas et al., 2019)

(Zhou et al., 2016) discussed the energy consumption in machining and the effectiveness of machine tools. The energy consumption in a machine tool comprises fixed and variable modes. Fixed energy consumption utilized for machine tool operation, lubricant supply, and chip disposal. Tool change and tool monitoring come under variable energy consumption. Energy efficiency and ecological aspects are discussed for sustainable assessment. (Kishawy et al., 2019) conducted a similar investigation during the machining of Ti-6Al-4V by considering surface quality, power consumption, and tool wear under MQL and nano-MQL environments. A specially designed algorithm is used for the estimation of design variables. The study's sustainable indicators were the worker's safety, environmental impact, and waste management. LCA results revealed that machining trials performed under nanofluids lubrication give better results in less power consumption and tool wear and fewer fumes inhalation by the operator.

LCA is a handy tool for environmental impact assessment during each product's life-cycle for sustainability. It is widely applied in various machining operations involving the use of lubricants. (Clarens et al., 2008) compared the LCA results of water and air-based delivery of lubricants. Air lubricant proved more effective in aquatic toxicity and solid waste and reducing the health concerns of the operator. From the cooling and lubrication perspective, air-delivered lubrication is not adequate; for these machining operations, supercritical CO₂ -based lubrication gives promising results in cooling and ecological advantage.

Moreover, it was concluded that gas-based lubricant is more promising toward global warming potential than water-based lubricant. (Campitelli et al., 2019) investigated the resource utilization in flood and MQL lubrication strategies during milling and turning on steel, cast iron, and aluminium. By hotspot analysis derived from the CML baseline 2001 method, electricity, lubricant, and compressed air are responsible for environmental impact. Due to less lubricant consumption in the MQL strategy, water toxicity is comparatively lower than flood lubrication. However, compressed air usage in MQL is significantly higher than flood lubrication.

(Narita et al., 2008) investigated climate change using the ReciPe method on seventeen impact categories in electric-discharge machining of medium carbon steel. Inventory data was collected on electricity consumption, lubricating oil, coolant usage time, and chip disposal. They analyzed that carbon dioxide emission is more prominent toward global warming. (Pereira et al., 2016) compared environmental footprints and carcinological and non- carcinological impact on operator health with wet machining, minimum quantity lubrication, cryogenic cooling, mixed cryogenic, CO₂, LN₂, and dry machining. As mineral-based oils produce more harmful fumes during machining, thus the inhalation capacity increases in all coolant conditions. But in dry machining conditions, heat dissipation is minimal and increases the temperature of whole working areas. That is why dry machining increases the impact of non-carcinogenicity. Due to the absence of lubricating oils, CO₂ gives the best 19% decrease in non-carcinogenic impact compared to dry machining (Fig 2.15).

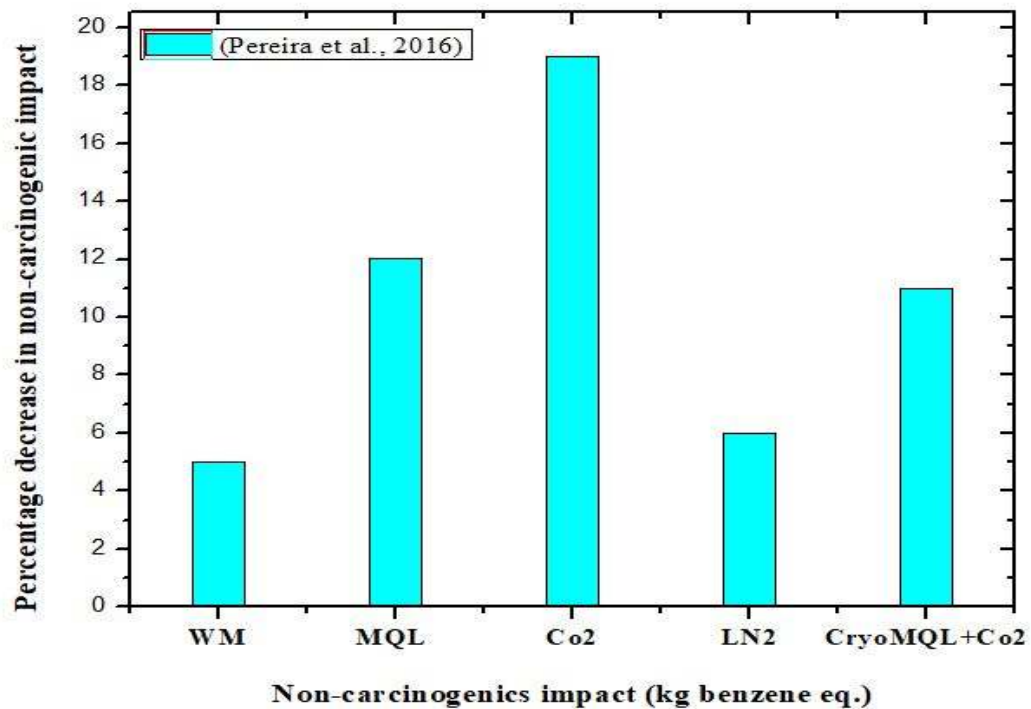


Fig 2.15 Percentage decrease in non-carcinogenic impact w.r.t dry machining (Pereira et al., 2016)

(Fratila, 2010) compared the dry, flood, and MQL lubrication during milling of alloy steel with the Eco-indicator 99(H) LCA method. The preparation of material and scrap management are also considered in the analysis, along with the material removal rate. Results revealed that flood machining has a higher environmental impact than dry and MQL machining. (Faludi et al., 2015) drawn a comparison by life cycle analysis on machine usage in additive manufacturing and CNC machining. LCA results governed by the ReciPe endpoint (H) method revealed that CNC machining is less sustainable than additive manufacturing (AM) due to more waste production.

(Yilbas et al., 2017) performed laser-assisted machining on Ti-6Al-4V alloy, steel 304, Inconel 625, and alumina with kerf width as a process parameter. Life cycle analysis is employed to assess the environmental effect of material wastes. Results revealed that material selection in laser machining is vital for environmental safety. Among all, Inconel 625 has the most environmental damage. However, its contribution can be reduced significantly by recycling the waste. (Singh and Madan, 2015) Gate-to Gate life cycle analysis in different cooling conditions (near dry, flood, and cryogenic) was performed by considering coolant consumption, land utilization, and water usage as sustainability indicators. The functional unit (FU) is selected as 1 kg of material removal and performed on SimaPro 8.0.1 software with Eco-indicator 99. Results interpreted that flood machining is more prone to human health and resources. Moreover, near-dry machining has more impact on the ecosystem than cryogenic machining.

(Winter et al., 2012) conducted turning of alloy steel under dry, mineral-based, and jatropha oil-based emulsion, considering cutting force and surface roughness as process parameters. The functional unit of the utilization of emulsion was selected through the cradle-to-gate approach for life cycle analysis. Results showed that jatropha emulsion is a sustainable substitute for metalworking fluids and has less environmental impact. (Mia et al., 2019) performed machining trials on Ti-6Al-4V under dry and liquid nitrogen lubrication. Life cycle analysis was carried out by EPS 2000 method, and inventory data was collected from the experimentation. Results presented a relationship between lubricating strategy and environmental indicators such as biodiversity and human health.

Liquid nitrogen cooling improves the machining quality in comparison with dry machining. (Shah et al., 2021) conducted life cycle analysis using the ReCiPe 2016 midpoint (H) method during drilling of Inconel 718 in cryogenic liquid carbon dioxide and LN₂ lubricating medium. LCO₂ gives higher machining performance by less cutting temperature generation and low power consumption. Furthermore, the ecological effects are better than LN₂ machining.

2.11 Summary

This segment presented a brief overview of the material and its various applications. Along with that, the machining characteristics of aluminium alloy are highlighted. The state of the art of vibrations induced and its various suppression techniques have been presented. Machining of aluminium alloy with different cutting tools, cutting conditions, and lubricating medium is highlighted. Furthermore, the introduction of life cycle assessment and its various applications, particularly in machining, is discussed effectively.

- As evident from the literature review, aluminium has good lightweight characteristics and is corrosion resistant. Due to these properties, it is widely accepted in the automotive sector, aerospace industry, and other engineering applications. Aluminium alloy has good machinability and can sustain high temperatures during machining. The selection of suitable cutting conditions affects the machining performance and increases the machining productivity.
- During low-to-medium speed machining aluminium alloy gives excellent machining productivity but will not be suitable for high-speed machining as the chip length increases, which can clog the cutting area resulting in an undesirable surface finish. Due to low chemical affinity, sometimes the possibility of adhesion is more during machining but can be overcome by using a lubricant. Suitable cutting tool selection during machining can significantly improve the machining performance by reducing tool wear and cutting temperature.

- The machining process involves the rotary and reciprocating parts during production. Due to this, unwanted chatter or vibration occurred in various components, decreasing the surface finish and reducing the tool life.
- Different vibrations observed during machining lead to poor productivity and decreased machining efficiency. From the literature analysis, several researchers developed various techniques such as active vibration control, passive vibration control, and semi-active vibration control for the vibration control, which can increase surface characteristics and machining productivity. Active vibration reduction techniques require continuous monitoring of the machining system and can be detected or overcome with the help of actuators and advanced sensors. However, different dampers and configurational changes in the cutting tool, customized tool holders, and insulations can significantly decrease the severe effect of vibration. When machining is carried out under the action of an electric or magnetic field in the presence of electrorheological or magnetorheological fluids also gives improved results in chatter suppression.
- Extensive work has been done on vibration control of a machining operation. But literature is minimal, particularly in active vibration control in the machining of aluminium alloy.
- In every machining operation, heat generation is high in the cutting zone, further deteriorating the surface quality, and excessive temperature decreases the tool life with increased tool wear. To overcome this issue, much work has been done to reduce the accumulated heat from the cutting regime by reducing the speed, feed, etc., or with the effective usage of lubricant. Lubricants can be water- or air-based, serving both the purpose of cooling and lubrication.
- Dry machining is a sustainable approach from an ecological perspective but offers high energy consumption. Wet machining can reduce the cutting temperature and can facilitate high-speed machining. But due to the abundant use of lubricants, machining costs increase, and disposal of lubricants in the environment is a prominent issue.

- Minimum quantity lubrication (MQL) offers a more sustainable approach by utilizing an aerosol of air and lubricants. Less utilization of resources decreases the overall production cost, and the release of toxins from the machining zone is less than in wet machining.
- Extensive literature is available on machining engineering material, composites, etc., with dry, flood, and MQL lubrication separately, but minimal work is done with the combination of these cooling/lubrication techniques.
- Life cycle analysis is a global tool used for ecological impact assessment for various applications such as sustainable building, production, chemicals, agriculture, and the automotive sector.
- Life cycle analysis is a sustainable approach for evaluating the environmental aspects based on raw material utilization, electricity consumption, and tool-workpiece-lubricant usage. Its scope also covers the economic and social impact on critical indicators governed by various methods such as Eco-indicator 99, EPS 2000, CML 2001, Impact 2002+, ReCiPe Midpoint (H), and ReCiPe Endpoint (H).

2.12 Problem formulation

After an extensive literature review, different types of vibration induced in a machining process and their repercussions on the machined component and tool state were studied. The magnitude of the vibrations must be less to achieve the dynamic stability of the system. Many researchers at national and international levels have established the latest vibration-damping technologies such as active, passive, and semi-active vibration control; with these damping techniques, the dynamic stiffness of the boring increases. It also increases the surface finish of the workpiece and achieves a considerable decrease in tool wear. From the pertinent literature review, it is understood that active vibration control tracks the vibrational amplitude continuously, and no configuration alteration in the system or boring bar is required. Any alteration in the configuration results in disturbed geometry of the boring bar or additional attachment, bringing instability of (Nguyen et al., 2018) cutting conditions much more than the passive vibration control, e.g., particle impact

damping. To investigate the cutting stability through vibration amplitude, recently utilized integrated piezoelectric shunt damping (Yigit et al., 2017) is used.

Similarly, the detailed review of literature on the various machining operations of numerous workpiece materials by different cutting tool materials and under various lubrication conditions shows that dry machining is far more sustainable. It offers less utilization of resources for machining and also reduces overall machining costs. Increased temperature and high energy consumption is the main drawback of this process. Usage of coolant/lubricant can significantly reduce the cutting temperature and facilitates the chip removal from the cutting regime. Most components in manufacturing industries are machined by flood or wet machining. But, excessive use of lubricants increases water contamination and exposes the machine operator to various carcinogenic and non-carcinogenic diseases (Brinksmeier et al., 2015). Due to the more resource usage during machining, wet machining increases the cost of production and is not a sustainable approach. The above limitation of dry and wet machining creates the idea of using the minimum quantity of lubrication or eco-friendly lubricants. As per the comprehensive review of literature, MQL utilizes a few ounces of lubricants in a mix with air which consequently serves both the persistence requirement of cooling and lubrication. Thus, MQL is a sustainable approach that reduces the overall usage of resources and energy for machining performance and also helps safeguard the operator's environmental pollution and exposure to harmful fumes (Kouam et al., 2015). Many global researchers tried various combinations of lubricating conditions on different workpiece materials (Davim et al., 2006; Sankar and Choudhury, 2015).

Sustainable assessment focus on human health and the effective use of available resources (coolant, electricity, air, cutting tool, workpiece, etc.). It also enlightens the effect of a manufacturing process on environmental impact indicators. As evident from the detailed literature database, LCA is a helpful technique for sustainable assessment for various applications and is widely explored nowadays (Khanna et al., 2020).

In the present study, experimentation focus on the measurement of vibrational amplitude and surface roughness with or without the presence of piezoelectric shunt

damping. The difference between the measured values of vibrational amplitude and surface roughness depicts the performance of the damping approach. Cutting speed, feed rate, and width of cut were selected as input parameters for boring experiments on aluminium alloy 6061 with coated carbide tool. Moreover, the optimization of responses was investigated by the statistical approach. For the experimentation on dry, wet, and MQL lubrication, experimentation uses conventional cutting conditions (cutting speed, feed rate, depth of cut) and three lubricating conditions in an internal turning operation on aluminium 6061 alloys to investigate the effect of cutting conditions and lubricating medium on surface roughness, chip morphological analysis, and tool wear. For the life cycle assessment, data collected during the experimentation was taken as inventories and further processed by the LCA database analysis. The software illustration focuses on comparing dry, wet, and MQL during machining in terms of sustainable indicators such as water toxicity, eutrophication, land usage, etc.

3.1 Selection of workpiece material

Specimen for boring operations were prepared from commercially available aluminium alloy 6061 extruded pipe. The length of the workpiece was 457 mm, the internal diameter was 69mm, and 3 mm in thickness [Fig 3.1](#). [Tables 3.1](#) and [3.2](#) showcased the chemical compositions and properties of the material as per ASTM standards. Silicon and magnesium are chief alloying elements that give resistance to high temperatures and maintain a substantial strength during machining.



Fig 3.1 Specimens for machining

Table 3.1: Chemical compositions of aluminium alloy 6061 ([Aamir et al., 2020b](#))

Element	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn	Al
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Amount	0.8-	0.4-	0.7	0.15-0.4	0.04-	0.25	0.15	0.15	96.85
(wt%)	1.2	0.8			0.035				

Table 3.2: Properties of aluminium alloy 6061

Properties	Value
Hardness (BHN)	95
Ultimate tensile strength (MPa)	310
Yield strength (MPa)	277
Machinability	50%
Elongation	13%
Modulus of elasticity (GPa)	69
Thermal conductivity (W/m-K)	168

Aluminium alloy 6061 has good machinability due to work hardening and good thermal conductivity. It is corrosion-resistant and widely used for various industrial applications. The x-ray diffraction (XRD) analysis reflects the composing elements of the material (Fig 3.2). It confirms the presence of silicon and magnesium in high peaks. Smaller peaks correspond to the other elements like zinc, nickel, iron, etc. (Fig 3.3) represent the EDS analysis of aluminium alloy 6061, the highest peaks of aluminium can be seen, followed by magnesium, copper, silicon, etc. (Fig 3.4) represent the scanning electron microscopy (SEM) of the workpiece before machining.

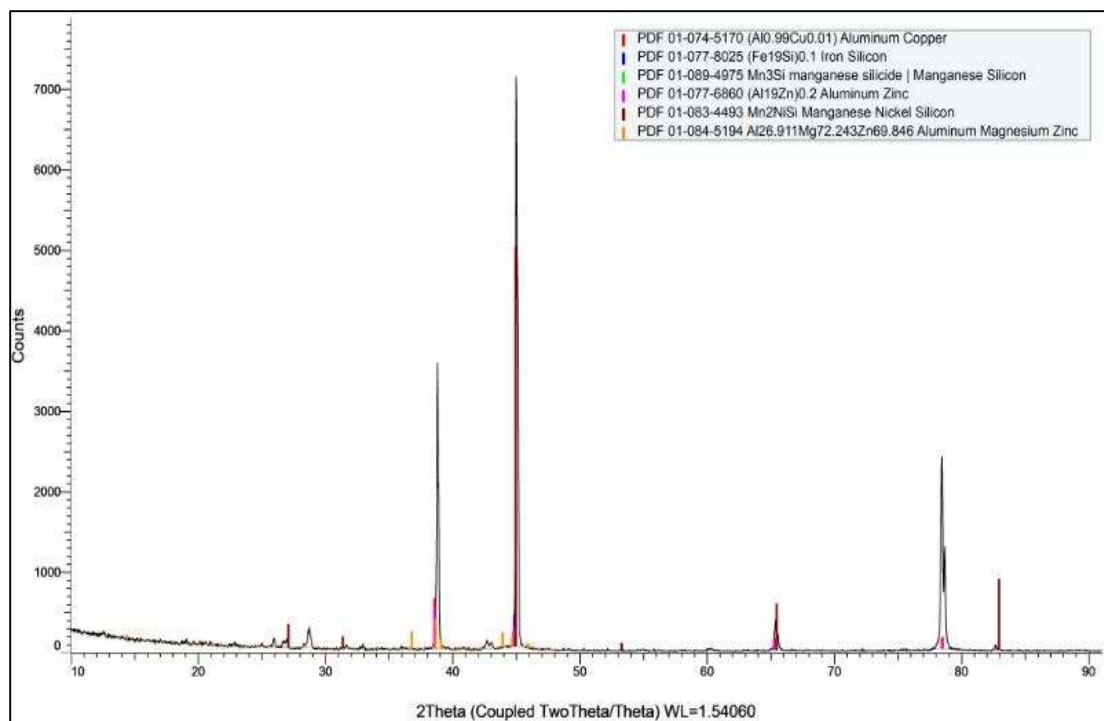
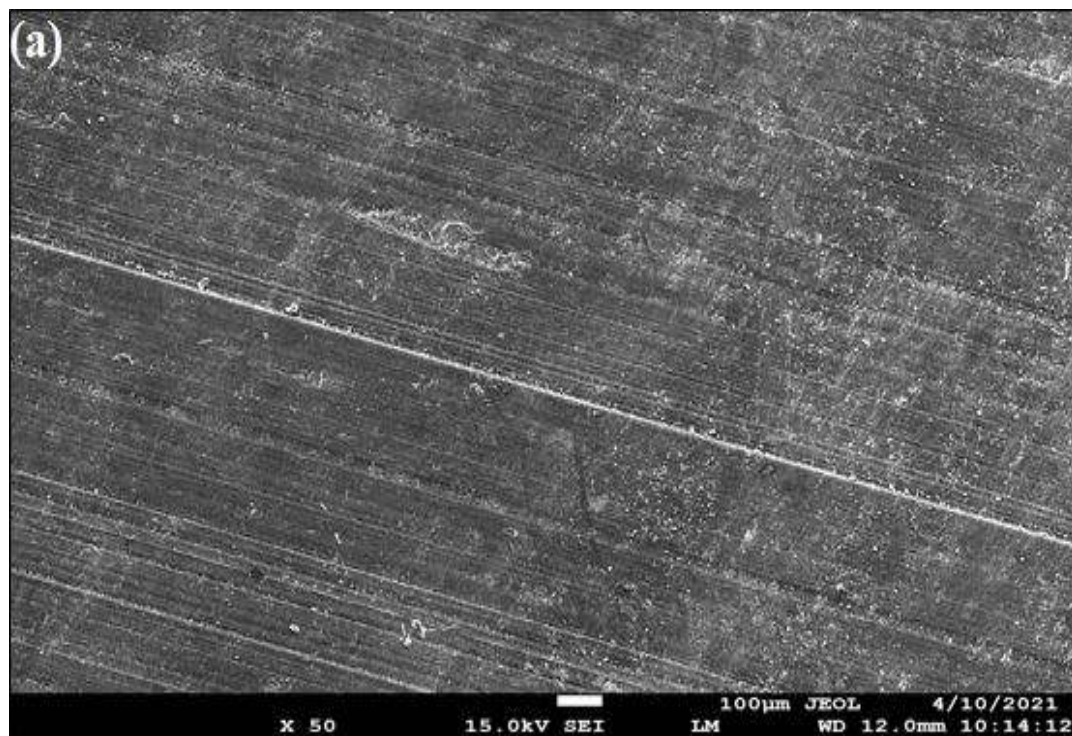


Fig 3.2 XRD analysis of the material



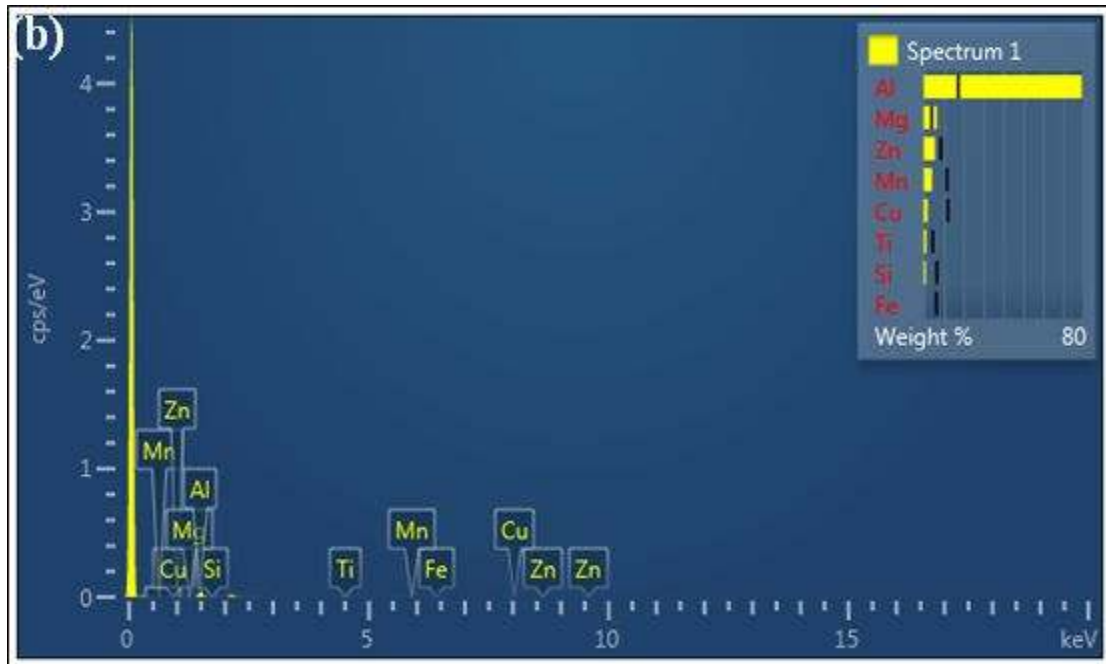


Fig 3.3 (a) SEM image of the workpiece before machining (b) Energy dispersive spectroscopy (EDS) spectrum of the material

3.2 Selection of cutting tool material and boring bar

Chemical vapor deposition (CVD) coated carbide inert manufactured by Wintech carbide is used for experimentation with ISO designation VNMG160408-QM. It has a fine-grain Al_2O_3 coating, which expands wear-resistance property and provides resistance against breakage failure. The dimension of the tool is given in (Fig 3.5).

