2 LITERATURE REVIEW

2.1 Conventional cutting fluids

2.1.1 Application of conventional cutting fluids in grinding process

In present scenario, grinding is a widely used process in manufacturing and other industries where material removal is required to achieve a desired shape and surface finish. It involves using a grinding wheel, which rotates at high speed and removes material by abrasive action. During the grinding process, more heat absorption at the workpiece may cause thermal damages like a surface burn, surface oxidation, microcracks, surface tempering, tensile residual stress, and changes in the microstructure and microhardness of the work surface, resulting in reduced grinding performance efficiency. The work material absorbs 60 to 80% of the total heat, and the remaining heat goes to the wheel and microchip [68]. To overcome these issues, cutting fluid is often used as a lubricant and coolant in the grinding process. Cutting fluid helps to reduce heat generation, prevent wheel loading, improve surface finish, and extend the life of the grinding wheel. Therefore, the use of cutting fluid is essential for achieving optimal grinding performance and improving the overall quality of the final product.

Conventional cutting fluids provide a lubricating and cooling influence at the interface between tool and workpiece. This can help to improve machined surface integrity, reduce tool wear, and remove chips from the cutting zone, all of which help to make metalworking more sustainable [69]. Because of their diverse properties, different methodologies have been employed to classify cutting fluids. Cutting fluids are classified into four groups, namely, oil-based, aqueous-based, gas-based and solid lubricants (refer to Fig. 2.1). Oil-based cutting fluids, called neat oils, are derived from mineral, animal, and vegetable oils. These cutting fluids are utilized in applications that demand a high lubricity. Generally, it has some additives to improve their applications. Neat oil lubricants offer superior lubrication, corrosion resistance, and anti-seizure properties, making them advantageous. Apart from this, the main drawback is the high flammability as they are good in lubrication but lacking in coolant. However, these properties diminish under high loads and temperatures, generating mist and smoke. Therefore, neat oil lubricants are best suited for low-speed operations with minimal temperature rise [70]. Although, aqueous-based cutting fluids are rather applied in the requirement of effective combined cooling and lubrication. These cutting fluids are further separated into emulsion and solution forms. The aqueous-based products. i.e., "emulsifiable" and "soluble" are mixed with water to form an emulsion and solution. Emulsions offer superior cooling due to the presence of water, while the oil component helps prevent water-induced oxidation. It has no fire hazard and a lower rate of oil misting. Besides, due to the presence of water, the growth of microorganisms like bacteria, yeasts, and fungi are the weaknesses of the emulsion's cooling and lubrication effects and also lead to corrosion. The emulsion is particularly well-suited for low-pressure and high-speed operations where the temperature rise is significant [71]. Gas-based coolant lubricants, including argon, nitrogen, air, and helium, are classified as environmentally friendly cutting fluids, existing in gaseous form at room temperature. These cutting fluids have high corrosion resistance, preventing the machined surface and cutting tool from oxidation at high cutting temperatures. [72]. In contrast, solid lubricants are those solid materials that reduce friction and wear between surfaces in relative motion without requiring a continuous supply of liquid or oil. They can be presented as dispersed particles or coated films on the surfaces. The benefits of solid lubricants are based on their ability to be used in specific applications under high stress or load. Furthermore, it maintains its form even at high temperatures owing to high thermal stability. It is used for many different applications, such as grinding and tapping. Apart from this, drawbacks of solid lubricants include their lower ability for heat dissipation when compared with fluids [73].

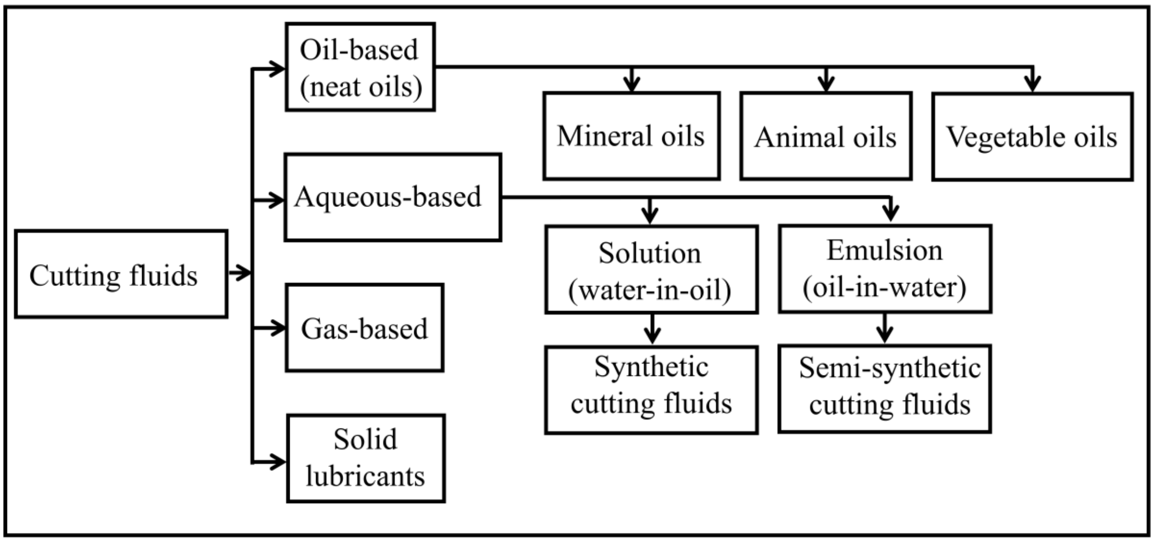


Fig. 2.1: Classification of cutting fluids.