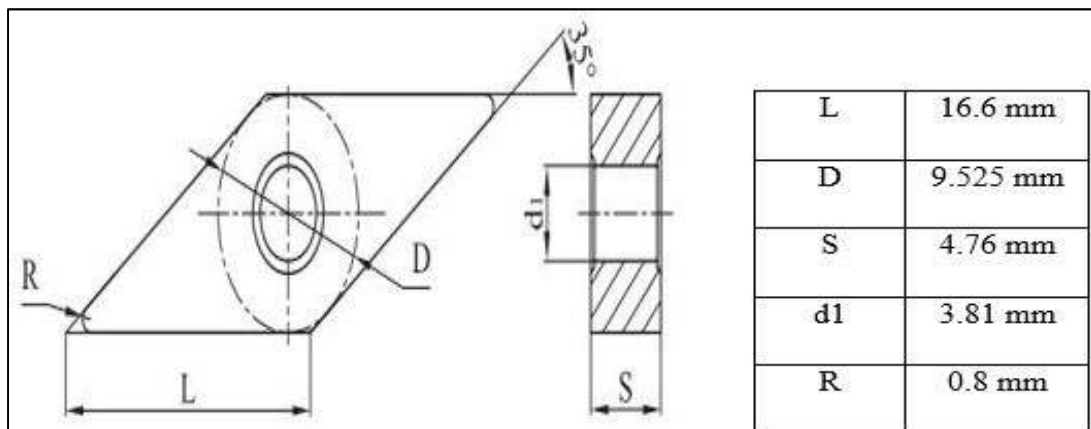




Fig 3.4 Cutting tool specifications and their geometry

The boring bar serves the purpose of a tool holder in an internal turning operation. For the experimentation, a through-hole boring bar having the designation A16TDCLNL4KC3 manufactured by Kennametal was used (Fig 3.6). The dimension of the boring bar is given in (Table 3.3).

Table 3.3: Dimensions of boring bar

Specification	Dimension/Designation.
SAP Material Number	2408507
ISO Catalog Number	A16TDCLNL4KC3
[D] Adapter / Shank / Bore Diameter	25.4 mm
[DM] Minimum Bore Diameter	30.48 mm
[F] F Dimension	16.26 mm
[L1] Tool Length	304.8000
[CS] Coolant Supply Size	1/4-18 NPT
Gage Insert	CN-432
Clamp Screw ID Drive Size	15 IP

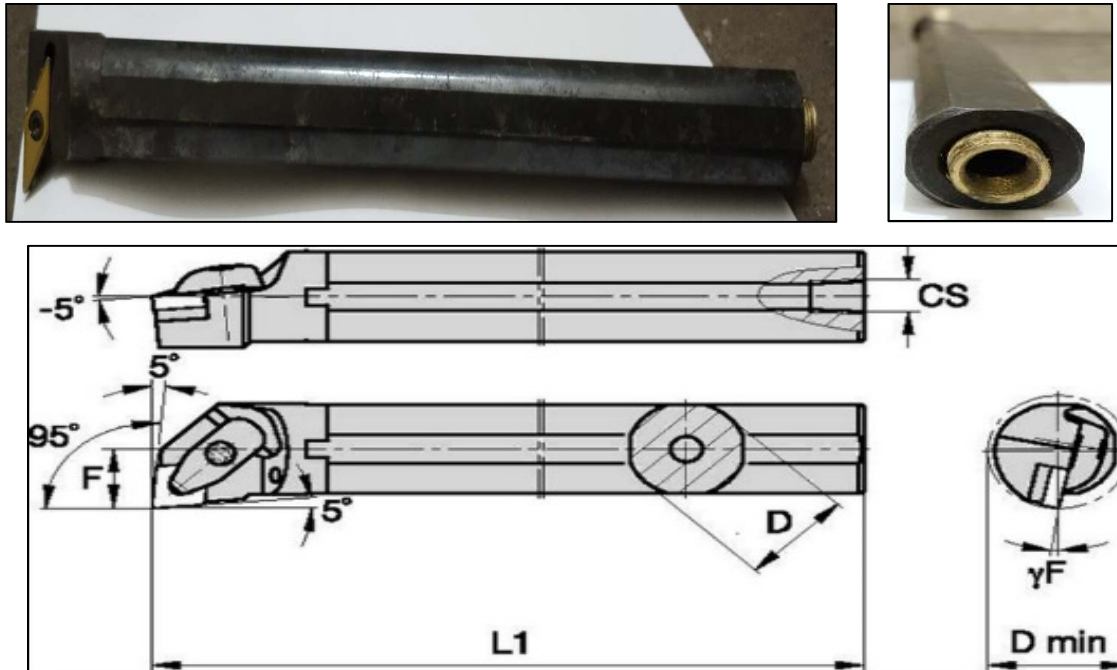


Fig 3.5 Boring bar and its geometry

The current experimental investigation is focused on vibration reduction by the piezoelectric shunt damping approach and the performance of machining responses in dry-cutting conditions.

3.3 Experimental details for vibration reduction

It includes the application of piezoelectric shunt damping techniques for vibration reduction. Piezoelectric shunt damping helps in the attenuation of vibration signals through active-vibration control. The experimentation focused on investigating the effect of damping strategy during machining and its effect on vibration amplitude and surface roughness. The adopted research methodology for this experimentation is given in [Fig 3.7](#):

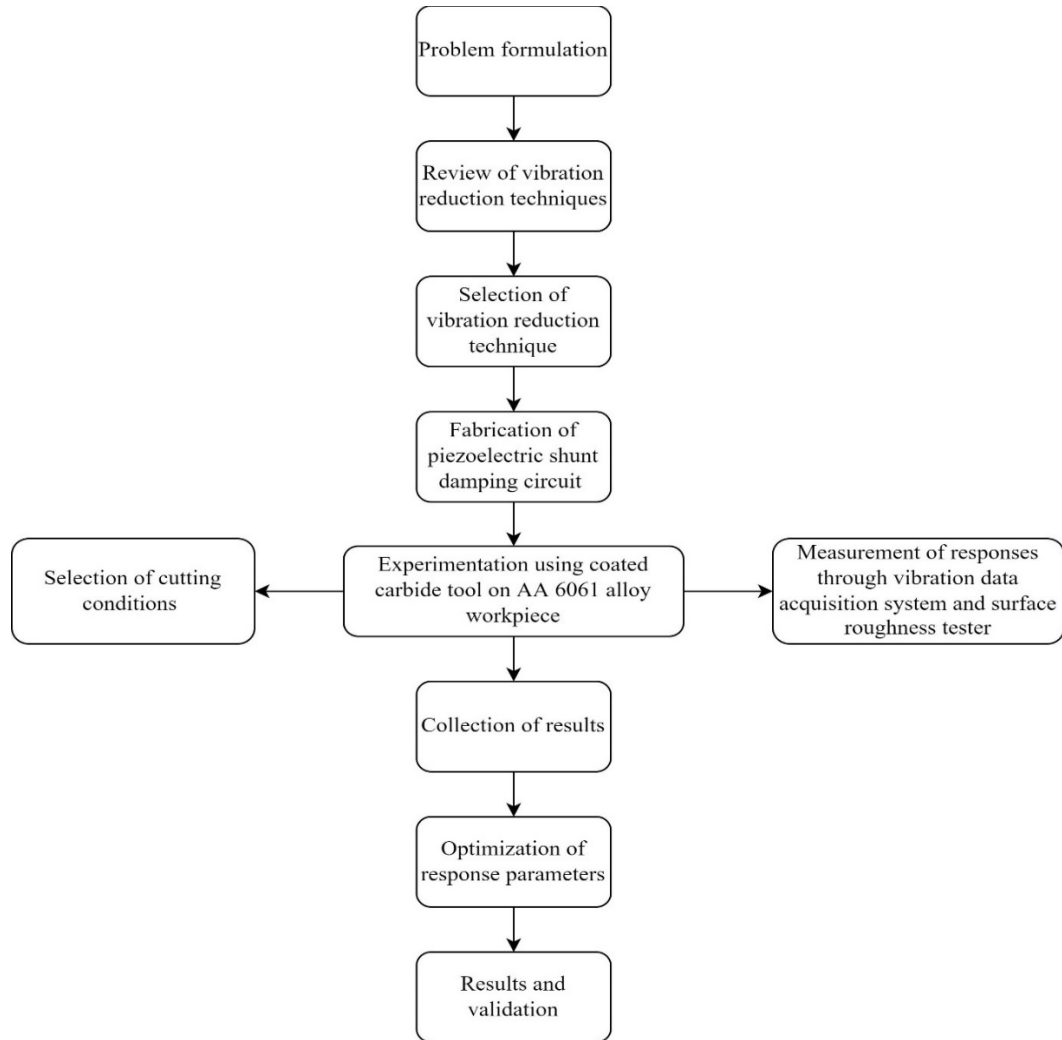


Fig 3.6 Adopted research methodology for vibration reduction

3.3.1 Selection of cutting conditions and design of experiments

The cutting length was selected of 15mm for all experimental trials. The boring bar overhang length was 260 mm. The factors and their levels considered in this study are shown in Table 3.4. Experiments are conducted with three factors, each at three levels; hence, a three-level orthogonal array (OA) is chosen. Experimental findings were statistically evaluated by grey relational analysis. Factors and levels are selected from the pertinent literature survey (Biermann and Iovkov, 2013; Cagan et al., 2020b; Davim et al.,

2006; Saikawa et al., 2004; Sreejith, 2008). The experiments are conducted using Taguchi L₉ OA as per Table 3.5.

Table 3.4 Factors and levels

Parameters	Units	Levels		
		1	2	3
Cutting speed (Vc)	m/min	200	260	320
Feed rate (f)	mm/rev	0.15	0.20	0.25
Depth of cut (w)	mm	0.3	0.5	0.7

Table 3.5 Taguchi experimental design L₉ orthogonal array

Trial number	Controllable input parameters		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3.3.2 Fabrication of piezoelectric shunt damping circuit

The graphic illustration of the boring bar, piezoelectric materials, and shunt circuit utilized for experimentation setup is given in Fig 3.8. The piezoelectric sensors attached to the four places on the boring bar are utilized to convert electrical energy into mechanical energy. The piezoelectric sensors are placed at 80 and 150 mm from the cutting insert. Because at these points, the magnitude of vibrations is more. It works on the principle that

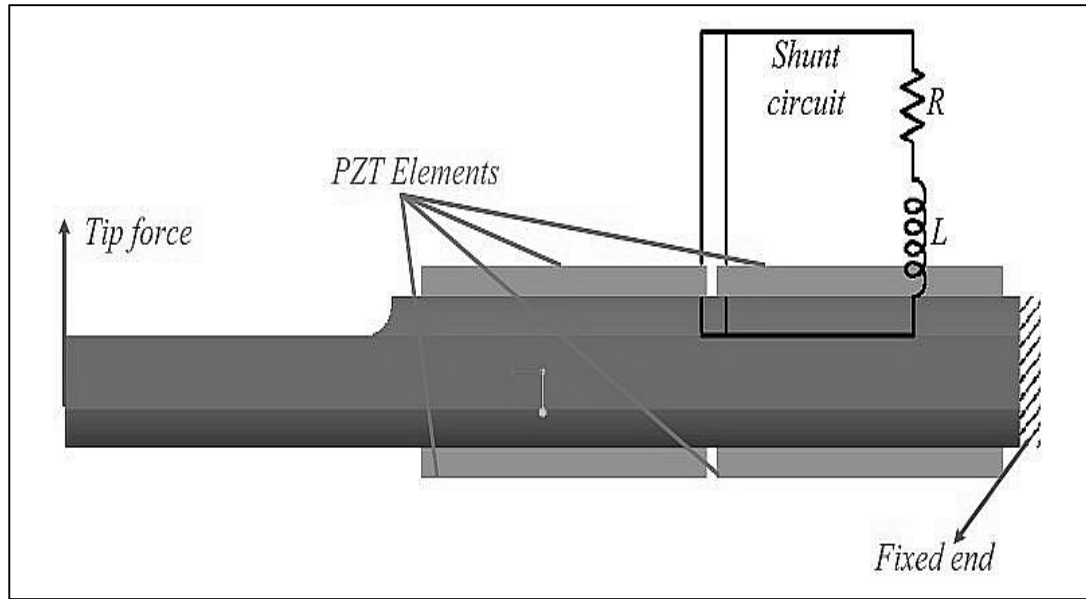


Fig 3.7 Circuitry on the boring bar for amplitude reduction (Yigit et al., 2017)

any structure experiences acceleration when it deviates from its original position, whether by rotation or translation. Physical acceleration produces a charge in the attached system and alters the output response, reducing the vibration. Four piezoelectric patches are attached to the boring bar based on the functionality. The piezoelectric patches convert voltage into vibration or vice-versa and work under the piezoelectric effect. The detailed characteristics of the piezoelectric sensors are given in Table 3.6.

Table 3.6 Specifications of piezoelectric patch

Dimensions	25.4 x 6.3 x 2 mm
Resonance frequency	4.63 KHz +/- 0.5 KHz
Impedance	205 Ohms
Capacitance	20nF +/- 35% at 1 KHz

The shunt damping method involves connecting an electrical impedance to the terminals of a transducer. A host structure is connected to the piezoelectric transducer. The transducer creates electricity when the host structure vibrates. An external shunt circuit

dissipates mechanical vibration energy, reducing the vibration of the host structure. A resistor linked to the transducer acts as a viscoelastic damper, dispersing the kinetic energy. If the shunt comprises an inductor and a resistor series-connected, it provides a decelerated electrical resonance that could be set so that shunt damping serves as a damped vibration absorber [Fig 3.9](#).

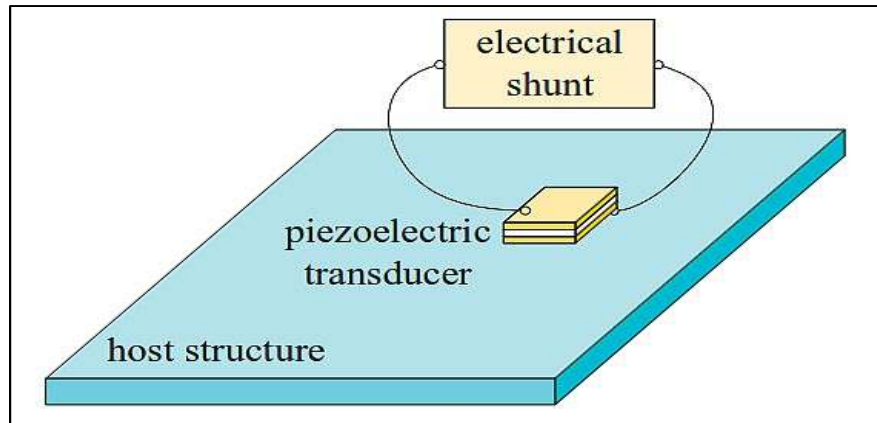


Fig 3.8 Used model of piezoelectric shunt damping (Yan et al., 2017)

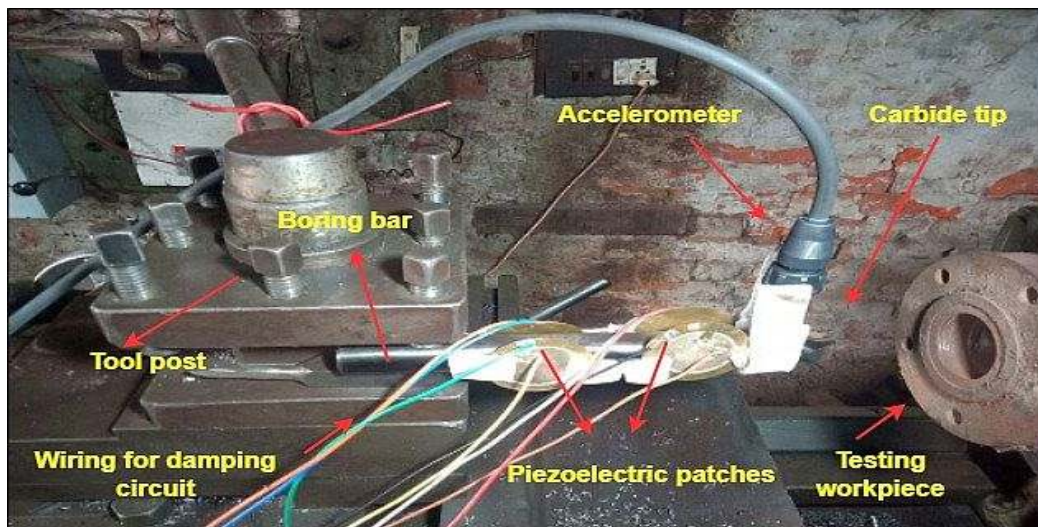


Fig 3.9 Boring bar equipped with piezoelectric transducers and accelerometer

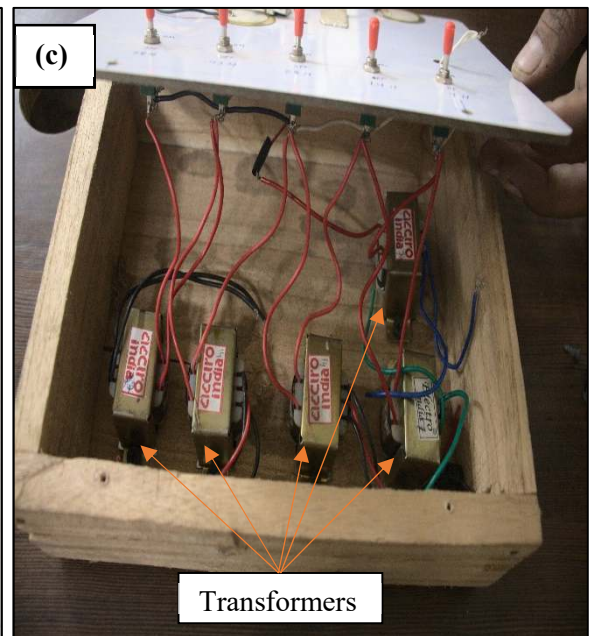
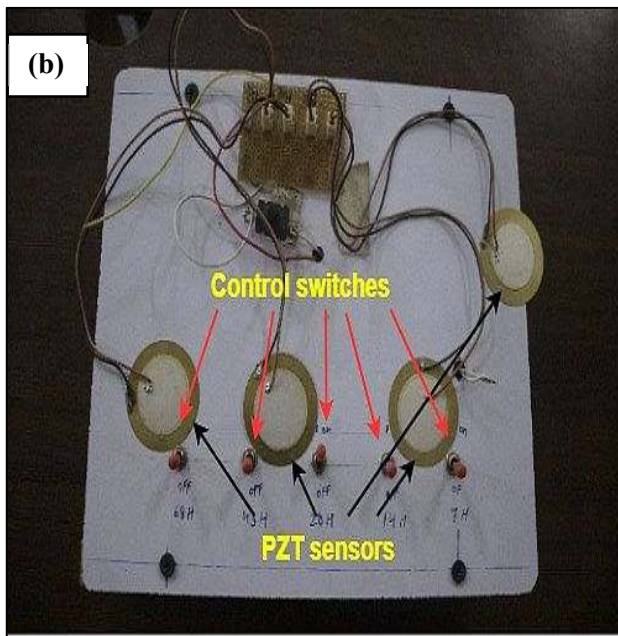
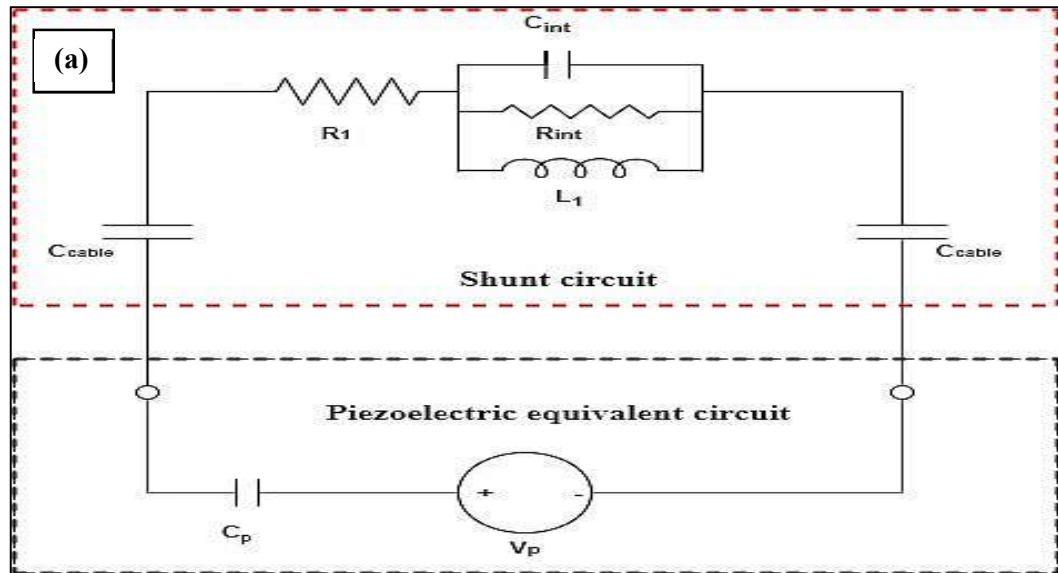


Fig 3.10 (a) Circuit diagram of R-L-C circuit (b) Fabricated R-L-C shunt damping circuit with piezoelectric sensors (c) Simplified view of R-L-C circuit

The inductor value is kept at 10H, and piezoelectric patches are located near the tool tip. This is to counter the effect of the first mode of vibration. The accumulation of

series capacitance in the shunting limb of the circuit just serves to modify the circuit's natural frequency, efficiently mistuning the shunt [Fig 3.11](#). It consists of internal resistance, capacitances of cable, and inductor.

3.3.3 Comparison of proposed setup with magnetic actuator-based damping

A technique similar to piezoelectric shunt damping is the magnetic actuator-based active vibration control, where there is no need to alter the configuration of the boring bar. It consists of a magnetic actuator with sensors for measuring the boring bar displacement. It decreases the motion of the boring bar electromagnetically by inducing the current across the system, particularly in the bending modes. With the help of sensors, the control system records the feedback in the axial or biaxial directions. One such setup was used by ([Lu et al., 2014](#)) for chatter reduction in a boring process.

The actuator consists of four similar magnetic units. Each magnetic unit comprises two excitation coil windings, one permanent magnet, a stator core, an armature core and an actuator housing. The assembly was mounted on the lathe machine for machining operation [Fig 3.12](#).

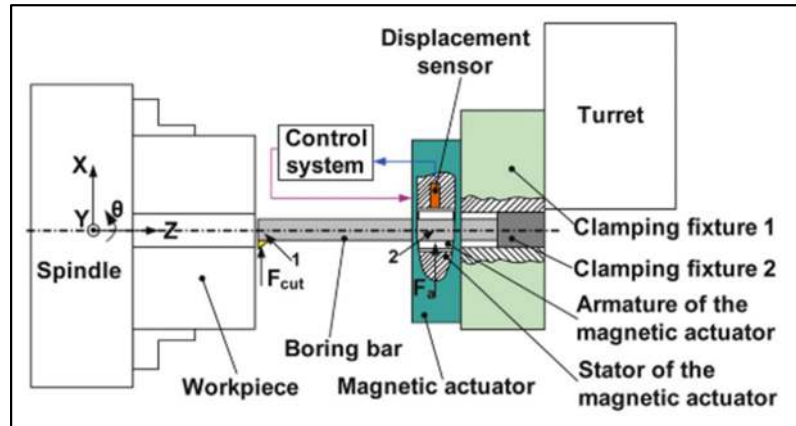


Fig 3.11 Damping through magnetic actuator for a boring operation ([Lu et al., 2014](#))

The displacement sensors act similar to the piezoelectric sensors in [Fig 3.11 \(b\)](#), and are used to record the modes of vibrations in the cutting directions. Additional attachment is required for clamping magnetic actuators with the boring bar. The

displacement sensor works similarly to the accelerometer for displacement measurement of the boring bar. This setup revealed a linear relationship between current and cutting forces. Also, magnetic actuator damping observed an increase in the dynamic stiffness of the boring bar.

3.3.4 Data acquisition system

The accelerometer commonly measures vibration. An accelerometer is a sensor that measures the dynamic acceleration of a device in terms of voltage. The accelerometer used for vibrational amplitude is given in Fig 3.10 and Fig 3.13. The piezoelectric effect, which happens when particular types of crystals are strained, is used in most accelerometers. The test structure's acceleration is transferred to a seismic mass within the accelerometer, which produces a proportionate force on the piezoelectric crystal. This external stress on the crystal causes a high-impedance electrical charge proportional to the applied force and consequently proportional to the acceleration.



Fig 3.12 Accelerometer for vibrational amplitude measurement

An accelerometer attached to the boring bar is further coupled with a data acquisition system supplied by National Instrument USA (NI-9234) Fig 3.14. NI-9234 was equipped with four (Bayonet Neil-Concelman) BNC connectors connected to four simultaneously sampled analogue input channels. When the IEPE current is switched off, the NI 9234 employs a common-mode bias current to bias the current-limiting diodes. This

current generates an error dependent on the AI-lead impedance when the NI 9234 uses grounded signal sources. Per Ohm of AI- impedance, this inaccuracy is around 50 ppm of range and 15 ppm of reading. Only grounded sources are affected by the common-mode bias current; floating signal sources are unaffected. When connecting grounded signal sources, utilize a floating connection or low-impedance leads for optimum accuracy. The specifications of the NI-9234 data acquisition chassis are given in [Table 3.7](#), respectively.

Table 3.7 Specifications of NI-9234 data acquisition chassis

No. of channels	4 analog input channels
Analog-to-digital converter (ADC)	24 bits
accuracy	
Type of ADC	Delta-Sigma (with analog prefiltering)
Sampling mode	Simultaneous
Data rate range (f_s) using external master timebase	Minimum: 0.391 kS/s Maximum: 52.734 kS/s
Data rates (f_s)	$\frac{f_m \div 256}{n}$, $n = 1, 2, \dots, 31$
Input coupling	AC/DC



Fig 3.13 NI- 9234 Data acquisition chassis with USB carrier

3.3.5 Surface roughness tester

Fig 3.15 shows a portable stylus-type surface roughness tester, the Surftest SJ-201 (Mitutoyo, Japan), used to measure roughness. On the touch screen, the measurement data are shown digitally. The Mitutoyo instrument (Surftest SJ-201) is a self-contained, portable surface texture assessment device. The specifications of surface roughness tester Surftest SJ-201 are: Measurement range--200 m to +250 m; Stylus material- Diamond; Measuring force- 4 mN (0.41gf); Cut-off length- 0.8 mm-2.5 mm; and Tip radius- 2 m. Surface textures may be assessed using three parameters: arithmetic average value (R_a), root mean square value (R_q), and the average distance between the highest peak and lowest valley (R_z). The average surface roughness (R_a) is used for analysis based on the literature study. It is the average total values of the profile height deviations from the mean line recorded within the evaluation length (Goodhand et al., 2016).

$$Ra = 1/L \int |z(x) - \mu| dx \quad (1)$$

R_a is defined as average absolute displacement from the mean level for a measured length, L. Surface roughness measurements on the workpieces were performed with a scan length of 5 mm, three times in the transverse direction to the cut, and an average of three measurements of surface roughness parameter values was recorded.



Fig 3.14 Surface roughness tester

3.3.6 Experimental procedure

The stepwise order of experimentation was performed to evaluate the chatter reduction during the boring of aluminium alloy 6061 in the dry cutting condition in terms of mean vibrational amplitude, and surface roughness is described below:

- 1) Setting the piezoelectric shunt damping circuit and data acquisition chassis for the experimentation.
- 2) Internal turning experiments were performed as per Taguchi L₉ orthogonal array on AA 6061 alloy specimens with a coated carbide tool enclosed in a standard steel boring bar for various possible combinations of cutting speed, feed rate, and depth of cut under a dry machining environment.
- 3) Mean vibrational amplitude (mV) was measured with an accelerometer using NI-9234 data acquisition chassis and surface roughness (μm) of the machined surface with the Surftest SJ-201 surface roughness tester.
- 4) Results were procured from each experimental run based on the output responses with or without the piezoelectric shunt damping technique.
- 5) The Grey relational method was used for multi-objective optimization of mean vibrational amplitude and average surface roughness for output minimization under dry machining for the AA 6061 alloy workpiece.
- 6) After the statistical approach for optimization of machining responses, it was required to test the performance of coated carbide tip. The confirmation experiment was carried out at the optimal settings to ensure that the quality characteristics of the boring process specified by the previous study are met.
- 7) The machined surface under piezoelectric shunt damping or without it was micro-examined by Scanning electron microscopy (SEM) for surface characteristics investigation.

3.4 Experimental details for machining under different cooling conditions

It deals with fabricating an experimental setup for machining in dry, flood, and minimum quantity lubrication. It includes the fabrication of a mixing nozzle for air and lubricant supply in a single channel and the delivery of aerosol through the nozzle in the cutting zone. The primary purpose is to analyze the effect of the machining parameters (cutting speed, feed rate, and depth of cut) on surface roughness (R_a) and tool wear (V_b) during cutting in dry lubrication, flood lubrication, and minimum quantity lubrication. Furthermore, evaluate the effect of cutting conditions and lubrication on the machined surface, tool condition, and chips and the optimization of responses. The research methodology adopted for this study is outlined below in Fig 3.16:

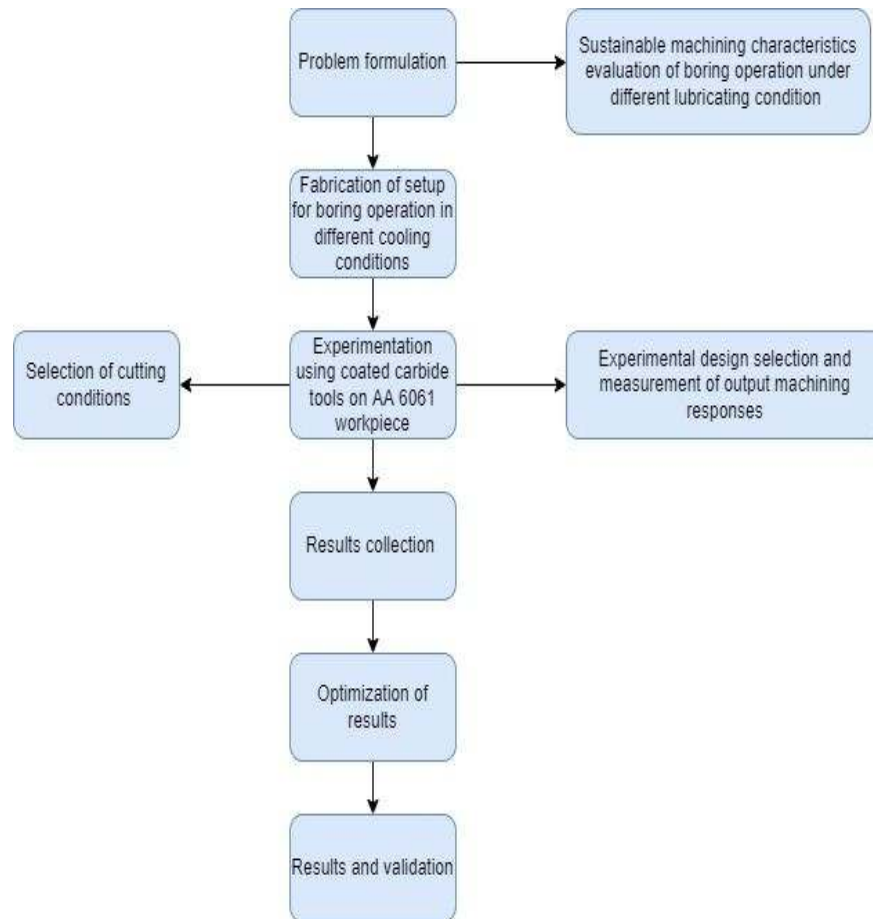


Fig 3.15 Adopted research methodology for machining under different cooling/lubricating techniques

3.4.1 Selection of cutting conditions and design of experiments

A constant cutting length of 80 mm was used for all machining trials. The boring bar was employed with an overhang length of 260 mm. From the detailed literature survey, cutting speed, feed rate, and lubrication medium was selected as input parameters. Taguchi L_{27} orthogonal array was selected for experimental combinations of cutting conditions and lubricating medium. Three input factors such as cutting speed, feed rate, and lubrication medium are used to evaluate the effect on output parameters (Aamir et al., 2020b; Biermann and Iovkov, 2013; Cagan et al., 2020b; Davim et al., 2006; Del Sol et al., 2019; Saikawa et al., 2004; Santos et al., 2016; Sreejith, 2008; Tisza and Czinege, 2018; Zaman and Dhar, 2019; Zhu et al., 2020). The factors and their levels are given in Table 3.8. The selected orthogonal array is given in Table 3.9.

Table 3.8 Machining limits with different settings

Limits	Symbol	Units	Settings		
			1	2	3
Cutting speed	V_c	m/min	185	215	245
Feed rate	f_r	mm/rev	0.15	0.20	0.25
Depth of cut	w	mm	0.3	0.5	0.7
Coolant medium	C_m	-	Dry	Flood	MQL

Table 3.9 Taguchi experimental design L_{27} orthogonal array

Trial number	Controllable input parameters			
	A	B	C	D
1	1	1	1	1
2	1	1	1	1

3	1	1	1	1
4	1	2	2	2
5	1	2	2	2
6	1	2	2	2
7	1	3	3	3
8	1	3	3	3
9	1	3	3	3
10	2	1	2	3
11	2	1	2	3
12	2	1	2	3
13	2	2	3	1
14	2	2	3	1
15	2	2	3	1
16	2	3	1	2
17	2	3	1	2
18	2	3	1	2
19	3	1	3	2
20	3	1	3	2
21	3	1	3	2
22	3	2	1	3
23	3	2	1	3
24	3	2	1	3
25	3	3	2	1
26	3	3	2	1
27	3	3	2	1

3.4.2 Experimentation plan for internal turning operation in different lubricating conditions

Internal turning trials were executed on 200mm long aluminium alloy 6061 workpieces (Fig 3.1) with carbide insert Kennametal through-hole boring bar on a conventional lathe at different cutting parameters. A specially designed mist nozzle with a mixing chamber was utilized, and output was taken through the boring bar (Fig 3.6) to lubricate the tool-workpiece interface Fig 3.17. The purpose of the mist nozzle is to mix the lubricating oil with water and convert it into an aerosol.

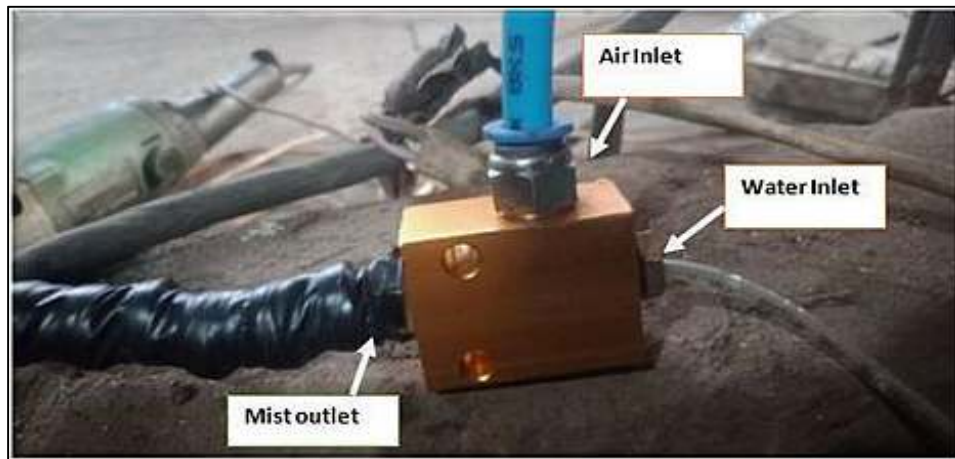


Fig 3.16 Mist nozzle for machining

A single line with a mixing chamber is created by grooving a slot, and a 120 mm long nozzle having a diameter of 8.8 mm was used for the MQL supply for the experimentation. Include spray angle kept at 60° to maintain the coverage distance of approximately 58mm. Nozzle output was further connected with a through-hole boring bar for the final delivery to the cutting area. The following assumptions were made in the MQL setup: a) the surface finish will increase by the lubricating actions during machining, b) Due to lubrication, it might decrease the tool wear, and c) Interfacial cutting temperature will decrease.

All the experiments were conducted on a single setup for dry, flood, and minimum quantity lubrication (MQL) machining to evaluate the extensive machinability features, as shown in Fig 3.18. The experimental conditions for this work were finalized after a

pertinent literature survey and as a tool and workpiece manuals recommendation. Water miscible cutting fluid is used for flood and mist lubrication which is commercially available. It offers substantial lubrication and cleaning of the machined surface and is less toxic than conventional coolants. The experimental details are given in Table 3.10. An Air compressor was used to supply the compressed air directly to the mist nozzle, where the aerosol formation was completed in the mixing chamber.

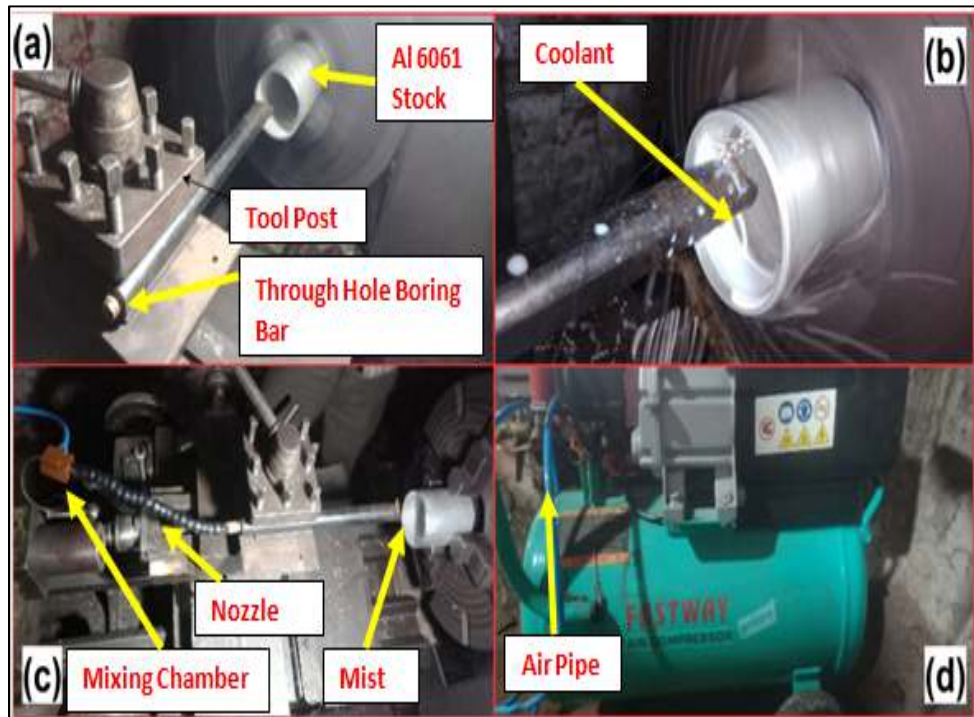


Fig 3.17 Experimentation setup (a) Dry Machining (b) Flood cooling (c) MQL machining (d) Air compressor

Table 3.10 Experimental conditions

Machine Tool	Manual Lathe Machine 6ft 14 x 12, HMT 6, 2 HP
Work material	6061 aluminium alloy (75mm outside diameter and 69mm internal diameter, 3mm thickness)

Boring Bar Specifications	Kennametal A16TDCLNL4KC3, Diameter: 30mm, Length: 304.8000, L/D ratio:10, Through hole type
Cutting insert geometry	VNMG160408-QM, L:16.6mm, D: 9.525, S: 4.76, d ₁ : 3.81, R: 0.8
Process parameters	v _c : 185, 215, 245 m/min, f _n : 0.15,0.20,0.25 mm/rev, a _p : 0.3,0.5,0.7mm
Cutting Condition	Dry, Flood and MQL
Air Pressure & Lubricant Flow rate	6 bar, Dry: 0ml/h, Flood: 120,000ml/h, MQL: 100ml/h though internal nozzle in boring bar
Metal working fluid	Hysol M70 soluble metalworking fluid

3.4.3 Cutting fluid for lubrication

Soluble metalworking fluid (MWF) was employed as a lubricant in the experimentation for flood and MQL lubrication. The lubricant was Hysol M70 (Castrol India). It can reduce friction and act as a coolant that directly minimizes the effect of heat generation during the machining of aluminium alloy. It also gives a cushion to transit from medium-speed to high-speed machining. Reduction in the operating cost and good surface quality are the chief characteristics of the selected cutting fluid. The technical specifications of the cutting fluid are outlined in [Table 3.11](#):

Table 3.11 Specifications of cutting fluid

Name	Value
Mineral Oil	40-50%
Concentration Range	6-15%
Metal Types	Aluminium, cast iron, high alloy steel / stainless steel, low/med alloy steel

Multi Metals Suitable	Yes
pH (5%) by DIN 51369 ASTM E70-97 method	9.8
Refractometer Factor	1.0
Formulated Without Chlorinated Paraffin	Yes
Formulated Without Boron	No
Appearance	Milky
Ester Extreme pressure Additives	Yes
Applicable to these sectors	Aerospace, automotive manufacture, machinery, metal goods
Product Type	Metalworking fluids

3.4.4 Air compressor used in experimentation

The air compressor was used to give a compressed air supply of 6 bar [Fig 3.19](#). It facilitates the mixing with cutting fluid supplied through the pump in the mixing chamber. The amalgamation results in an aerosol which was directed with the help of a mist nozzle on the machining area. It was a single-stage belt-driven compressor. Technical specifications of the air compressor are given in [Table 3.12](#).