2.1.2 Behaviour of conventional cutting fluids in the grinding zone

Cutting fluids provide many advantages that are widely acknowledged in industry. A cutting fluid serves three primary functions during the grinding process. They include the flushing away of swarf and dislodged wheel grits, bulk cooling of the workpiece, and lubrication [18]. The effects of bulk cooling and flushing are relatively well understood, while the impacts of the cutting fluid's lubrication are less so. Cutting fluids are widely assumed to lower the grinding zone temperature by lubrication, which minimizes wheel dulling rather than eliminating heat from the grinding zone. Reduced wheel dulling reduces friction, and thus power is lowered, which limits heat generation. Bulk cooling and flushing can be achieved when little fluid enters the grinding wheel-workpiece contact region. Lubrication depends on cutting fluid penetrating the grinding zone region. Although a large volume may not be essential to achieve this purpose, cutting fluid delivery will be inefficient if no fluid penetrates the grinding zone.

Fluid flow under a grinding wheel has been studied in an effort to find the ‘useful flow rate' [74].The amount of cutting fluid that flows through the grinding zone and affects the grinding mechanism is called the 'useful flow rate'. Guo and Malkin [75]'s theoretical study, based on experimental results from Engineer et al. [74], concluded that the most effective fluid flow rate was equal to the amount of cutting fluid held in the grinding wheel's pores between the point of application and the start of grinding. Based on the findings of the experiments, a theoretical model for fluid flow through a porous medium was presented. Conventional cutting fluid delivery methods often deliver huge quantities of cutting fluid, only a small percentage of which can be considered a useful flow rate.

Powell [76] developed a model to calculate the penetration depth of fluid from a shoe nozzle into a porous wheel, which can also be used to evaluate the flow rate in the grinding zone, referred to as the 'useful flow rate'. Radial pressure in the shoe was assumed to be the primary factor impacting the penetration depth, as the pressure propels the liquid into the pores of the wheel. The essential variables of the model are the wheel speed, radius, porosity, and permeability. Compared to the grain size of the wheel, the penetration depth is typically quite shallow, suggesting that the cutting fluid mainly stays on the surface of the wheel, not permeating its pores.

Metzger [77] proposed a flow rate model based on evidence. This model showed a link between the amount of flow rate needed to achieve desired grinding results and the power used by the spindle. It was logical to assume that the flow rate of the cutting fluid should be dependent on the grinding power, as it had been established that power and temperature rise in the cutting zone are related. In forming this model, the nozzle efficiency, type of fluid, as well as its density and heat capacity were taken into account.

Schumack et al. [78] successfully utilized Reynolds' equation to ascertain the flow rate through the grinding zone, and their results were found to be in reasonable agreement with experiments associated with laminar flow.

Klocke [79] used Reynolds' equation for laminar flow to create a model of the flow pattern within the grinding zone. This model was based on the gap between the wheel and the workpiece, as well as the velocity of the fluid within that gap. Unfortunately, the model was unsuccessful in turbulent flow situations, limiting its applicability.

Hryniewicz [80] developed a model to analyze the flow of a non-porous wheel against a workpiece, utilizing a modified version of Reynolds' equation to account for the turbulent flow. It was determined that the results were satisfactory when utilized with low Reynolds numbers, although significant discrepancies were seen with higher Reynolds numbers.

In order to maximize efficiency, a delivery method must be established such that a higher amount of cutting fluid can pass through the grinding zone. While some loss can be expected, further research into the process may help increase the flow rate.

2.1.3 Boundary layer effects of conventional cutting fluids

The cutting fluids not only helps dissipate the heat but also creates a boundary layer of air surrounding the grinding zone. The boundary layer of air in grinding is an important factor affecting the grinding process's efficiency and quality. This boundary layer of air acts as a thermal insulator and helps minimize heat transfer from the grinding zone to the workpiece. Several variables, such as the fluid's velocity, viscosity, and angle of incidence, affect the thickness of the boundary layer of air. When the velocity of the coolant fluid is high due to less distance from the nozzle to the grinding zone, the boundary layer of air becomes thinner, and heat transfer from the grinding zone to the workpiece rises. On the other hand, when the velocity of the fluid is low, the boundary layer of air becomes thicker, reducing heat transfer and protecting the workpiece from thermal damage. The viscosity of the coolant fluid also plays a role in determining the thickness of the boundary layer of air.

When the fluid is viscous, it is more difficult to penetrate the grinding zone, resulting in a thicker air barrier layer. In contrast, when the fluid has a low viscosity, it can easily penetrate the grinding zone, resulting in a thinner boundary layer of air. Finally, the angle of incidence of the fluid also affects the thickness of the boundary layer of air. When the fluid is directed perpendicular to the grinding zone, it creates a thinner boundary layer of air than when it is directed at an angle [18]. The grinding wheel speed is another factor that creates a hydrodynamic boundary layer around the wheel during the flow of cutting fluids at the grinding zone. Engineer et al. [74] reported that under high wheel speed, cutting fluids fail to maintain adequate cooling and lubrication in the grinding zone area because the fluid's energy is insufficient to penetrate the boundary layer of air surrounding the wheel. There is a need for a better understanding of the hydrodynamics of cutting fluid delivery and methods to optimize it. Many researchers experimentally investigated and reported the effect of the boundary layer of the air surrounding the grinding wheel. Because of the wedge effect between the grinding wheel and the work surface, a stiff air layer called the hydrodynamic boundary layer may form in front of the grinding zone area. This decreases the depth of cut and raises the total grinding resistance and spindle deformation, which impacts the machining accuracy [20]. The hydrodynamic fluid pressure generated over the ground surface is illustrated graphically in Fig. 2.2.

Li et al. [81] developed a mathematical model for hydrodynamic pressure and hydrodynamic lift force based on the Navier-Stokes and continuous equations. They reported that the hydrodynamic pressure of the fluid is generated in front of the interface area owing to the wedge effect where the grinding wheel–workpiece meets. The findings demonstrated that hydrodynamic pressure increases with increased grinding wheel velocity, wheel diameter and the decreased gap between the wheel and workpiece (refer to Fig. 2.3 (a)-(c)). Thus, based on the results, they also found that hydrodynamic lift force was inversely correlated with the minimum film thickness and correlated with the wheel velocity and fluid viscosity.

Fig. 2.3 (d) depicts the hydrodynamic pressure vector distribution, which reveals that a sufficient quantity of coolant can be wiped off the workpiece surface longitudinally or slip across the edge in a transverse direction due to side leakage. The cutting fluid was diverted away from the grinding zone at the entrance. Some researchers generated a mathematical model to determine the hydrodynamic pressure.

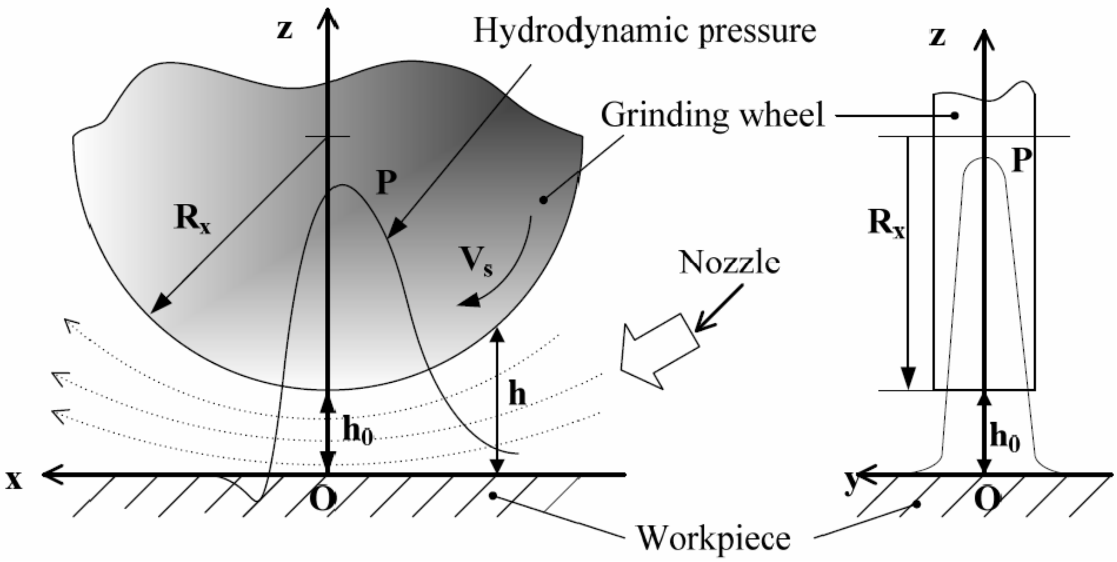
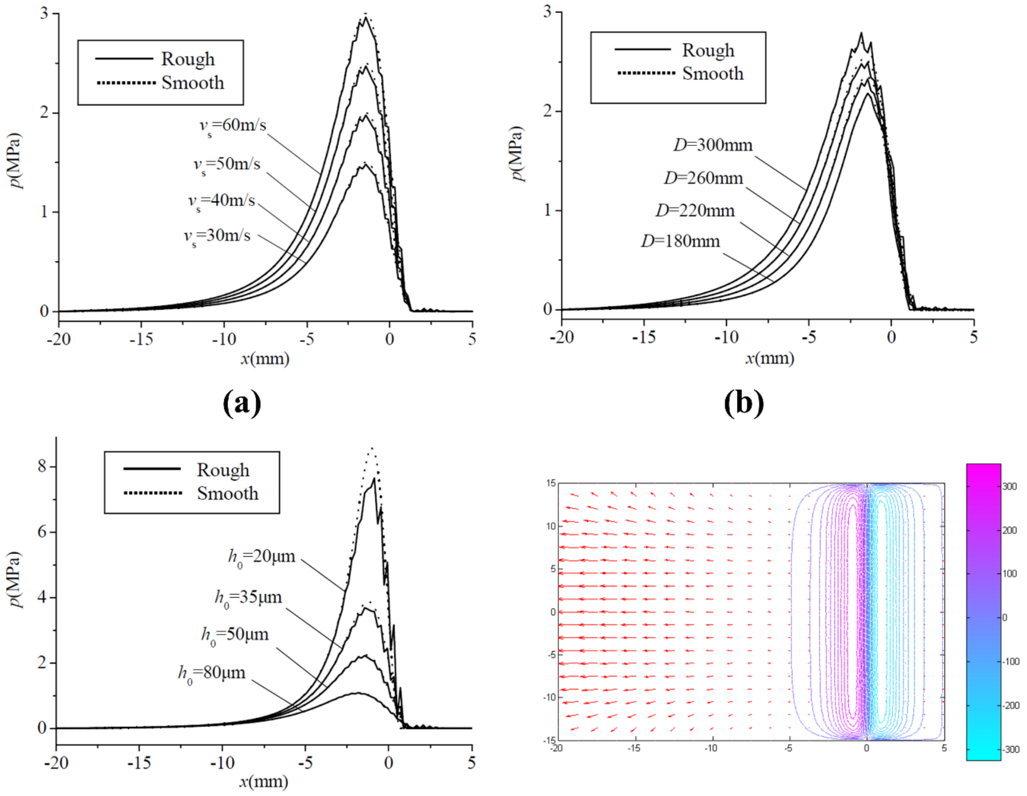