Fig 3.18 Air compressor used for compressed air supply

Table 3.12 Specifications of air compressor

Name	Value
Power	3 HP
Air tank	24 litre
Flow rate (max.)	84.2 bar
Cooling method	Air-cooled
Frequency range	40-50 kHz
Operating voltage	220V
Body material	Mild steel
Certification	CE (EU safety, health, and environmental protection requirements)

3.4.5 Experimental procedure

The stepwise order of experimentation was performed to evaluate the machining characteristics, i.e., surface roughness and tool wear during the boring of aluminium alloy 6061 under dry, flood, and MQL lubricating conditions is described below:

- 1) Fabrication of mist nozzle for near dry machining to have the supply from the through-hole boring bar.
- 2) Utilization of machining components required for internal turning experiments.
- 3) Consideration of Taguchi orthogonal array for numerous combinations of machining trials in different lubricating conditions
- 4) Designated experiments are performed with a new cutting insert.
- 5) Internal turning experiments were conducted on a conventional lathe machine with coated carbide cutting on an aluminium 6061 alloy workpiece.
- 6) Measurement of average surface roughness and tool wear as machining response parameters.
- 7) Macro and microscopic morphological analysis of machined surfaces under different lubricating conditions.

- 8) Microscopic morphological analysis of tool wear during different lubricating conditions
- 9) Microscopic morphological analysis of generated chips at different cutting conditions and lubrication.
- 10) Multi-objective optimization of response parameters using Grey relational analysis in an internal turning process.
- 11) Calculation of optimal setting and confirmation tests for validation

This chapter analyses the experimental data collected during the boring of aluminium alloy 6061 with coated carbide tip in dry cutting conditions under shunt damping conditions.

4.1 Experimental results under shunt damping

The experiments were conducted with or without the piezoelectric shunt damping (PZT). The response parameters were surface roughness and vibrational amplitude at different cutting parameters settled through an orthogonal array in Table 3.5. Experiments are conducted with three factors, each at three levels; hence, a three-level orthogonal array (OA) was chosen. The experiments are conducted using L₉ OA, and the response values are obtained.

Table 4.1 Results produced from cutting experiments on surface roughness and vibrational amplitude

Cutting Speed (m/min)	Feed rate (mm/rev)	Width of Cut (mm)	Mean Vibration amplitude (mV)		Average Surface Roughness (μm)	
			Without PZT	With PZT	Without PZT	With PZT
200	0.15	0.3	4.08	3.36	1.738	1.128
200	0.20	0.5	3.74	3.26	1.764	1.505
200	0.25	0.7	4.05	3.98	1.812	1.712
260	0.15	0.5	4.22	4.06	1.888	1.125
260	0.20	0.7	4.28	4.17	2.048	1.985
260	0.25	0.3	4.25	4.18	2.245	1.999
320	0.15	0.7	4.26	4.08	2.234	2.025

320	0.20	0.3	4.78	4.28	2.464	2.236
320	0.25	0.5	4.88	4.59	2.218	2.145

From the experimental findings, it is clear that both the responses decrease significantly under piezoelectric shunt damping. A decrease in the vibrational amplitude occurs due to the piezoelectric layer attachment on the boring bar governed by the R-L-C circuit. Shunt damping reduces the accumulation of energy generated during the cutting operation by obtaining the frequency response function. Chatter recorded with a microphone occur at a corresponding depth of cut. Any further increase in the depth of the cut could result in instability and non-linear effects. Fig 4.1. A decrease in vibrational amplitude reduces the chatter induced on the machined surface, and as a result, a good surface finish was observed.

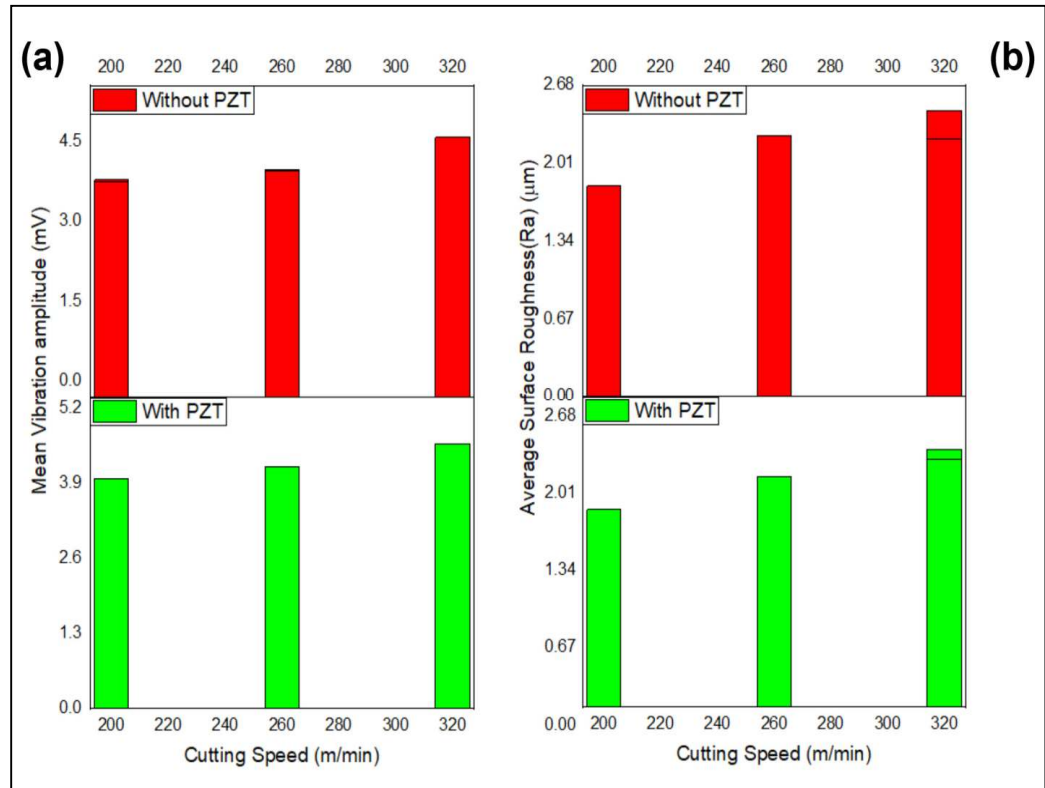


Fig 4.1 (a) Experimental correlation of amplitude and surface roughness without PZT damping (b) relationship of amplitude and surface roughness with PZT damping

4.2 Multi-objective optimization using grey relational analysis

The effect and interaction between different parameters in a multi-response problem are complicated and unclear. This is referred to as grey, which denotes weak and ambiguous detail. This proposed methodology explores the intricate complexity within multiple responses in a given structure and uses grey relational grade to optimize it (Zaman and Dhar, 2019). As a result, a multi-response optimization problem becomes a single-response optimization problem known as a single relational grade.

Step 1: Determination of S/N ratios for vibrational amplitude and surface roughness under piezoelectric shunt damping of the initial settings. S/N ratios for responses are calculated by a smaller-the-better approach, as minimum machining characteristics are intended.

$$\frac{S}{N}ratio(\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^n y_{ij}^2\right) \quad (1)$$

where n=number of replications y_{ij} =observed response value where $i=1, 2, \dots, n$; $j=1, 2, \dots, k$

Calculation of S/N ratios as per equation number (1) for each quality characteristic is given in Table 4.2.

Table 4.2 S/N ratio value and normalized S/N ratio values

S/N Ratios		Normalized values of S/N ratios Z_{ij}	
Mean Vibration amplitude (mV)	Average Surface Roughness (μm)	Mean Vibration amplitude (mV)	Average Surface Roughness (μm)
-10.527	-1.046	0.088	0.004
-10.264	-3.551	0.000	0.424
-11.998	-4.670	0.583	0.611
-12.171	-1.023	0.641	0.000
-12.403	-5.955	0.720	0.827

-12.424	-6.016	0.727	0.837
-12.213	-6.129	-1.023	0.856
-12.629	-6.989	0.796	1.000
-13.236	-6.629	1.000	0.940

Step 2: Normalized values of the S/N ratio calculated from equation (2) given in Table 4.2.

$$Z_{ij} = \frac{\max(y_{ij}, i = 1, 2, \dots, n) - y_{ij}}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (2)$$

Step 3: Grey's relational coefficient calculation for the normalized S/N ratios values as per equation (3) is given in Table 4.3.

$$\gamma(y_0(k), y_1(k)) = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{oj}(k) + \xi \Delta_{\max}} \quad (3)$$

- a) $j=1, 2, \dots, n; k=1, 2, \dots, m$, n is the number of experimental data items and m is the number of responses.
- b) $y_0(k)$ is the reference sequence ($y_0(k)=1, k=1, 2, \dots, m$); $y_j(k)$ is the specific comparison sequence.
- c) $\Delta_{oj} = \|y_0(k) - y_j(k)\|$ = The absolute value of the difference between $y_0(k)$ and $y_j(k)$.
- d) $\Delta_{\min} = \min_{\forall j \in I} \min_{\forall k} \|y_0(k) - y_j(k)\|$ is the smallest value of $y_j(k)$.
- e) $\Delta_{\max} = \max_{\forall j \in I} \max_{\forall k} \|y_0(k) - y_j(k)\|$ is the largest value of $y_j(k)$.
- f) ξ is the distinguishing coefficient defined in the range $0 < \xi < 1$. In the calculation, taken as 0.5.

Table 4.3 Deviation sequence and Grey relational coefficients

Δ_{oj}		Grey relational coefficient	
Mean Vibration amplitude (mV)	Average Surface Roughness (μm)	Mean Vibration amplitude (mV)	Average Surface Roughness (μm)
0.912	0.996	0.354	0.334
1.000	0.576	0.333	0.465
0.417	0.389	0.545	0.563
0.359	1.000	0.582	0.333
0.280	0.173	0.641	0.743
0.273	0.163	0.646	0.754
2.023	0.144	0.198	0.776
0.204	0.000	0.710	1.000
0.000	0.060	1.000	0.892

Step 4: Generation of grey relational grade as per given equation (4) presented in Table 4.4.

$$\bar{Y}_j = \frac{1}{k} \sum Y_{ij} \quad (4)$$

where Y_j is the grey relational grade for j^{th} experiment and k is the number of response parameters (Haq et al., 2008).

Table 4.4 Grey relational grades and ranks

Grey relational grade	Rank
0.344	9
0.399	8
0.554	5
0.458	7
0.692	4
0.700	3

0.487	6
0.855	2
0.946	1

Step 5: Optimal factor calculation and its grouping

The greater the grey relational grade, the higher the product quality; hence, the factor effect and the optimal level for each controllable factor can be evaluated using the grey relational grade. Thus, the optimum orthogonal array combination is **V₃-f₃-d₂**, 320 m/min, 0.25 feed rate, and 0.5 depth of cut as per [Table 4.4](#).

Step 6: Confirmation experiment on the optimal factors

The confirmation experiment is carried out at the optimal settings to ensure that the quality characteristics for the boring process specified by the previous study are met. The acceptable output parameters are amplitude = 2.01mV and Ra = 4.34μm. It is calculated that the grey relational grade is 0.973. This result falls within the anticipated optimal 95 percent confidence range. As a result, the grey relational analysis of multi-response problems is a highly effective technique for forecasting surface roughness and vibrational amplitude in the internal turning of aluminium alloy 6061.

4.3 Morphology analysis of machined surface

Another vital feature of internal turning of 6061 Al alloy is the characterization of surface morphology, and it is evident from the micrograph when internal turning is done at a cutting speed of 320m/min, feed rate of .25mm/rev, and width of 0.5 mm, fewer chatter marks observed in comparison with shunt damping. Due to high energy dissipation, less heat is generated on the machined surface in [Fig 4.2](#). This also leads to the acceptability of the product and experimentally proves that damping in the internal turning process ([Biju and Shunmugam, 2014](#)) leads to a better surface finish, consequently decreasing the production cost.

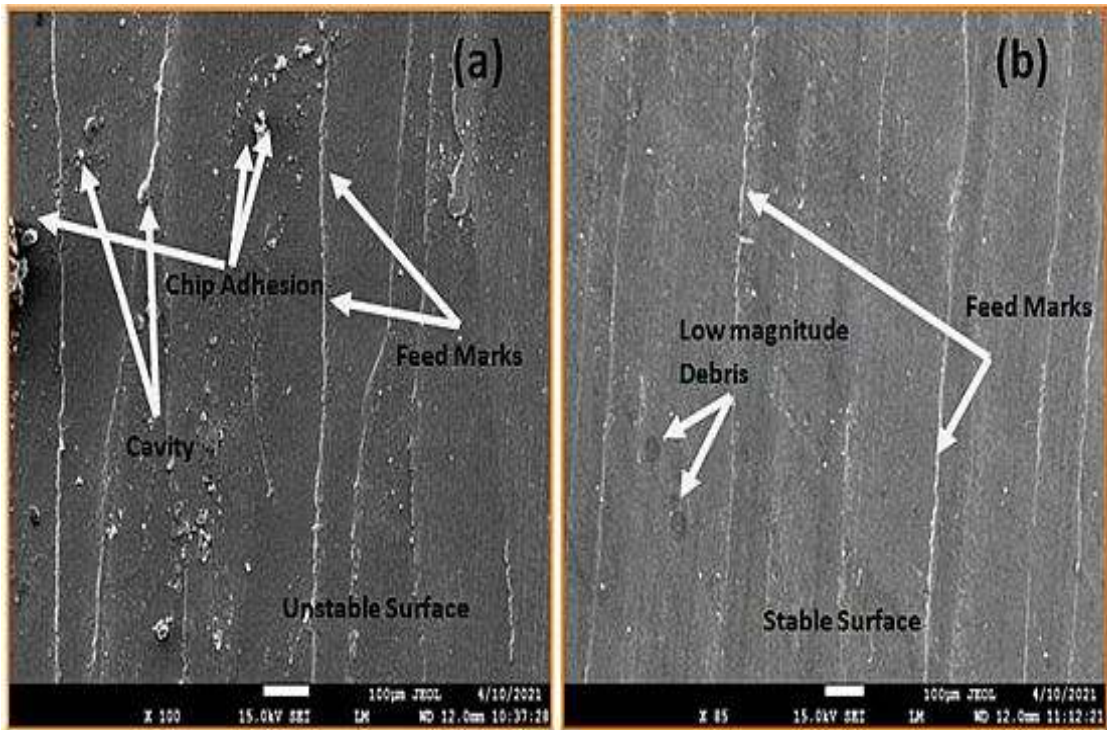


Fig. 4.2 SEM micrograph of turned surface (a) without PZT damping (b) with PZT damping

CHAPTER 5

RESULTS AND DISCUSSION- MACHINING UNDER DIFFERENT LUBRICATING CONDITIONS

This chapter analyses the experimental data collected during the boring aluminium alloy 6061 with coated carbide tip under dry, flood, and MQL lubrication.

5.1 Experimental results under dry, flood and MQL lubrication

The response parameters were average surface roughness and tool wear at different combinations of cutting parameters settled through an orthogonal array given in [Table 3.9](#). Experiments are conducted with four factors, each at three levels; hence, a three-level orthogonal array (OA) was chosen. The experiments are conducted using L₂₇ OA and the response values obtained [Table 5.1](#).

Table 5.1 Results produced from cutting experiments under dry, flood and MQL lubricating conditions

Lubrication	Cutting	Feed	Depth of	Tool	Average
Type	Speed	rate(mm/rev)	Cut(mm)	Wear(μm)	Surface
	(m/min)				roughness
					(μm)
Dry	185	0.15	0.30	0.22	1.13
Dry	185	0.20	0.50	0.24	0.95
Dry	185	0.25	0.70	0.29	1.17
Dry	215	0.15	0.50	0.36	1.27
Dry	215	0.20	0.70	0.45	1.10
Dry	215	0.25	0.30	0.42	1.20
Dry	245	0.15	0.70	0.56	1.07
Dry	245	0.20	0.30	0.58	1.12
Dry	245	0.25	0.50	0.67	1.05

Flood	185	0.15	0.50	0.41	0.99
Flood	185	0.20	0.70	0.42	0.88
Flood	185	0.25	0.30	0.41	1.12
Flood	215	0.15	0.70	0.32	1.10
Flood	215	0.20	0.30	0.33	0.96
Flood	215	0.25	0.50	0.36	0.94
Flood	245	0.15	0.30	0.51	0.88
Flood	245	0.20	0.50	0.53	0.86
Flood	245	0.25	0.70	0.49	0.99
MQL	185	0.15	0.70	0.18	0.94
MQL	185	0.20	0.30	0.18	0.82
MQL	185	0.25	0.50	0.19	0.90
MQL	215	0.15	0.30	0.28	0.70
MQL	215	0.20	0.50	0.26	0.69
MQL	215	0.25	0.70	0.24	0.62
MQL	245	0.15	0.50	0.31	0.76
MQL	245	0.20	0.70	0.29	0.72
MQL	245	0.25	0.30	0.27	0.80

5.2 The consequence of lubrication conditions on Surface roughness

Average surface roughness was estimated alongside the feed with a surface roughness analyzer on three distinct points and the average for plotting the diagrams. According to [Fig 5.1](#) and [5.2](#), the dissimilarity of surface roughness is revealed by the behavior in different cooling regimes. Since the tool ploughed the workpiece continuously, mainly during the machining process, adhesion is the main reason for the tool-work interface. Because mist lubrication is used, a thin layer is formed on the tool-work interface, improving surface integrity.