Fig. 2.2: Schematic diagram of hydrodynamic fluid pressure on smooth surface. "With permission from Ref. [81]".

Ganesan et al. [82] studied hydrodynamic forces and found that the fluid pressure increases gradually with wheel speed. Feed rate and cutting depth had a negligible impact. The normal hydrodynamic force was also measured for different gap thicknesses. Hydrodynamic forces (pressure) were examined in the wedge-shaped zone using the classical hydrodynamic theory and laminar flow.

Zhang and Nakajima [83] calculated the hydrodynamic pressure using the Reynolds equation at the grinding zone area. According to their findings, the hydrodynamic pressure is increased by less distance between the grinding wheel and the workpiece.



(a) (b)

(c) (d)

Fig. 2.3: Comparison with rough and smooth models of hydrodynamic pressure with different: (a) Wheel velocities; (b) Wheel diameter; (c) Gap between wheel and workpiece; (d) Hydrodynamic pressure vector profile. “With permission from Ref. [81]”.

Gviniashvili [84] investigated the hydrodynamic pressure and flow in the grinding zone area. The mathematical model relates essential factors, including contact pressure in the grinding zone, wheel velocity, delivery flow rate and fluid density. Additionally, it was found that there was a connection between air pressure and the retention of fluid particles in the boundary layer around the wheel. Relevant experiments were conducted to explore the comparison between porous and nonporous wheels by this model.

Vesali and Tawakoli [85] presented a new model to calculate the hydrodynamic pressure using grinding parameters and wheel specifications. According to this model, increased grinding wheel speeds and decreased gap heights (between wheel and workpiece) result in larger hydrodynamic pressures. Furthermore, a larger grain size decreases the hydrodynamic pressure in the grinding zone, which can be attributed to the grinding wheel's higher porosity. They also studied the hydrodynamic pressure in the grinding zone and found that the most intense pressure at the center of the grinding wheel when measured along the wheel width.

Hwang et al. [86] performed a simulation to study the effect of hydrodynamic pressure in flat surface grinding and then tested the results by changing the wheel tooth geometry. A comparison indicated that the hydrodynamic force was reduced by 20–35% and that the inflection pattern (grinding tool mark) of the ground surface was significantly reduced in rotationally symmetric grinding.

2.1.4 Ecological issues of conventional cutting fluids

In recent years, environmental pollution has been a severe problem utilizing cutting fluids in manufacturing industries because of the toxic nature of chemical composition and less biodegradable cutting fluids. The appearance of hazardous elements like chlorine and microbial growth in cutting fluids is considered hazardous for the environment and operators’ health [15]. According to a report, 80% of all industrial pollutions affect the operators' health due to physical contact with cutting fluids during machining [87]. It is reported that cutting fluids are delivered into the environment in the United States by about 155 million gallons per year, and around 700,000 to one million workers are exposed to cutting fluids [88]. Due to the intricate nature of their composition, cutting fluids can cause irritations or allergic reactions. Furthermore, bacteria and fungi in water-soluble cutting fluids can generate microbial toxins, posing an even greater risk to operators [89].

Numerous machining operations required millions of gallons of cutting fluids for appropriate lubrication and cooling. In the case of the generation of high temperature during the grinding process, cutting fluids are utilized to enhance machining performance. Their primary function is to act as a cooling and lubricant. Cutting fluids are used extensively throughout the grinding process. Therefore, using conventional cutting fluids causes several technological and environmental issues:

1. Conventional cutting fluids can hinder visibility during machining due to mist formation, impacting machining precision. Additionally, they may negatively affect tool life and surface finish.
2. Pollution in the atmosphere is caused by the boiling of conventional cutting fluids at elevated temperatures during the reaction of chemical elements, such as carbon, carbon dioxide, and carbon monoxide, under the dissociation process, which pollutes the working area.
3. Operator health issues, such as skin disease, respiratory diseases, lung cancer, as well as biological and genetic diseases, can occur due to the split of cutting fluids over the body during operation.
4. The improper disposal of cutting fluids can lead to water pollution and soil contamination.
5. More space is required to store the cutting fluids and keep additional systems.

Shokrani et al. [90] reviewed and identified the materials known as difficult-to-cut and their properties under different cutting fluids. They also discussed the effect of cutting fluid on the machining performance, environment, and the operator's health. In order to maintain their ideal properties, cutting fluids need routine maintenance. The emulsion may split, and the fluids' ability to lubricate surfaces may be reduced if bacteria are present in the cutting fluids. They might also alter the pH of the cutting fluid, which would increase the possibility of corrosion occurring on the machine tool as well as the workpiece. Furthermore, they may be highly hazardous to shop floor workers.

Brinksmeier et al. [91] studied that in order to prevent microbial growth and corrosion of machine tool components, the pH of water-based cutting fluid (emulsions or solutions) should generally be in the moderate alkaline range of 8.0-9.5 pH. Emulsion instability and machine/workpiece corrosion are all risks associated with values less than 8.0 pH. It is also known that high pH levels above 9.5 might cause skin irritation.

Cutting fluids in wet cooling mode is viewed as more expensive and damaging to the environment and the operator. However, stringent international pollution regulations, greater attention to human health, and the need for green, sustainable manufacturing following ISO 14000 standards are pushing researchers to reduce the large-scale use of cutting fluids [92], [93]. To mitigate these environmental and health impacts, alternative cutting fluids, such as vegetable oils and synthetic fluids, are being developed and used in grinding operations. These alternative fluids are often biodegradable, have lower toxicity, and produce less waste. Additionally, modern machining techniques, i.e., sustainable techniques, can reduce the use of cutting fluids and minimize their negative environmental impact.

2.2 Sustainable technique alternatives to conventional cutting fluids

The current demand for machining processes that are both technically proficient and environmentally friendly is increasing, necessitating the advancement of more efficient machining methods. Environmentally friendly machining is like sustainable manufacturing. The three pillars of sustainable manufacturing serve as a depiction of the requirement for sustainable manufacturing techniques (refer to Fig. 2.4) [94]. One of the requirements is to enhance things from social, economic, and environmental perspectives.

It maintains equilibrium between social, economic, and environmental factors. Concerns about social impacts arise when promoting fair labour practices, safe working conditions, and positive relationships with local communities. On the other hand, environmental responsibility underscores the need to minimize resource consumption, reduce waste generation, and reduce emissions throughout production. Simultaneously, economic viability involves innovative technologies, streamlining processes, and optimizing resource utilization to enhance productivity and competitiveness in the long term.

According to the U.S. Department of Commerce, most articles published after 2008 define sustainable manufacturing [95], as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound."

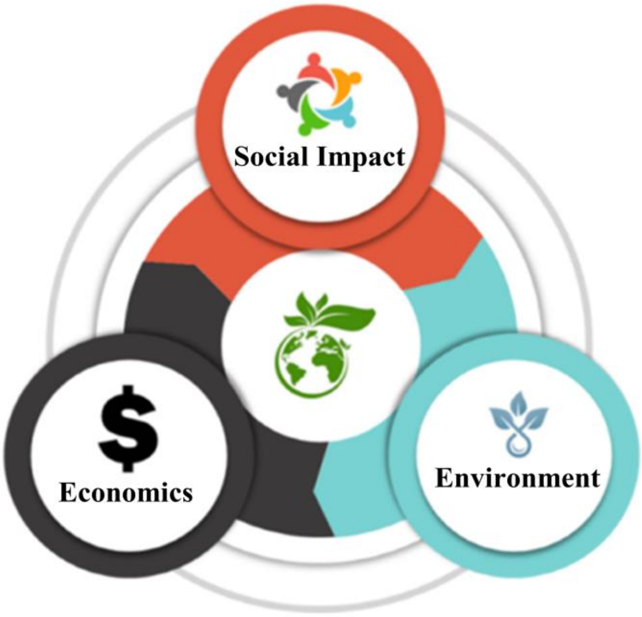


Fig. 2.4: Three pillars of sustainability. "With permission from Ref. [94]".