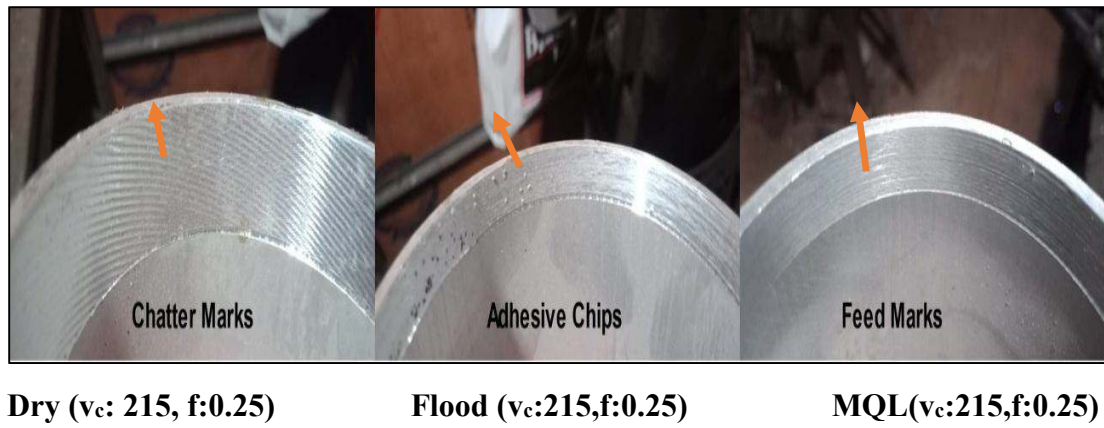
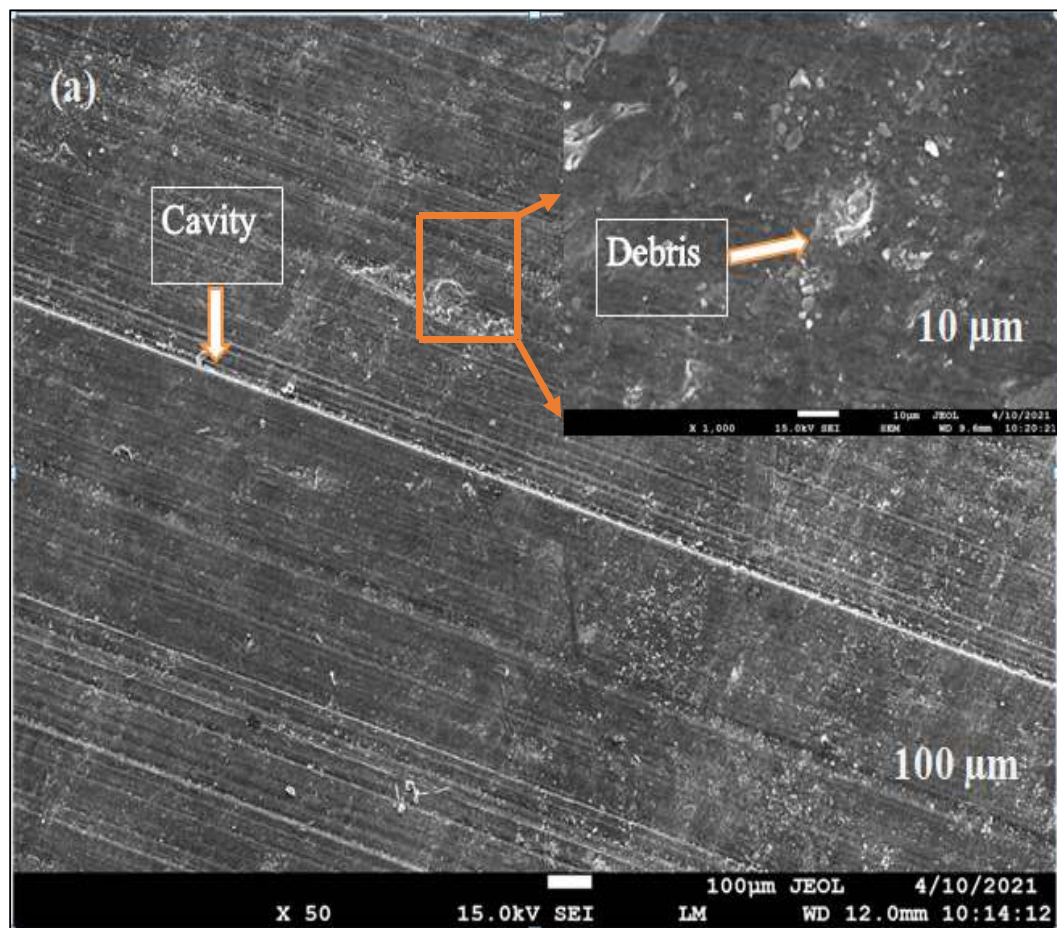
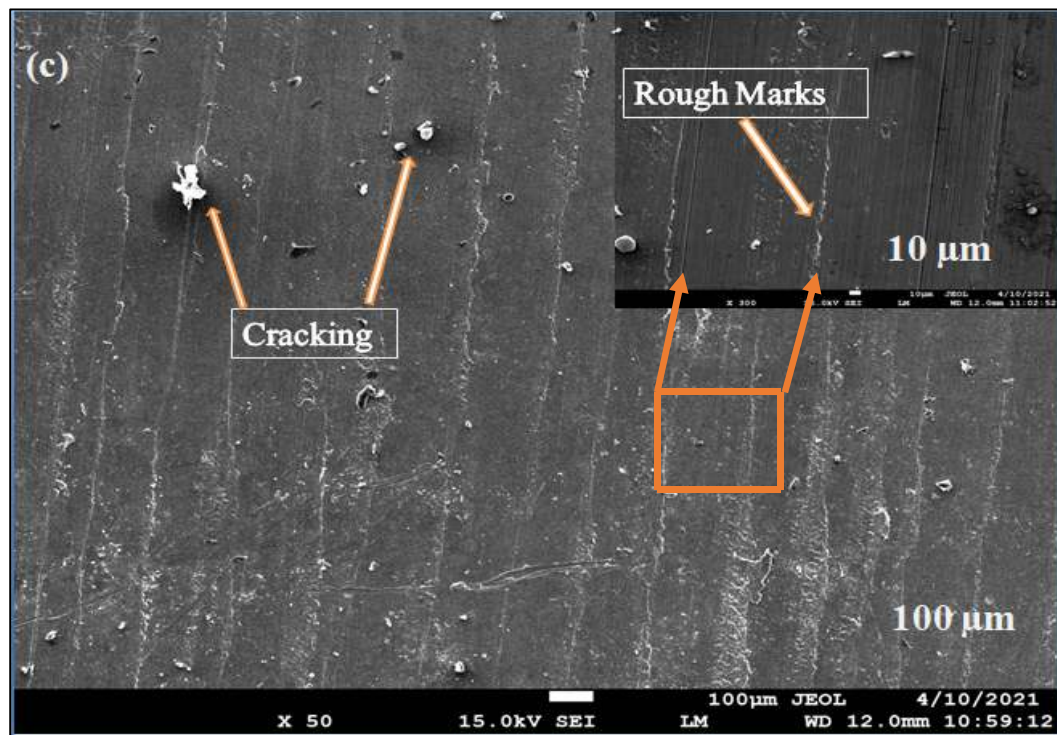
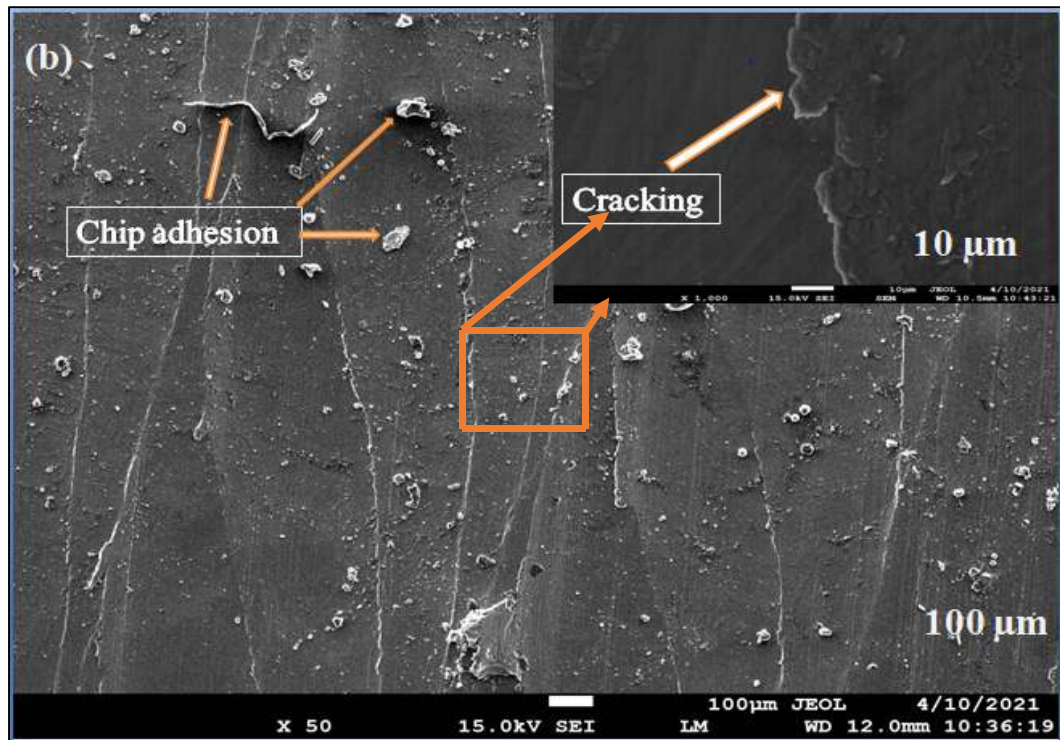


Fig 5.1 Optical images of the finished surface





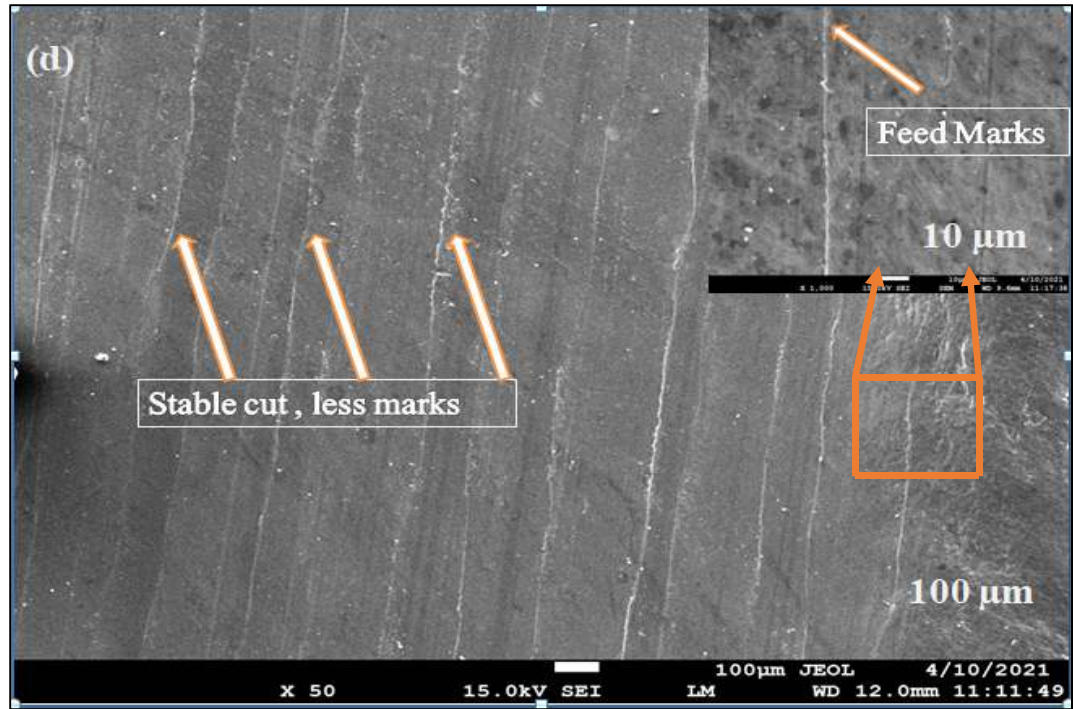


Fig 5.2 Surface investigation (a) Original workpiece (b) Dry machining (c) Flood machining (d) MQL machining at cutting speed and feed rate of 215 m/min, 0.25mm/rev.

During an investigation into turning Al 6061 alloy, we discovered that using MQL decreased friction observed at the tool-chip interface and resulted in a better surface quality than using dry, flood cooling, which results in suppressing chips, vibrations, built up and wear on cutting tip as validated from the macrograph in figure 4. The same work was reported earlier by (Okonkwo et al., 2015) while milling aluminium alloys under near dry cutting conditions. At all cutting conditions, the mist lubrication produced lower surface roughness values with no abscesses Fig (5.3-5.5). In reality, pressurized mist air significantly improved lubricating for the machining (Dhar et al., 2006).

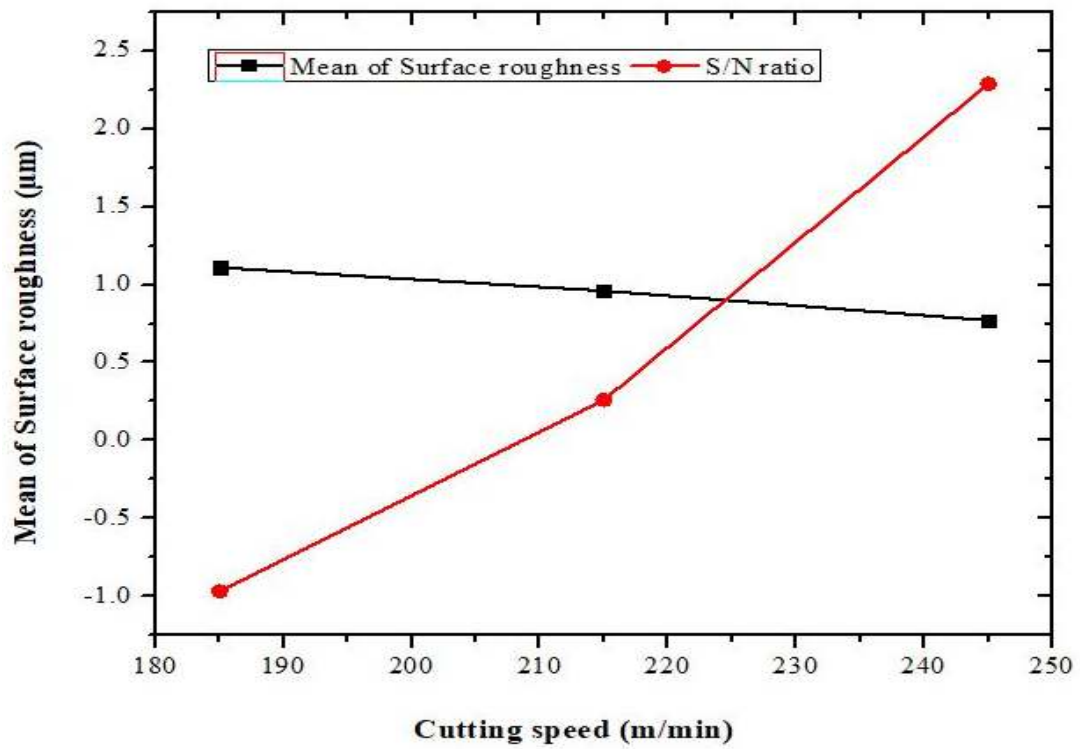


Fig 5.3 Means and S/N ratios of surface roughness result with cutting speed

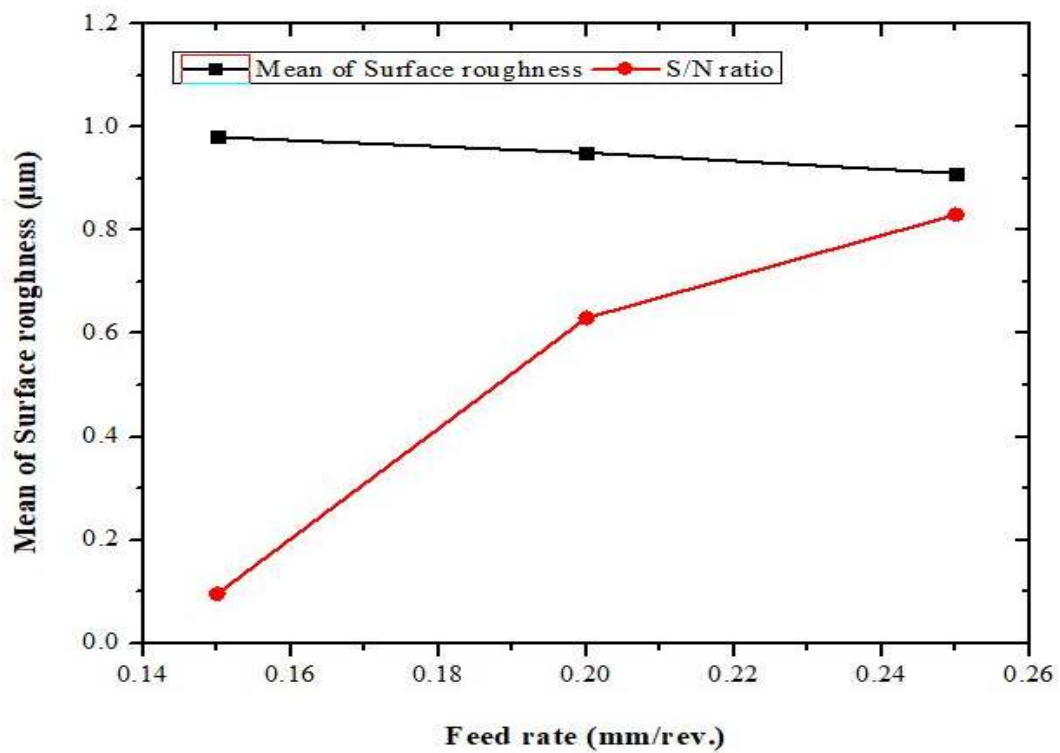


Fig 5.4 Means and S/N ratios of surface roughness result with feed rate

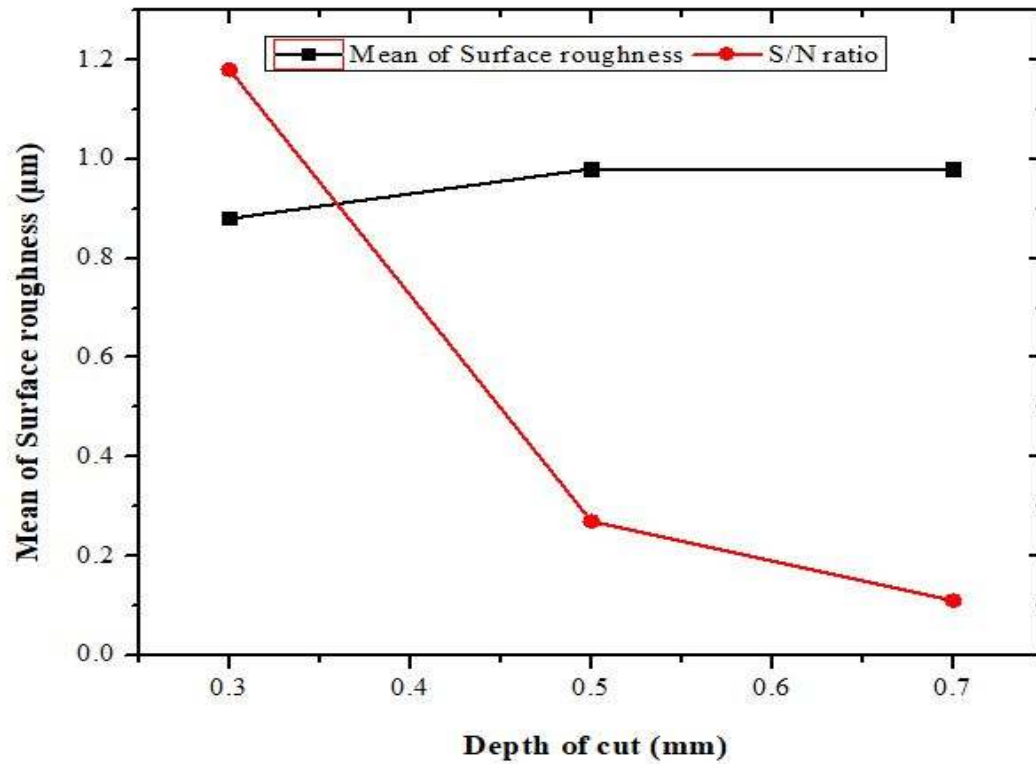


Fig 5.5 Means and S/N ratios of surface roughness result with depth of cut

In environmentally friendly machining, MQL machining is the preferred method. The environmental risks of using much-cutting fluid removed during machining. Experimental trials validate that surface textures improve due to the mist layer between the cutting tool, workpiece, and chip. Considerable decrease in Ra value observed under different cooling conditions with utilized machining parameters Fig (5.3-5.5). Thus, it also validates the surface produced under mist lubrication represented in Fig 5.2. The main reason for this behavior is the capillary action produced by the air and fluid mixture, which reduces the cutting temperature. Flood cooling also accounts for minor surface roughness. Still, due to chip adhesion, the surface texture is slightly improved in dry conditions.

5.3 Effect of cutting condition on tool wear

A machining system cannot be implemented without generating heat, both mechanically and physically. The heat generated may impact tool life, cutting force

variation, chip geometry, and morphology. Adhesion, abrasion, and diffusion were the most common types of tool failure. Partially de-bonding of the tool's protective coating, which is exacerbated by the high-speed–feed mix, has been found to increase the amount of flank wear (Nouari et al., 2003). The higher hardness can be counterproductive to dry machining tool life since it suppresses the tool's strain rate; when it exceeds a certain threshold, the harm is clearly defined by accentuated tool wear. Similar research is already proved by (Arora et al., 2015). In Fig 5.6 (b), Owing to the unavailability of fluid lubrication, abrasion of the work surface with the tool causes rubbing of the workpiece, raising the temperature at the chip-tool interface (Iqbal et al., 2009) and blunting the cutting edges (Khan et al., 2017) for subsequent cuts at increased speeds and feed. Work material sticks on the tool's edges during machining in all cutting conditions; however, the amount of attached material varies depending on the coolant environment. The adhesion between the tool and the chip grew in lockstep with increased machining speed. It could be due to the chip's thermal softening as the temperature rose in tandem with the cutting speed. During flood cutting, the work material's adherence to the tool was seen to be at its maximum Fig 5.6 (c).

Under cutting fluid actions, a lubricating film preventing the direct contact between tool and workpiece lowers the cutting temperature, which, consequently, abrasive the particles' actions but increases adhesion observed as illustrated in Fig 5.6 (c). High adhesion is observed in flood lubrication due to splashing of the microparticles of the chip under high cutting temperature (Sharma et al., 2016) and generates the possibility of formation of the auxiliary cutting edge. (Razy and Sakib, 2019) Tool replenishment is not required in this case, unlike in a dry machining environment. Mist lubrication penetrates the inner region of the tool-work interface, decreases the cutting temperature, and reduces the chances of chip clogging.