Here, the main focus of the sustainable technique is to make minimal use of cutting fluids. However, sustainable technique alternatives to conventional cutting fluids are often gaining popularity due to their environmentally friendly and cost-effective nature. Conventional cutting fluids are commonly used in machining processes to reduce friction and heat generated during metal cutting. However, as discussed above, these fluids contain harmful chemicals that can threaten the environment and human health. Sustainable techniques such as dry machining, minimum quantity lubrication (MQL), and cryogenic machining have been introduced as alternatives to conventional cutting fluids. This technique is a cost-effective and eco-friendly approach which increases machinability and is one of the most recent developments in sustainability.

Sharma et al. [96] studied a comprehensive analysis of existing literature on environmentally friendly machining techniques to improve the implementation of eco-friendly machining strategies. It has been determined that the use of environmentally friendly machining techniques can be both economically viable and ecologically sound when compared to conventional cutting fluids. They also compared the outcome of four types of environmentally friendly machining techniques, i.e., dry machining, MQL, cryogenic cooling and high-pressure cooling than conventional cutting fluids.

2.2.1 Dry machining

Dry machining refers to the process of machining without the use of cutting fluid. It helps in reducing production costs and environmental problems [97]. It is a sustainable approach that offers the safety of the environment. Therefore, manufacturing industries must be compelled to consider dry machining to enforce environmental protection laws for occupational safety and health regulations. Dry machining avoids cutting fluid issues such as contamination, disposal, and harmful elements. It does not contribute to air or water pollution. As a result, cutting fluid disposal costs are decreased. Advanced cutting tools materials like multi-layer coated carbides, ceramics, cermet, Cubic Boron Nitride (cBN), Polycrystalline Cubic Boron Nitride (PCBN), and Polycrystalline Diamond (PCD) are developed for use in dry machining. Dry machining at slower cutting speeds, which results in a lower production rate, is preferable to increase the tool's lifespan [98]. Fig. 2.5 shows the benefits of dry machining.

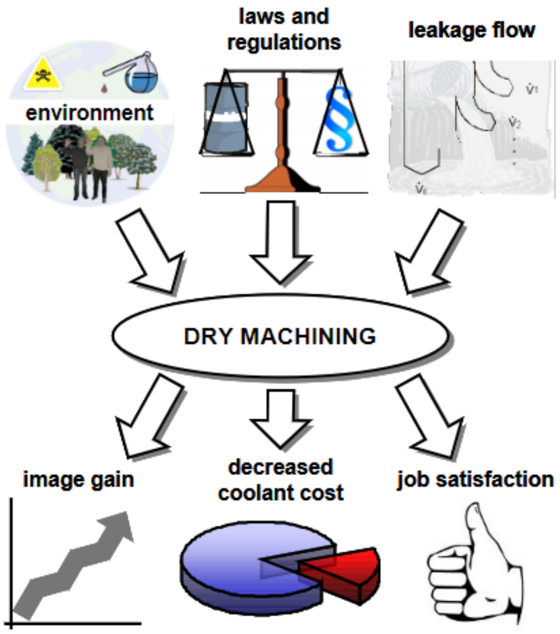


Fig. 2.5: Benefits of dry machining. “With permission from Ref. [99]”.

Nevertheless, dry machining causes issues such as tool overheating. In dry cutting conditions, high friction between the tool and the workpiece substantially raises the temperature, resulting in greater abrasion, diffusion, and oxidation. A lot of heat is also applied to the workpiece, which makes it challenging to obtain precise tolerances and causes metallurgical damage to the surface layer. Furthermore, the formation of chips, which could lead to the deterioration of the machined surface, cannot be washed away. Thus, it is not possible to completely remove cutting fluid from certain machining processes [100]. Therefore, dry machining is feasible for various steel, steel alloy, and cast iron machining by turning, milling, drilling, and gear cutting. Due to the extreme ductility of the workpiece material, it is not possible to drill aluminum-silicon alloys under dry conditions [101]. Consequently, some researchers have attempted to improve the cutting tool materials with a lower coefficient of friction and heightened heat resistance, coating, and tool geometries to make the application of dry machining more feasible [102], [103], [104]. On the other hand, continuous shearing, ploughing, and rubbing modes by numerous randomly oriented abrasive grits needed a higher cutting speed to eliminate undesirable material from the workpiece during grinding operations. In dry grinding, more rubbing action happens due to the occurrence of blunt edges of abrasive grits. These blunt edges produce more heat, which raises various concerns, such as increased wheel wear and lower surface quality [40]. Therefore, dry grinding presents challenges compared to coolant-based grinding due to heat buildup in the workpiece, wheel, and chips.

Silva et al. [93] presented a comparative study of dry and MQL grinding using alumina and CBN wheels. Performance measures included roughness and residual stresses. A poor grinding process performance was observed with higher residual stresses, increased wheel wear, and worst surface roughness under dry conditions.

Sinha et al. [47] carried out experiments using alumina (Al_2O_3) and silicon carbide (SiC) wheels on the grinding of Inconel 718 in dry environment. The adherence of the debris is mainly caused by the creation of high temperatures between the cutting arcs. Because of the chemical reactions that were favoured by the high temperature, the work material stuck to the grits. Further, this debris is subsequently redeposited on the ground surface. The primary conclusion of the present work is that Inconel 718 can be ground more efficiently using alumina grinding wheels compared to the SiC grinding wheel.

Awale et al. [26] compared the grinding performance of hardened H13 hot die steel in terms of specific grinding force, specific grinding energy, grinding force ratio, surface roughness and morphology of ground surface, microchip, and microhardness upon dry, flood, MQL with deionized water (MQL-DIW), MQL with liquid paraffin oil (MQL-LP), and MQL with castor oil based on vegetable oil (MQL-VO) grinding. They found poor results in dry grinding due to generation of high temperature at grinding zone area.

Abhimanyu et al. [105] conducted the plunge surface grinding of AISI D2 tool steel with an alumina grinding wheel. The study compares the influence of traditional dry and wet grinding modes with ultrasonic vibration-assisted dry grinding at different amplitudes. Experimental results showed that dry grinding increased tangential and normal grinding forces, specific grinding energy, and surface roughness parameters compared to other modes. Thermal damage was also increased in dry grinding. Overall, this study suggests that dry grinding is beneficial regarding environmental pollution and operator health but has poor outcomes for hard materials like AISI D2 tool steel.

Dry machining is the best solution for environmental issues and to avoid the use of cutting fluid. But, it is unsuitable for machining harder materials [106], making MQL and other advanced hybrid MQL technologies more viable alternatives than conventional flood cooling methods.

2.2.2 Minimum Quantity Lubrication (MQL) machining

Minimum quantity lubrication (MQL), also known as Near dry machining (NDM), is an additional substitute for conventional cutting fluids. It is a method of applying oil that uses high-pressure air as a carrier, atomized and sprayed in the cutting zone. Compared to the flood lubrication method, 10,000 times less flow rate of cutting fluid is utilized in MQL [107]. The most noticeable advantages it offers are reduced energy consumption, reduced costs, and less use of fluids, all of which contribute to improving the environment [108]. Typically, MQL maintains a fluid flow rate of 50 to 500 ml/h [109]. MQL has been widely adopted in various precision manufacturing industries due to its low consumption of cutting fluid and improved surface finish of finished components. The pictorial view of a wet cooling and MQL setup utilized in a grinding process is shown in Fig. 2.6. In the case of wet cooling, a large percentage of the cutting fluid is simply wasted, but in MQL mode, the liquid-air mixture enters the grinding area, as seen in Fig. 2.6 (picture taken at IIT BHU, IDC, lab).

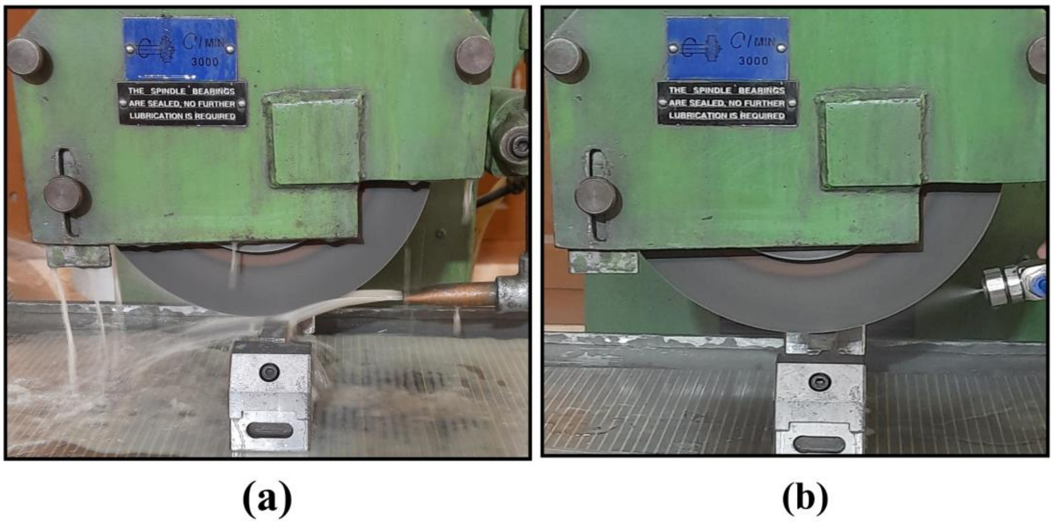


Fig. 2.6: A pictorial view: (a) Wet cooling; (b) MQL system.

MQL principle: In the MQL system, a mixture of cutting fluid and compressed air, also referred to as an aerosol or mist, is used to deliver into the machine zone. Overall, the effectiveness of MQL system depends on the quality of the aerosol formation. The fundamental principle of the MQL method is schematically displayed in Fig. 2.7.