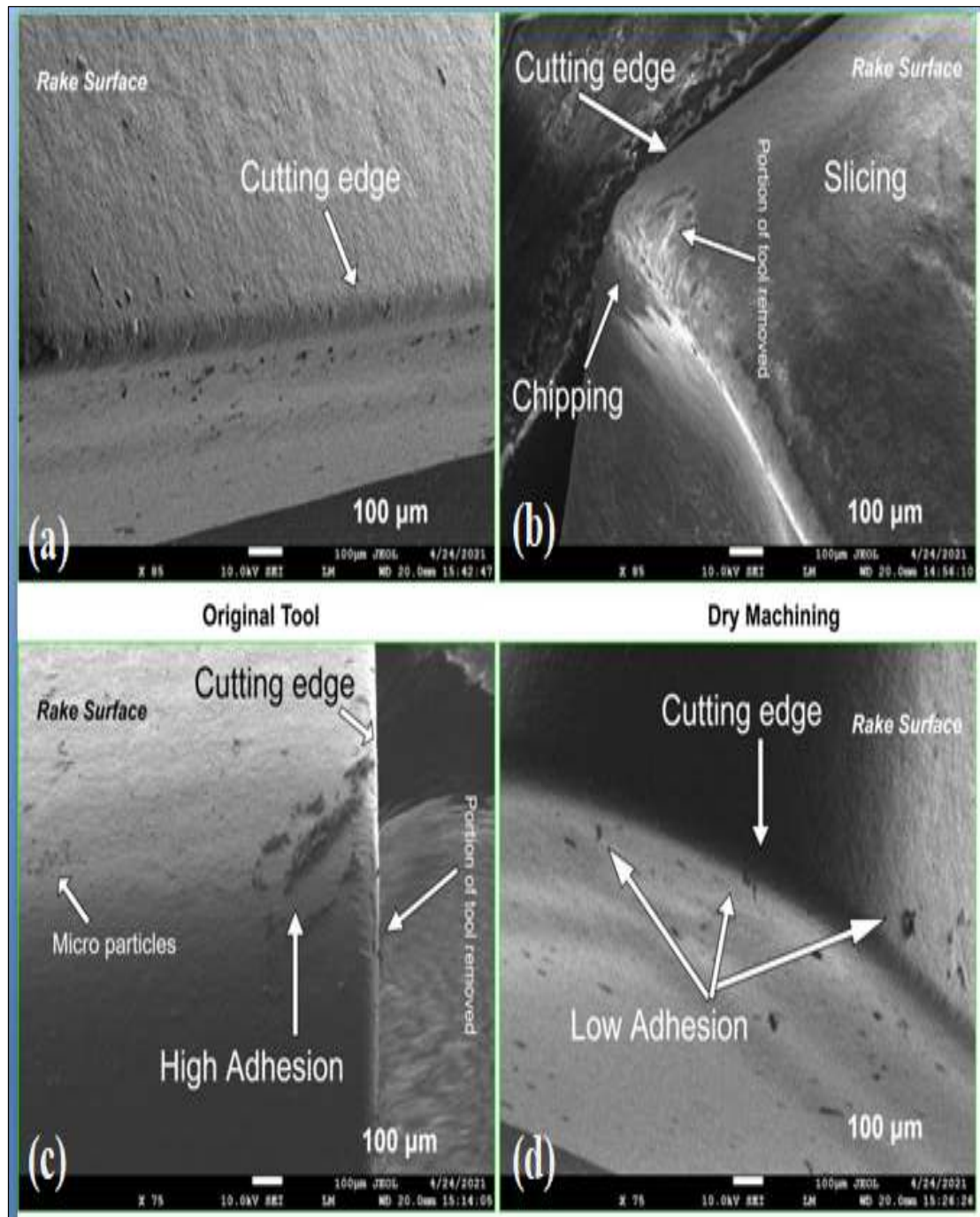


Fig 5.6 Micrograph of cutting inserts (a) Original Tool (b) Dry machining (c) Flood machining (d) MQL machining

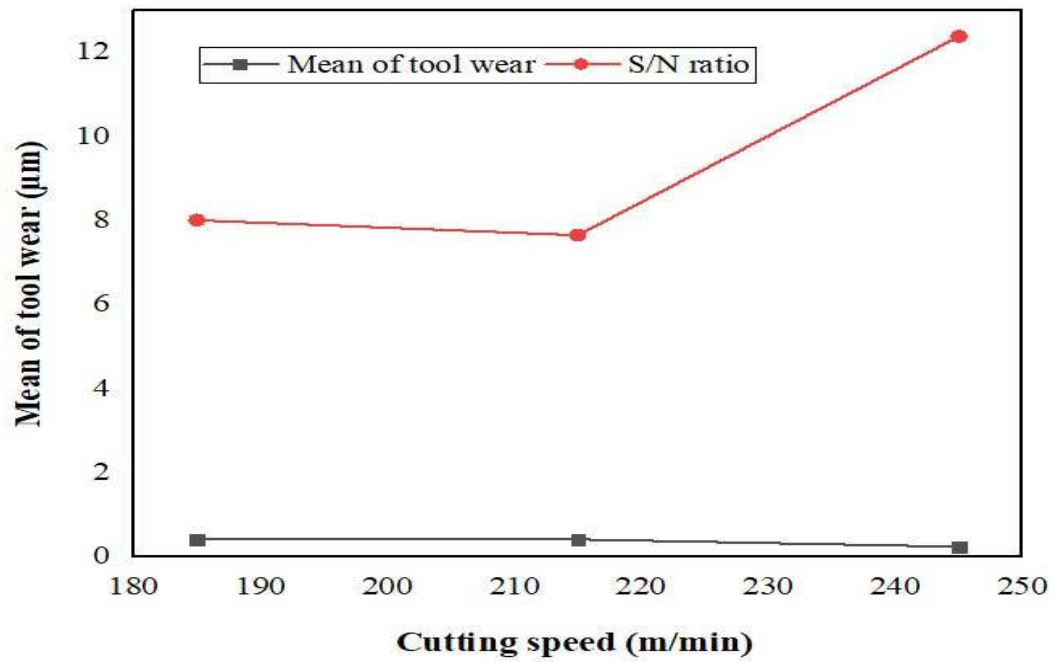


Fig 5.7 Means and S/N ratios of tool wear result with cutting Speed

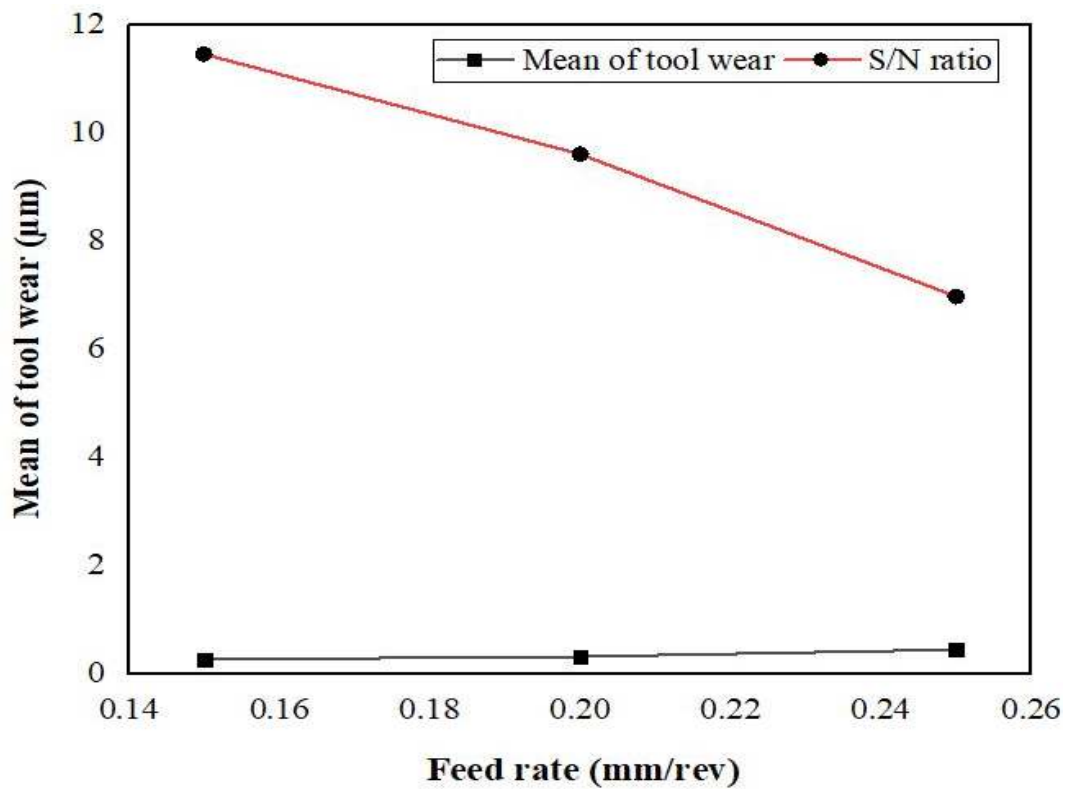


Fig 5.8 Means and S/N ratios of tool wear result with feed rate

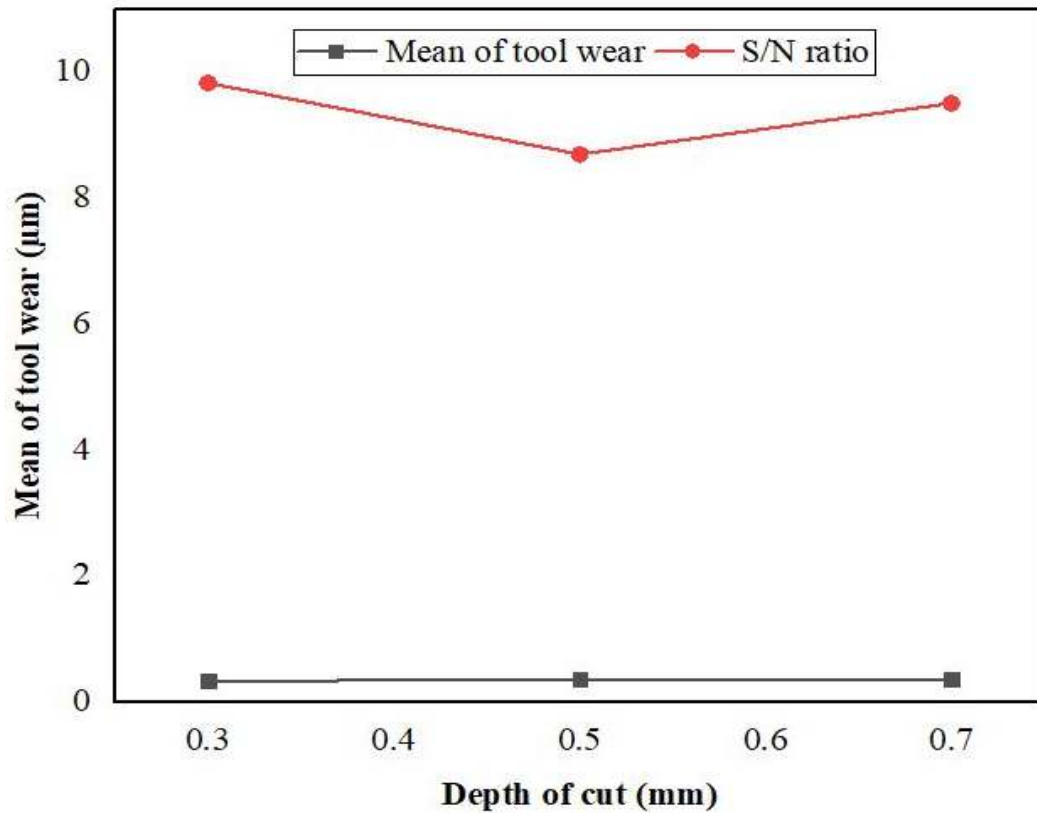


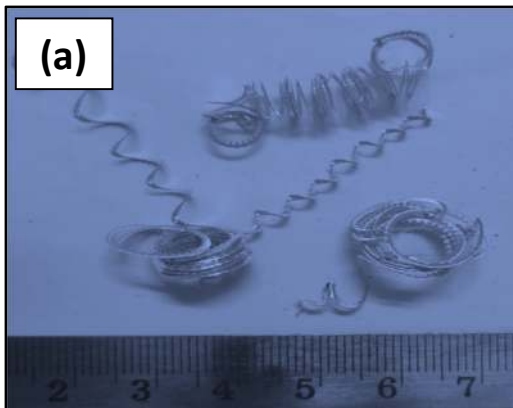
Fig 5.9 Means and S/N ratios of tool wear result with depth of cut

Tool geometry is to blame for the quantity of attached material in MQL circumstances. The amount of attached material can be reduced by decreasing the tool's nose radius and making other geometrical adjustments (Khan et al., 2017). This behavior is also validated by the response behavior with cutting parameters under different cutting conditions Fig (5.7-5.9). MQL reduces heat generation, abrasion of the particles, and adhesion of the chips compared to dry and flood conditions, as illustrated in Fig 5.6 (d). Other researchers also reported similar work (Cagan et al., 2020a; Krishnan Unni et al., 2020). Friction decreases due to minuscule oil droplets in cutting regimes, resulting in stable cut and long chips.

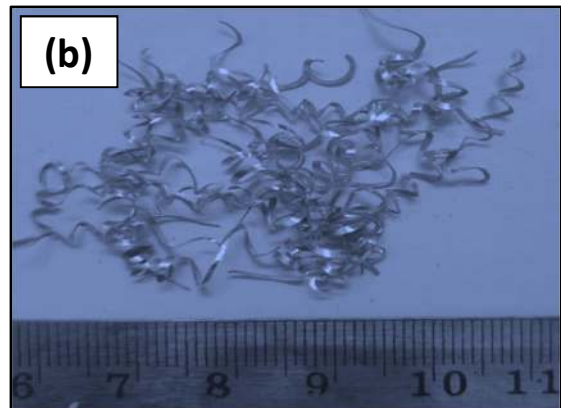
5.4 Morphology of chips produced in dry, flood, and MQL machining

The chip surface will probably have high tension spilling across the rake face. Strong adhesion may cause extra shear in the secondary shear zone. The capability of fruitful cutting fluids rather than coolants to infiltrate the chip-tool interface and limit the rake face attachment by shaping low-shear-strength limit films is generally recognized (Yılmaz et al., 2020). Chip morphology is vital as it reveals the work material's mechanical, thermal, and thermal interactions during boring and offers critical information about the cutting process's stability. Chip morphology in metal cutting is affected by machining parameters, cutting tool qualities, and the tool/work-materials combination. Chips have been distinguished for a long time based on the parameters mentioned: a) Continuous (segmented), (b) Discontinuous (serrated), and (c) Serrated (saw-toothed) Fig 5.10 represents chips generated in dry cutting conditions at different machining levels (Komanduri and Brown, 1981).

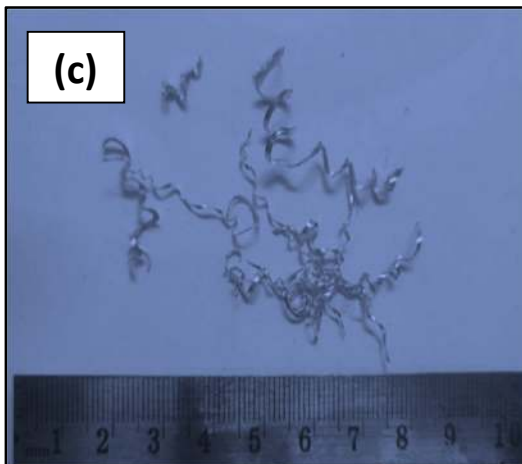
At less speed and moderate feed, dense curl Fig 5.10 (a) is observed in chips. This is mainly due to bending moment formation at the deformation region and the non-collinear forces acting across the shear planes. Another reason is that the ductile behavior of aluminium at high speed and less feed consequently affects tool characteristics. Wrapping of chip curl Fig 5.10 (b) is also observed due to heat accumulation in the tool-work interface without lubricating agents. Chips break down into thin lengths when cutting speed and feed rates increase, as shown in Fig 5.10 (c, d). A chip's free surface is the part of the chip that is not interacting with the tool. The saw tooth profile is visible on this surface, essentially a continuation of the top surface. A rough surface with a lamella pattern is common. For dry machining chips, the free surface has the highest peak-to-valley length. Dry machining is perhaps the most likely to cause chattering, leading to a poor workpiece surface quality Fig 5.10 (b). Because of top-to-bottom distance in jagged chips grows with the extent of serration, it was more prominent in dry conditions.



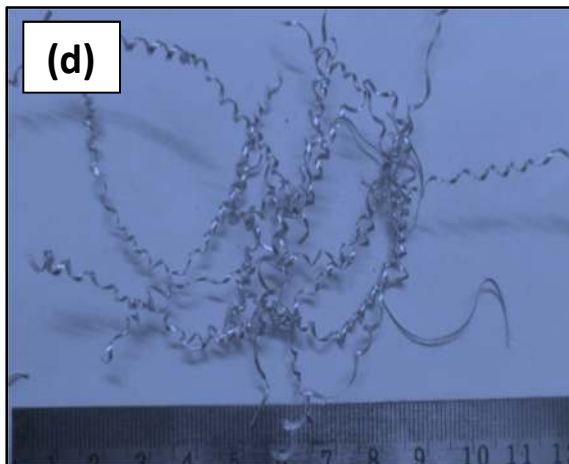
(V_c: 215 m/min, f:0.20 mm/rev)



(V_c: 215 m/min, f:0.25 mm/rev)



(V_c: 245 m/min, f:0.15 mm/rev)



(V_c: 245 m/min, f:0.25 mm/rev)

Fig 5.10 Generated chips in dry machining at different machining parameters

Flood cooling permits the greasing oil to rise out of a nozzle as a fluid jet, surrounding the whole cutting area. A massive part of cutting liquid is required to swarm the entire cutting zone. Thus, the stream rate is exceptionally high. It might ingest a more noteworthy measure of hotness from the machining zone. The chips produced in the traditional flood coolant application are moist. They must be dried before being recycled, contributing to an additional expense. [Figure 5.11 \(a-d\)](#) during machining under flooded

conditions, pictorial scrutiny revealed mostly discontinuous, band-type, tube-shaped, and coiled chips.

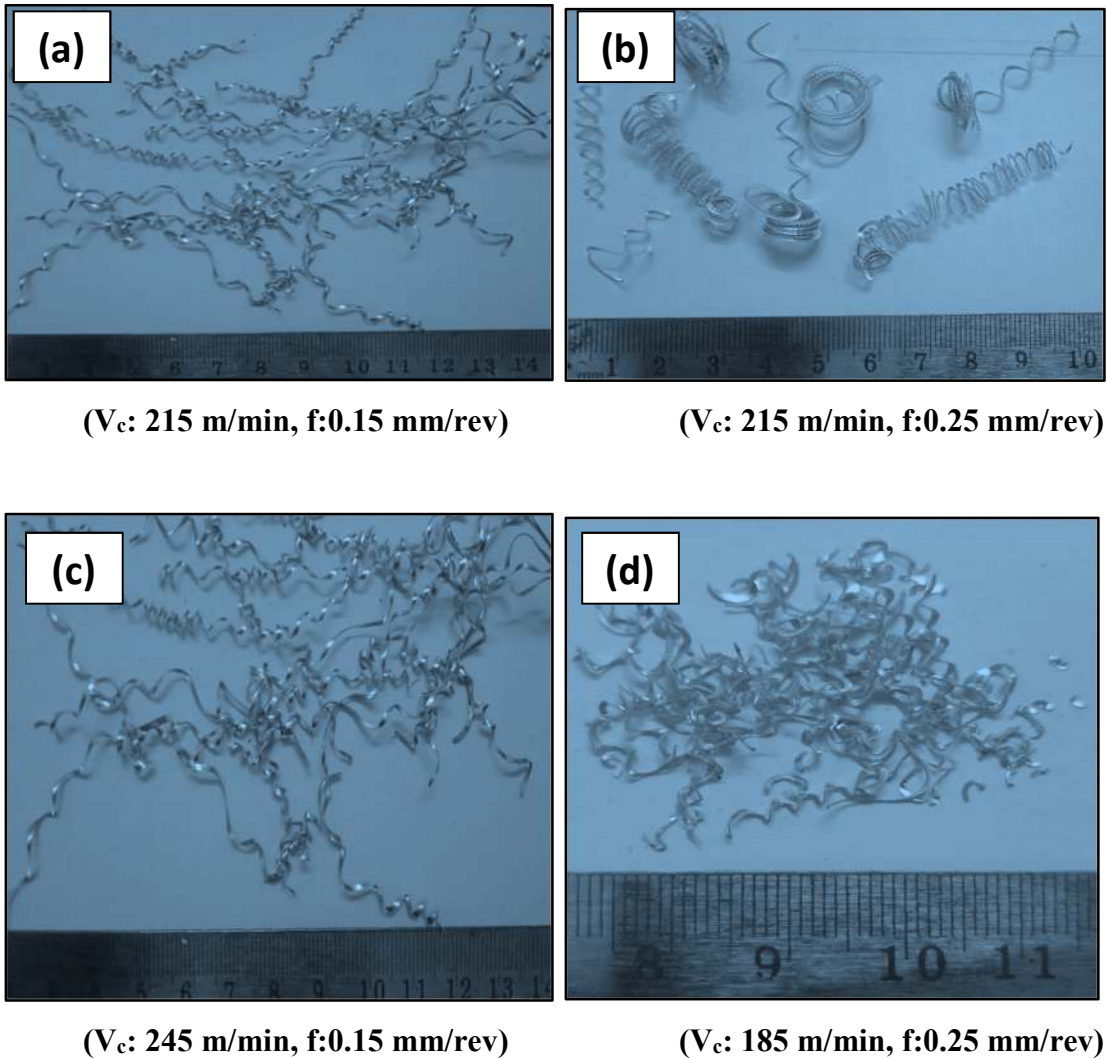


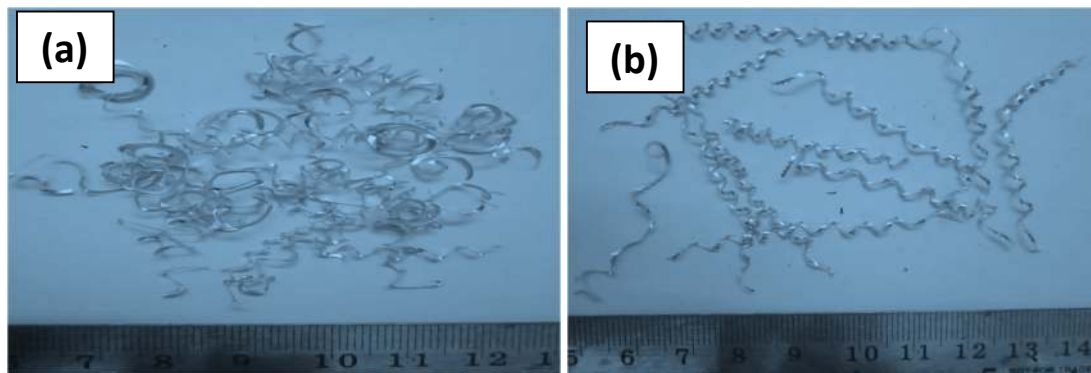
Fig 5.11 Generated chips in Flood machining at different machining parameters

The rear surface of the chips is generally quite smooth because this may be the very first layer separated from the workpiece with significant forces; the texture of this can recover information about machining performance. This layer additionally slides since it has direct rake contact. The back surface is smooth and liberated from breaks due to the mentioned limitations working simultaneously. The smoothest back surface was found in

the flood coolant machining condition. Albeit the dry machining chips were generally smooth, they contained a couple of equal lines of strident imprints.

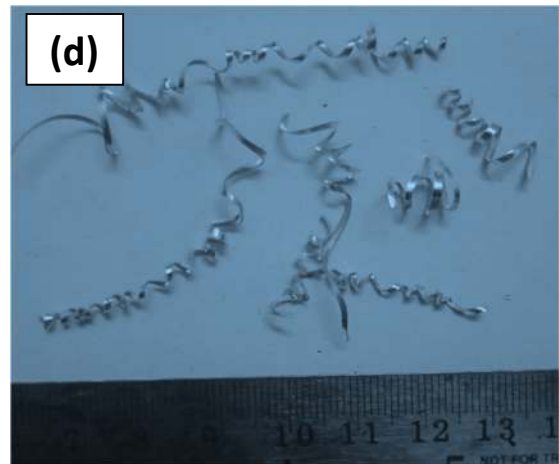
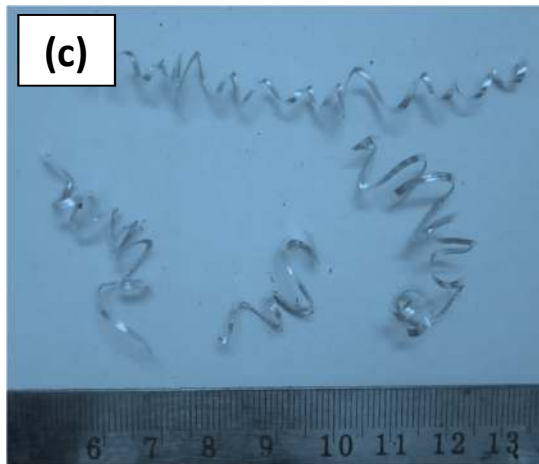
MQL is an absorption lubricant, which implies that most of the lubricant is evaporated at the application site. The workpiece cools due to this evaporation and convection, aided by the compressed mist air stream. The remainder of the heat is dispersed by the tool and the chips (Park et al., 2011) while turning with coated carbide tooltip. Chip separation directly affects contact length, surface integrity, etc. Chip morphology in metal cutting is affected by machining parameters and cutting tool qualities. On the other side, MQL yields substantially dry chips, reducing the cost of drying chips (Hegab et al., 2018) Shiny, segmented chips were observed during MQL machining at different machining parameters Fig 5.12 (a-d). The form of the chips did not alter as much when machined with MQL as it did when they were flooded, but their surface seemed shiny and segmented.

This suggests that in the case of flooded chips, the level of temperature decrease permitted favourable chip–tool interaction, but chips created with MQL reveal that in most situations, higher cutting speed and feed rate make them undesirable. The identical marks were evident on the reverse of the chips gathered under MQL conditions. Tool wear from adhesion on the cutting edges might cause this aberration. Because adhesive wear is much more developed in a dry environment than in others, chips produced in dry conditions show adhesion on the rear surface. On the reverse surface of MQL-generated chips, material adherence is likewise less of a concern.



(V_c: 215 m/min, f:0.15 mm/rev)

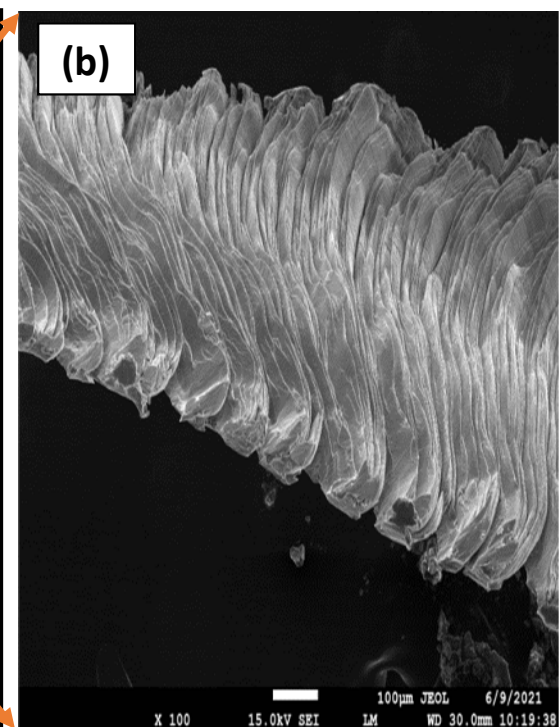
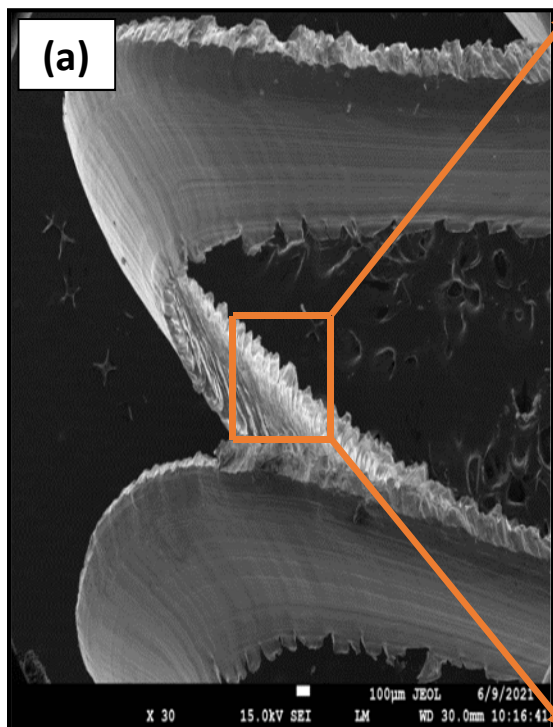
(V_c: 215 m/min, f:0.20 mm/rev)

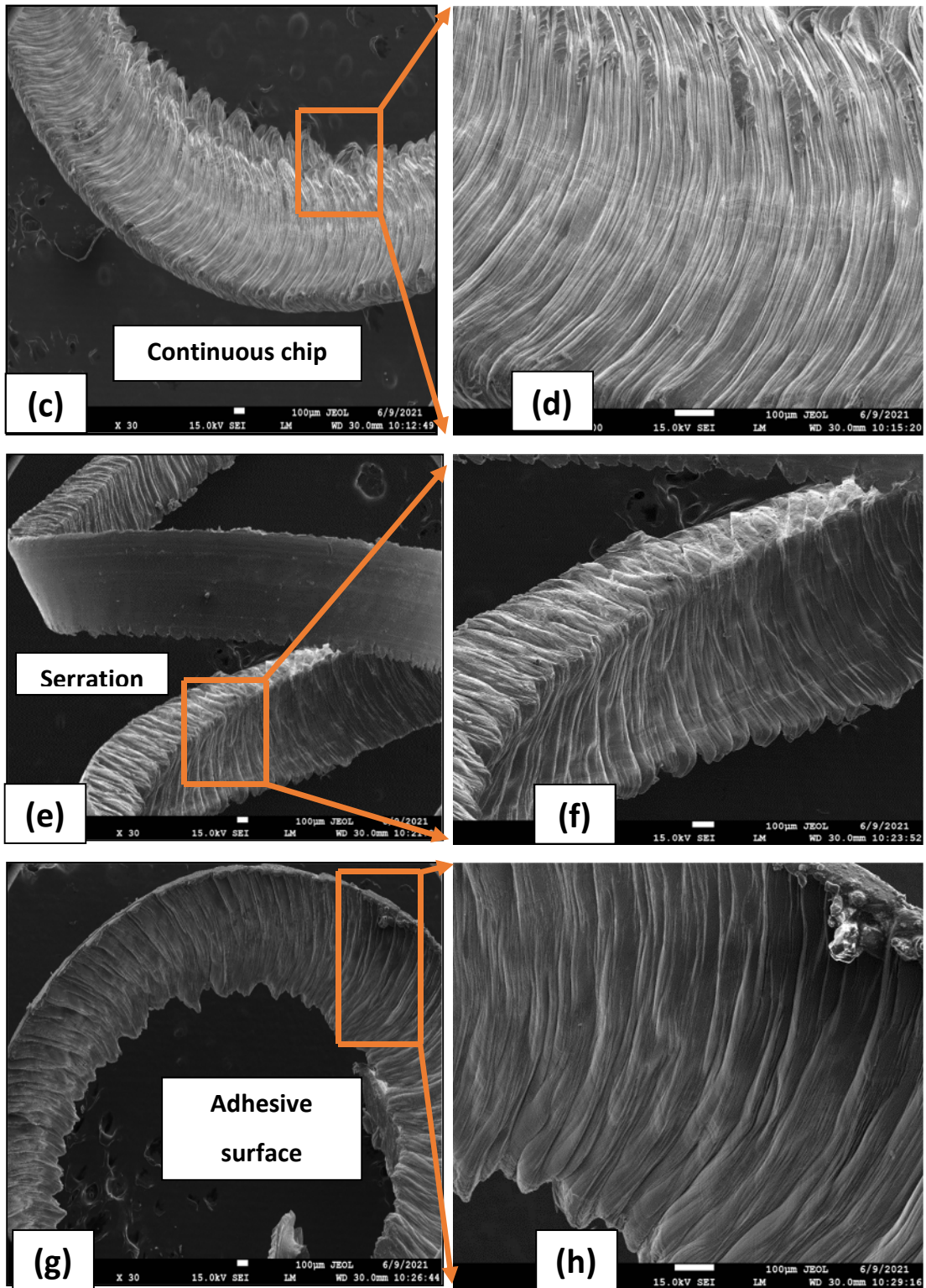


(V_c : 185 m/min, f :0.15 mm/rev)

(V_c : 185 m/min, f :0.20 mm/rev)

Fig 5.12 Generated chips in MQL machining at different machining parameters





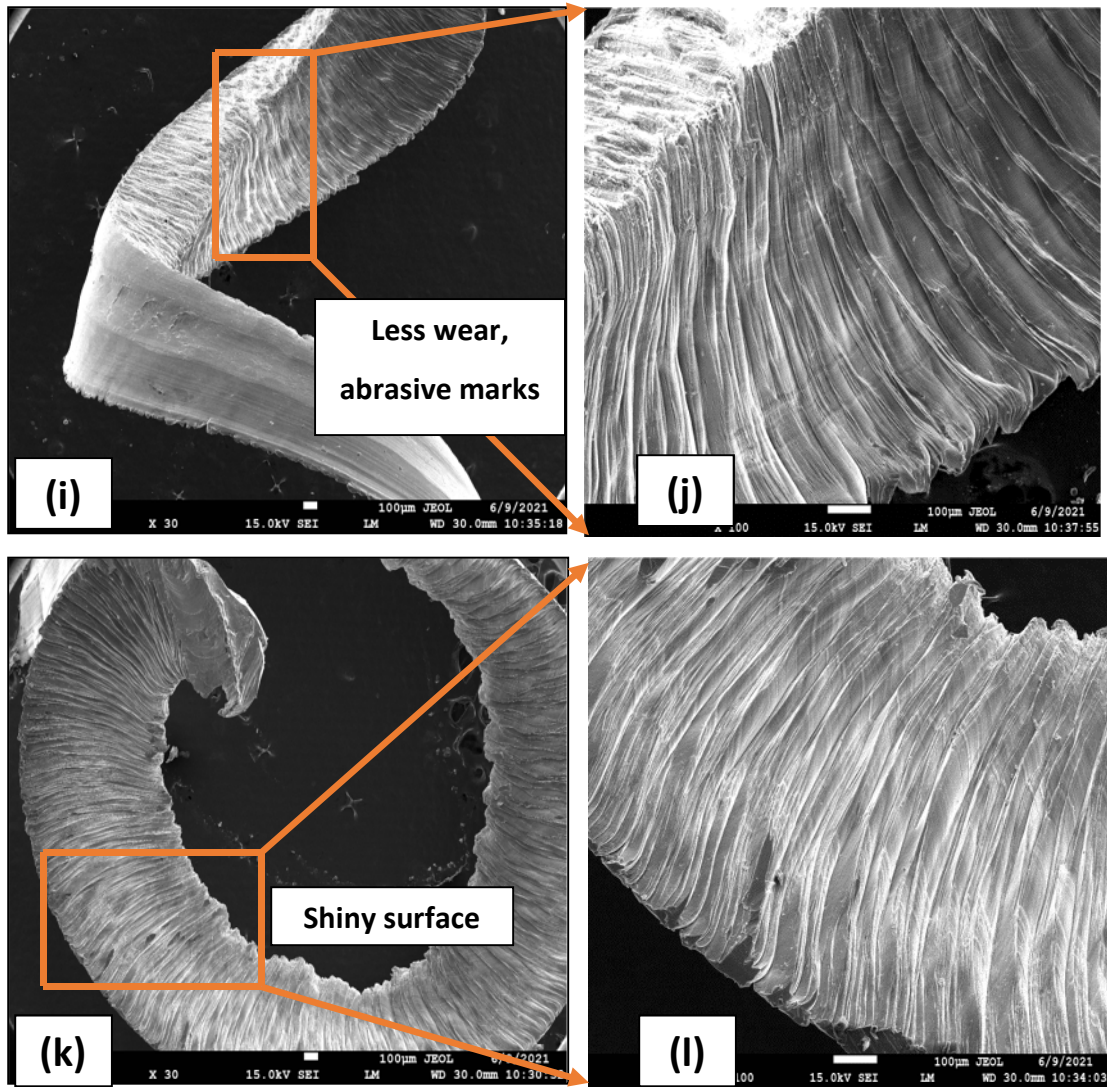


Fig 5.13 Morphologies of chips (a-d) Dry machining; (e-h) Flood machining; (i-l) MQL machining, respectively.

As a result, the free surface was determined to be the roughest in dry machined chips, then flood MQL machining Fig 5.13 (a-l). Flood coolant chips have a smoother back surface, while the free surface offered in dry, MQL circumstances had a few scratch

inscriptions. Furthermore, material adhesion was found on the posterior surface of chips in dry and near dry conditions, most likely due to cutting tool diffusion wear.

5.5 Multi-objective optimization using grey relational analysis

A grey system is one in which only part of the information is known, and the rest is unknown. Grey systems will provide various potential answers because of the inherent ambiguity. Based on this approach, a grey relational analysis may also be used to resolve the intricate links between the specified performance criteria. The grey relational grade (GRG) is effectively described as an indicator of several performance aspects for assessment through this approach. Grey relational analysis has developed into a potent tool for analyzing processes with various performance criteria in recent years. Complex multiple response optimization issues in grey relational research can be reduced to the optimization of a single response grey relational grade. Below is a discussion on how to determine the grey relational grade.

Step 1: Normalized values of the S/N ratio are calculated from equation (1) in Table 1.

$$Z_{ij} = \frac{\max(y_{ij}, i = 1, 2, \dots, n) - y_{ij}}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (1)$$

Table 5.2: S/N ratio value and normalized S/N ratio values

Normalized values of S/N ratios Z_{ij}	
Tool Wear(μm)	Average Surface roughness (μm)
0.915	0.215
0.874	0.492
0.772	0.154
0.630	0.000

0.447	0.262
0.508	0.108
0.224	0.308
0.183	0.231
0.000	0.338
0.528	0.431
0.508	0.600
0.528	0.231
0.711	0.262
0.691	0.477
0.630	0.508
0.325	0.600
0.285	0.631
0.366	0.431
0.996	0.508
1.000	0.692
0.976	0.569
0.793	0.877
0.833	0.892
0.874	1.000
0.732	0.785
0.772	0.846
0.813	0.723

Step 2: Grey's relational coefficient calculation for the normalized S/N ratios values as per equation (2) is given in Table 2.

$$\gamma(y_0(k), y_1(k)) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{oj}(k) + \xi \Delta_{max}} \quad (2)$$

- g) $j=1,2,\dots,n$; $k=1,2,\dots,m$, n is the number of experimental data items, and m is the number of responses.
- h) $y_0(k)$ is the reference sequence ($y_0(k)=1$, $k=1,2,\dots,m$); $y_j(k)$ is the specific comparison sequence.
- i) $\Delta_{oj} = \|y_0(k) - y_j(k)\|$ = The absolute value of the difference between $y_0(k)$ and $y_j(k)$.
- j) $\Delta \min = \min_{\forall j \in I} \min_{\forall k} \|y_0(k) - y_j(k)\|$ is the smallest value of $y_j(k)$.
- k) $\Delta \max = \max_{\forall j \in I} \max_{\forall k} \|y_0(k) - y_j(k)\|$ is the largest value of $y_j(k)$.
- l) ζ is the distinguishing coefficient defined in the range $0 < \zeta < 1$. In the calculation, taken as 0.5.

Table 5.3: Grey's relational coefficient calculation for output parameters

Grey relational coefficient	
Tool Wear(μm)	Average surface roughness (μm)
0.854	0.389
0.799	0.496
0.687	0.371
0.575	0.333
0.475	0.404
0.504	0.359
0.392	0.419
0.380	0.394
0.333	0.430
0.515	0.468
0.504	0.556
0.515	0.394
0.634	0.404

0.618	0.489
0.575	0.504
0.426	0.556
0.411	0.575
0.441	0.468
0.992	0.504
1.000	0.619
0.953	0.537
0.707	0.802
0.750	0.823
0.799	1.000
0.651	0.699
0.687	0.765
0.728	0.644

Step 3: Generation of grey relational grade as per given equation (3) presented in Table 3.

$$\bar{Y}_j = \frac{1}{k} \sum Y_{ij} \quad (3)$$

where Y_j is the grey relational grade for j^{th} experiment, and k is the number of response parameters.

Table 5.4: Grey relational grade and rank

Grey relational grade	Rank
0.621694	11
0.647442	10
0.52929	15

0.45405	22
0.439315	23
0.431607	24
0.405537	25
0.386785	26
0.381898	27
0.491135	18
0.529827	14
0.454292	20
0.518874	16
0.553406	12
0.539321	13
0.490581	19
0.493296	17
0.454243	21
0.747906	5
0.809524	2
0.745339	6
0.754683	4
0.786392	3
0.899351	1
0.674859	9
0.725928	7
0.685688	8

Step 4: Optimal factor calculation and its grouping

The greater the grey relational grade, the higher the product quality; hence, the factor effect and the optimal level for each controllable factor can be evaluated using the

grey relational grade. Thus, the optimum OA combination is **A₃B₂C₃D₃**, MQL (100ml/h), cutting speed 215m/min, feed rate 0.25 mm/rev, and 0.7 mm depth of cut as per Table 4.

Table 5.5: Optimal parameters by Grey relational analysis

Lubrication Flow rate (ml/h)	Cutting Speed (m/min)	Feed rate(mm/rev)	Depth of Tool Cut(mm)	Wear(μ m)	Average Surface roughness (μ m)
0	185	0.15	0.3	0.22	1.13
0	185	0.2	0.5	0.24	0.95
0	185	0.25	0.7	0.29	1.17
0	215	0.15	0.5	0.36	1.27
0	215	0.2	0.7	0.45	1.1
0	215	0.25	0.3	0.42	1.2
0	245	0.15	0.7	0.56	1.07
0	245	0.2	0.3	0.58	1.12
0	245	0.25	0.5	0.67	1.05
12000	185	0.15	0.5	0.41	0.99
12000	185	0.2	0.7	0.42	0.88
12000	185	0.25	0.3	0.41	1.12
12000	215	0.15	0.7	0.32	1.1
12000	215	0.2	0.3	0.33	0.96
12000	215	0.25	0.5	0.36	0.94
12000	245	0.15	0.3	0.51	0.88
12000	245	0.2	0.5	0.53	0.86
12000	245	0.25	0.7	0.49	0.99
100	185	0.15	0.7	0.18	0.94
100	185	0.2	0.3	0.178	0.82

100	185	0.25	0.5	0.19	0.9
100	215	0.15	0.3	0.28	0.7
100	215	0.2	0.5	0.26	0.69
100	215	0.25	0.7	0.24	0.62
100	245	0.15	0.5	0.31	0.76
100	245	0.2	0.7	0.29	0.72
100	245	0.25	0.3	0.27	0.8

Step 5: Confirmation experiment on the optimal factors

The confirmation experiment is carried out at the optimal settings (**A₃B₂C₃D₃**) to ensure that the quality characteristics for the boring process specified by the previous study are met. The acceptable output parameters are tool wear = 0.25 μm and Ra = 0.64 μm . It is calculated that the grey relational grade is 0.886792. This result falls within the anticipated optimal 95 percent confidence range. As a result, the grey relational analysis of multi-response problems is a highly effective technique for forecasting surface roughness and tool wear in the internal turning of aluminium alloy 6061.

CHAPTER 6

RESULTS AND DISCUSSION- SUSTAINABLE ASSESSMENT OF MACHINING WITH LIFE CYCLE ANALYSIS

This chapter deals with the sustainable assessment of machining performance under different cutting conditions through life cycle assessment. The inventories used during the experimentation are given as input for life cycle inventory analysis (LCIA) and its environmental impacts studied by the assessment techniques on SimaPro 8.0.1 software. Gate-to-gate approach methodology adopted for life cycle assessment of selected functional unit to investigate the ecological impact using ReCiPe 2016, Endpoint (H) method.

6.1 Life cycle analysis

This work aims to compare the environmental implications of three different cutting procedures for the internal turning of aluminium alloy: dry, flood, and MQL. LCA analysis was carried out using the ReCiPe 2016 (H) LCIA methodology by ISO 14040:2006 and ISO 14044:2006 standards ([Shah et al., 2021](#)). Corrective measures can be taken to find the hotspots with the most significant environmental effect due to the cutting fluid procedure. The Gate-to-Gate technique is used to evaluate environmental consequences based on a cooling strategy, which wipes out transportation and energy utilization to separate crude materials, handle crude materials, and use aluminium stock. Material is removed once its life is finished ([Kurukulasuriya et al., 2020](#)). In this case, a streamlined LCA was used to assess solely the consequences caused by the cutting process on ecological parameters. As a result, the LCA study of machine tools, workplaces, and components required in cutting operations is negated because their environmental consequences are more petite and not dependent on the cutting conditions.

[Fig 6.1](#) specifies the system boundary of the fundamentals being considered and the relationship among input-output flows during boring operations.

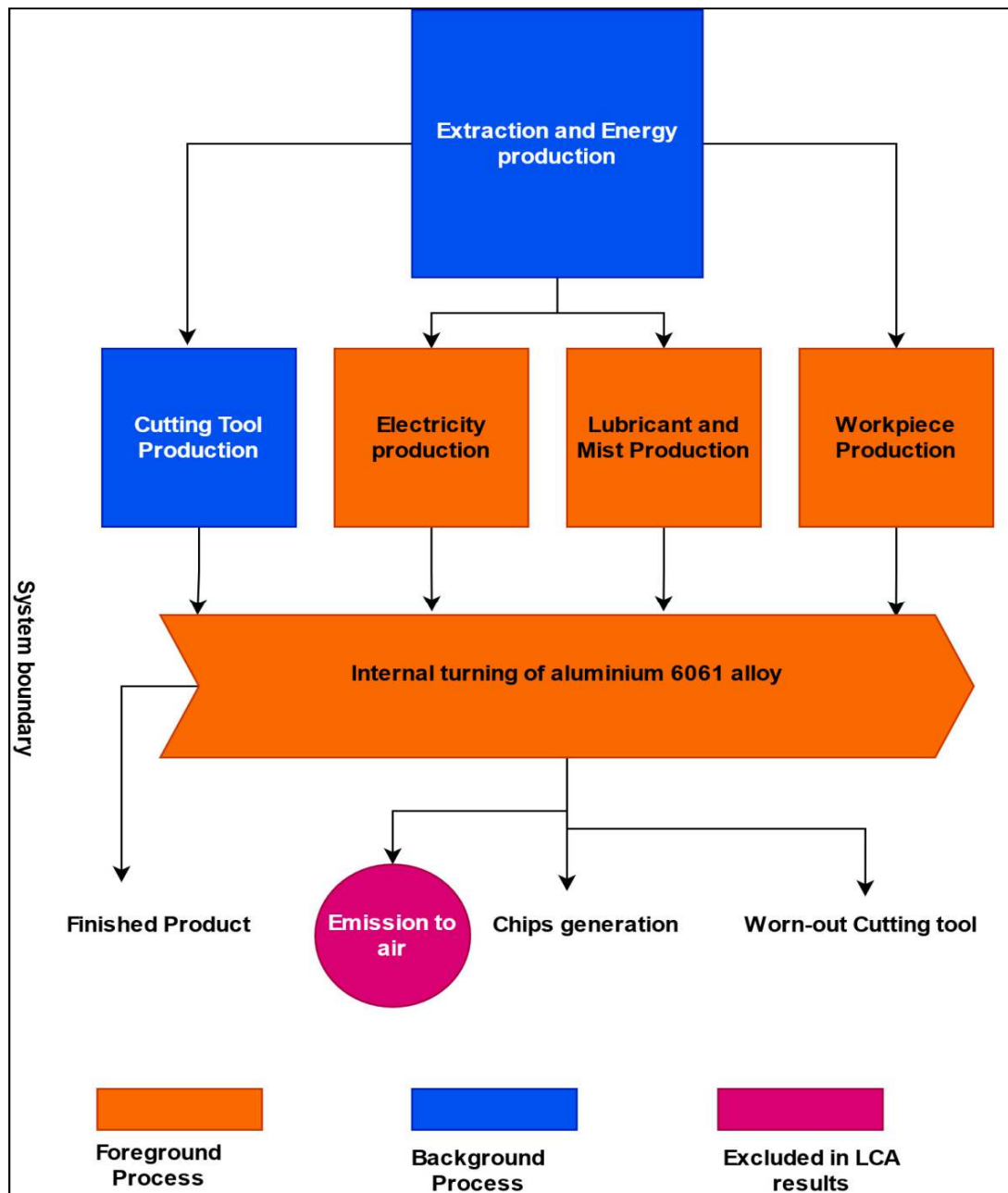


Fig 6.1 System boundary assumptions for life cycle assessment

Foreground and background procedures were identified for the processes for which data was gathered from the trials conducted and Ecoinvent 3.5, respectively. ReCipe 2016

constituents' key indicators of Eco-indicator 99 and CML 2000 (Ingarao et al., 2018) are why ReCipe 2016 endpoint(H) was utilized for LCA.

Twenty-two different sustainable indicators were used to produce the précised results. This research isn't confined to a single effect category. In exploratory research, LCA was used to identify high-priority locations where the dry, flood, and MQL cutting conditions differed the greatest. The differences in environmental and human health consequences across the cutting settings are highlighted in this priority category. For the internal turning process, processes related to the input-output processing units for cutting fluids have an insignificant impact for comparison purposes. Due to this reason, it was excluded from the research analysis.

6.2 Function Unit

The Functional Unit (FU) is used as a critical indicator, especially compared to competing methodologies based on their environmental implications. Cutting time of one minute was preferred as a functional unit. It is more preferred than metal removal in the Ecoinvent database and per industrial specifications (Campitelli et al., 2019). The functional unit is directly related to the input and output of inventory and assessment indicators. It also acts as a reference to compare sustainable machining conditions, i.e., dry, flood, and MQL. The following process has been excluded while doing the inventory analysis for life cycle assessment:

- a) The elements required to make the Al 6061 alloy and cutting tool and the workpiece manufacturing are used for three different cutting conditions.
- b) Manufacturing of coated carbide bit and its inability to enumerate the exact environmental impact of a coated carbide insert is inadequate due to a lack of appropriate datasets. This impacts the study's absoluteness and highlights the necessity for machining-specific datasets. This omission, however, has no significant impact on the outcomes of this study. According to a recent study, a thorough evaluation may still be done by factoring in power and coolant usage, which are essential aspects of the life cycle assessment (Khanna et al., 2021).
- c) Transportation costs, cutting inserts, coolant, air compressor, and workpiece.

- d) Carbon dioxide emissions were observed while machining the stock, particularly in flood and mist lubrication. Due to the lack of adequate recorded data during experimentation, this parameter was kept out of the assessment approach.
- e) The inventory analysis detailing all three cutting conditions has been streamlined on similar aspects. Because the cutting parameters have different subsets, the amount of material removed is different, and the finished product has variable material removal volume. As a result of the streamlining, the metal portion, the generated chips, and the finished product, all made of Aluminium alloy, are excluded from LCA calculations.

Regardless of the cutting fluid used, the machined part is expected to be used for the same purpose. As a result, the assessment does not include the use phase, end-of-life processing, or disposal.

6.3 Inventory handling

Experimental data were recorded as electricity consumption, lubricant quantity, and air compressor capacity. Total material removed from the machining trials in distinct cutting environments forms the calculation of impact assessment on hired method and damage assessment. The data set used for analysis is given in [Table 6.1](#), acquired from the Ecoinvent database:

Table 6.1 Background process details for impact assessment ([Khanna et al., 2021](#))

System input	Units	Description
Electricity	KWh	Electricity, high voltage {IN-Northern grid} market for electricity, high voltage Cut-off, U
Lubricants	Kg	Lubricating oil {RoW} production Cut-off, U
Compressed air	m ³	Compressed air, 600 kPa gauge {GLO} market for Cut-off, U

Table 6.2 Results of process inventories for ecological impact assessment

Impact category	Dry Machining	Flood Machining	MQL Machining
WCAE	0.446295248	2.894786623	1.228534727
GWFE	0.025276316	0.029656757	0.026704487
MEPH	1.5108E-05	2.30615E-05	1.87118E-05
TET	1.14466E-05	1.68921E-05	1.37951E-05
MEET	5.64461E-06	6.29877E-06	5.94589E-06
WCTE	2.90409E-06	3.99026E-06	3.3172E-06
FET	1.27713E-07	2.44696E-07	1.67599E-07
SOD	3.45428E-08	5.09771E-08	4.16301E-08
LU	2.65697E-08	5.44577E-08	3.68118E-08
IR	1.08775E-08	1.70753E-08	1.33206E-08
FEP	3.79969E-09	9.05197E-09	5.65674E-09
OFTE	2.9101E-09	4.16935E-09	3.54382E-09
TAD	2.46612E-09	5.49413E-09	3.56468E-09
OFHH	2.18029E-09	3.06603E-09	2.52884E-09
GWTE	1.77457E-09	4.15298E-09	2.62462E-09
WCHH	1.67895E-09	1.78713E-09	1.7213E-09
HNCI	7.14548E-10	1.43275E-09	9.63035E-10
HCCT	3.15225E-10	3.39062E-10	3.24476E-10
GWHH	3.10573E-10	4.88937E-10	3.72797E-10
FPMF	1.2653E-12	1.48789E-12	1.37192E-12
MRS	9.43388E-13	1.39223E-12	1.13696E-12
FRS	4.69181E-14	8.47677E-14	6.09106E-14

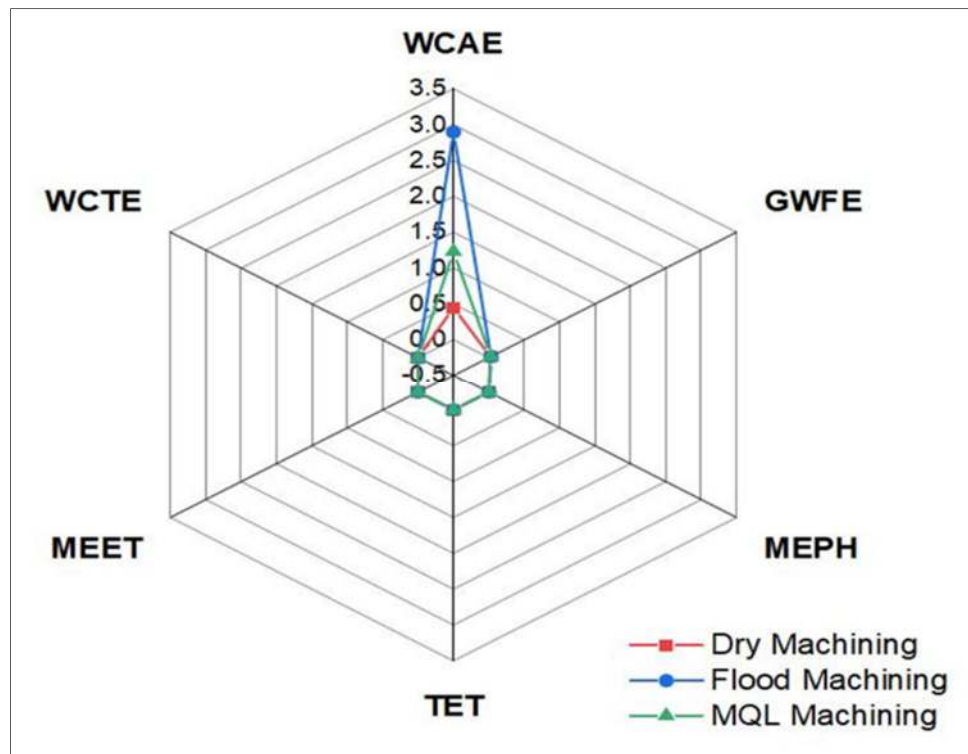


Fig 6.2 Phase I impact category comparison between the three machining environments.

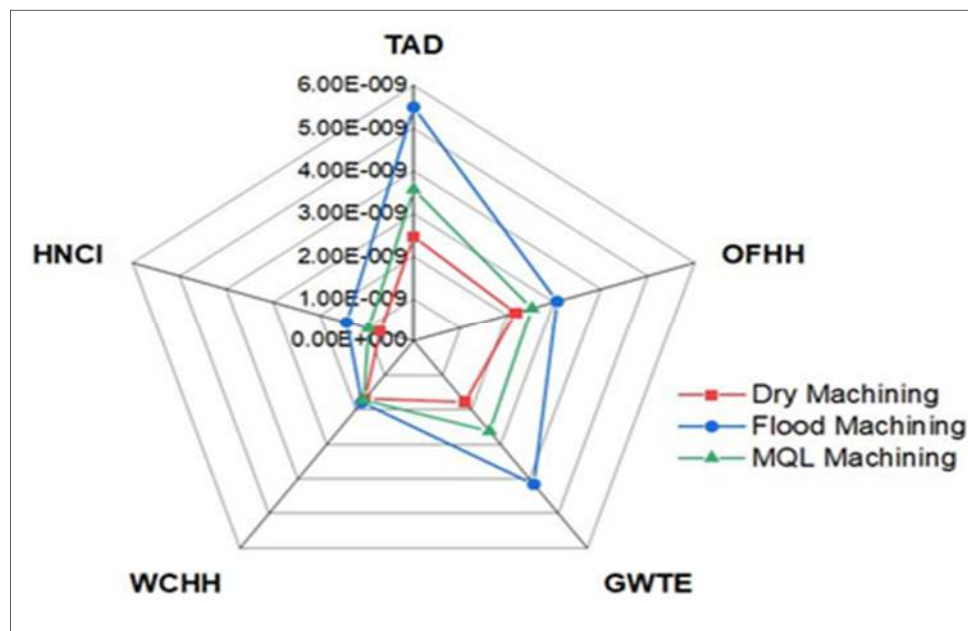


Fig 6.3 Phase II impact category comparison between the three machining environments.

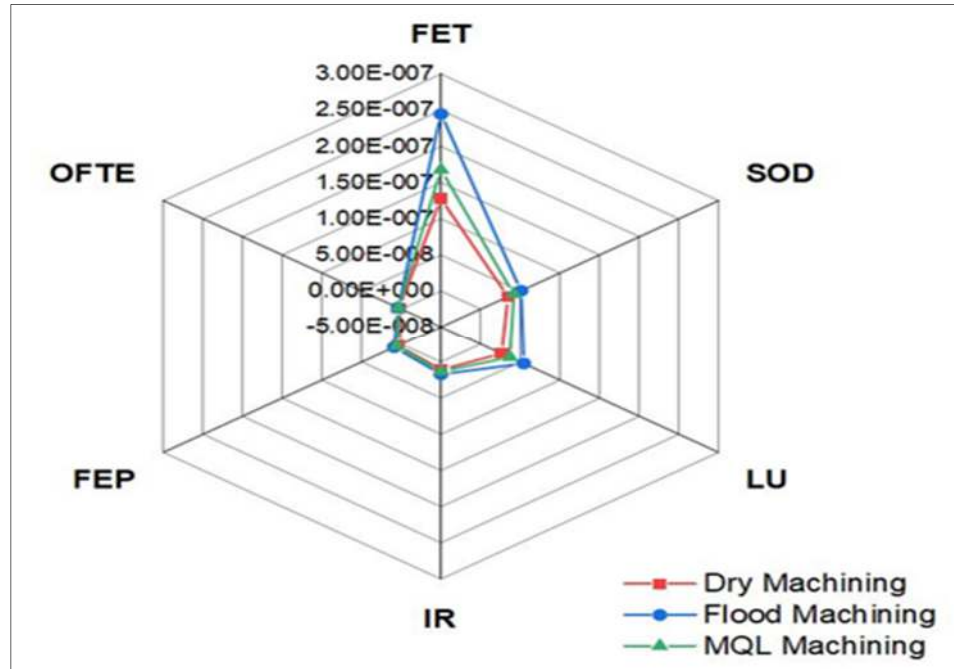


Fig 6.4 Phase III impact category comparison between the three machining environments.

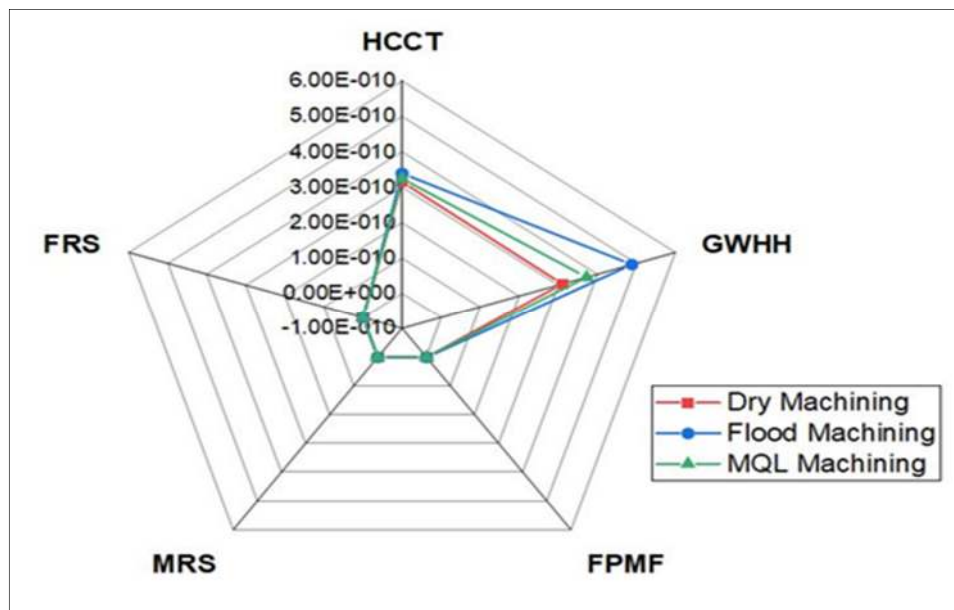


Fig 6.5 Phase IV impact category comparison between the three machining environments.

Table 6.3 Damage assessment characterization

Impact Category	Dry Machining	Flood Machining	MQL Machining
Human health	4.45E-05	6.18E-05	5.21E-05
Ecosystems	7.17E-08	1.06E-07	8.57E-08
Resources	0.563933	3.036894	1.355779

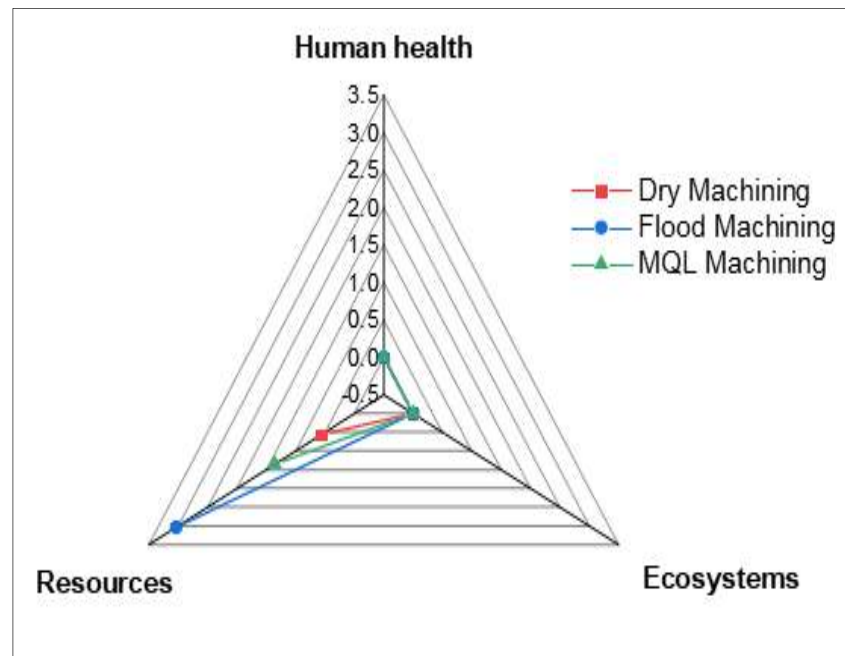


Fig 6.6 Characterization of cooling conditions for damage impact indicators

6.4 Interpretation of LCIA results

This section enlightens the ecological and health parameters associated with the internal turning of three different machining environments. Data mentioned in Table 6.1 is given as a technosphere input for comparing the indicator results given by the ReCipe endpoint 2016(H) methodology. Table 6.2 represents the comparative results of different machining conditions per the Ecoinvent database.

The radar diagrams in Fig 6.2-6.5 reflect that dry machining is more sustainable than flood cooling and near dry machining. This is due to less amount of electricity

consumption and no coolant usage. With an increase in these two inventories input, ecological indicators decrease abruptly, and ultimately, flood machining accounts most significantly for ecological impacts.

[Fig 6.6](#) Similarly, for damage characterization, human health and ecosystems are worst affected in flood machining compared to MQL and dry machining [Table 6.3](#). As expected from the experimental trials, excessive coolant usage in flood conditions utilizes more resources than in dry and near dry machining conditions. A similar kind of work has already been reported by ([Khanna et al., 2021](#)) while using similar inventories for cryogenic drilling. This analysis reflects one limitation of not using location-specific lubricant and compressed air, as mentioned in [Table 6.1](#). For lubricant, the global market specification was utilized, and for compressed air RoW, specified data was employed for LCA analysis due to the non-availability of datasets. These datasets could be added to the Ecoinvent database for the exact measurement of ecological and damage assessment.

The present research work investigated piezoelectric shunt damping, machining characteristics evaluation in different lubricating conditions, and the life cycle assessment of machining data during boring aluminium alloy 6061.

7.1 Conclusions

After inclusion of the result analysis of the presented work, the following significant conclusions can be drawn:

1. In a non-damping state, chatter occurs continuously on the cutting tip, increasing the tool wear and surface roughness during machining. This arises due to variation in the chip thickness created due to overlapping width produced during the machining operation.
2. When piezoelectric transducers are used, they generate energies that will be utilized to damp the vibration amplitude of the long boring bar by using the resistance from the current supplied through the RLC circuits.
3. Surface roughness and vibrational amplitude decrease under damped conditions due to an increase in the stiffness of the boring bar.
4. Statistical analysis revealed an improved grey relational grade upon the confirmation test and experimentation, improving the machined surface's surface quality and chatter reduction.
5. Improved surface texture achieved in MQL proceeded by flood and dry cutting conditions due to decreased cutting temperature and mist layer presence between cutting regimes.
6. Wear decreases significantly in MQL media as less abrasion was observed in the micrograph analysis compared to other lubricating environments.

7. The optimal parameters calculated by the grey relational analysis were **A₃B₂C₃D₃**, i.e. MQL (100ml/h), cutting speed 215m/min, feed rate 0.25 mm/rev, and 0.7 mm depth of cut.
8. The mist produced by supplying aerosol internally through a boring bar proved an effective technique for better surface integrity than conventional and flood lubrication.
9. MQL can be adopted as a permanent technique for boring operation, and it may be an economical approach compared to flood and dry machining.
10. As per assumptions made during the fabrication and working under MQL media, surface roughness and tool wear decrease in MQL than in dry and flood machining.
11. Dry machining outperforms flood and MQL machining in terms of sustainability in terms of global warming, freshwater ecosystems, water usage, and human health.
12. Flood machining contributes more toward ecosystems and resources than dry and MQL machining.
13. In Water consumption, aquatic ecosystems, marine ecotoxicity, stratospheric ozone depletion, and land use, flood machining dominates more than dry and MQL cutting conditions.
14. As per damage impact indicators analysis, human health assessment was better in dry machining, followed by MQL and flood machining.

7.2 Scope for future work

The learned result analysis from the research can propose a few possible extensions. Some of them are listed here:

1. Chatter reduction can be made with advanced sensors for continuous signal recording.
2. The usage of minimum quantity lubrication can be used to study the effect of cutting temperature, residual stresses and dimensional accuracy of the finished surface.
3. The inclusion of hard particles in mist lubrication or flood conditions can be explored to analyze the various machining characteristics.
4. The vibration effect, in combination with the cooling/lubrication, can be discovered to increase the surface finish of the machined surface.
5. Cost analysis of equipment and overall production cost may be investigated upon machining with different cooling conditions.
6. Carbon footprints and energy calculations can be done with machining experimentations.

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