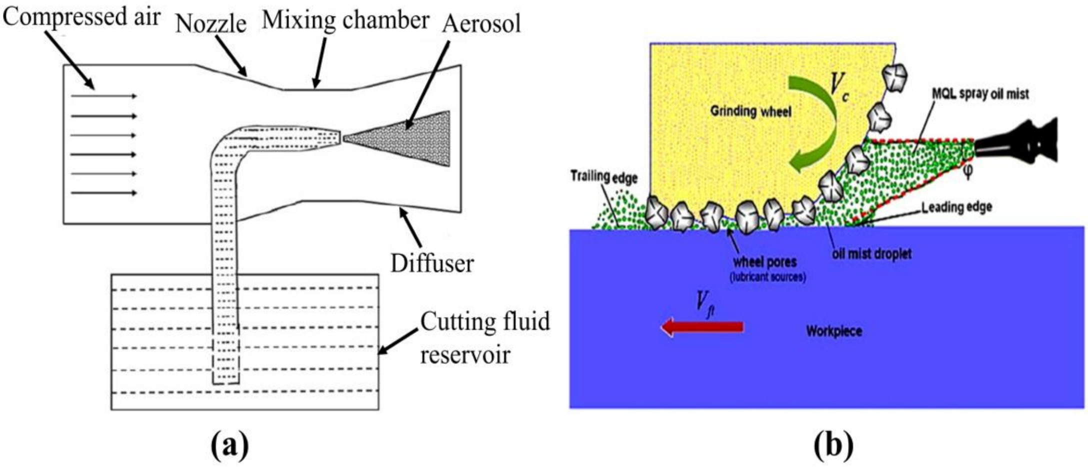


Fig. 2.7: The schematic view illustrating: (a) Basic principle of aerosol formation; (b) MQL application in grinding. “With permission from Ref. [110]”.

In MQL, compressed air is passed through a converging section, generating a partial vacuum that is beneficial in pulling the cutting fluid from the reservoir. The compressed air works as a carrier, and it helps in the separation of the liquid into small droplets. These small droplets improve cooling behaviour by primarily extracting heat from the cutting zone. During machining, it also offers lubrication by producing a metastable fluid film between the mating surfaces. The cause behind this phenomenon is that the lubricating layer adheres to the metal surface and comprises a solid film of oil created by the active radicals of an oiliness agent, which facilitates the adsorption of the metal surface. The boundary oil layer on the metal surface is formed by the gravitational attraction between the metal lattice molecules and the polar molecules of the oil [42]. This led to the formation of a robust metastable lubricating layer over the ground surface during MQL grinding. MQL occupies a significant position in machining from an economic and environmental perspective, producing positive results in a high heat generation process like grinding [111]. This approach has become one of the most eco-friendly and efficient techniques, and various manufacturing sectors have embraced it.

According to numerous studies, MQL uses only minimal amounts of oil throughout the cutting operation to ensure optimal lubrication. Several researchers have achieved satisfactory outcomes using the MQL technique in various machining processes such as turning [112], [113], [114], drilling [115], [116], [117], and milling [118], [119], [120]. In light of the MQL technique being successfully implemented in the turning, drilling, and milling operations, several authors have also explored using this technique in geometrically undefined cutting-edge processes, such as the grinding process.

Mao et al. [121] carried out the surface grinding experiments under different cooling conditions, i.e., dry, wet, pure oil MQL, and oil–water MQL (50 vol.% for mineral oil and 50 vol.% for water). Traditional wet grinding used a flow rate of 6 l/min of grinding fluid.

The flow rate and air pressure settings for MQL grinding were 60 ml/h and 0.6 MPa, respectively. MQL grinding for hardened AISI 52100 steel, compared to dry grinding, considerably improved grinding performance regarding improving grinding force, temperature, roughness, and surface quality. They also provided better lubrication and cooling of water and/or oil at the grinding zone area.

Rahim et al. [122] implemented MQL in the grinding process to reduce defects. They compared the outcomes of this approach with the traditional flood cooling method in terms of grinding force, temperature, and specific energy. The input variables included cutting speeds, depth of cut, and feed rate, each tested at three different levels. The grinding wheel material used was white alumina oxide with a vitrified bond, and the workpiece was mild steel AISI 1020. All tests were done by choosing the wheel speed of 900,1200, and 1500 m/min, table speeds of 400, 500, and 600 mm/min, and downfeed of 0.2 mm. The flow rate of flood and MQL were 30 l/min and 80 l/hour, respectively. The findings of the study demonstrate that using MQL leads to a reduction in surface temperature compared to conventional cooling.

Adibi et al. [123] utilized SiC matrix composites reinforced with carbon fiber as a workpiece to study the impact of MQL in the grinding process under up-grinding mode. They compared the outcomes of MQL with wet and dry machining, analyzing various parameters such as depth of cut (0.1, 0.2, 0.3, and 0.4 mm), feed (500, 1000, 2000, and 3000 mm/min), and cutting speed (25, 35, 40, and 45 m/s) and their effects on forces and grinding energy. The findings suggested that MQL at 100 ml/min flow rate and 4 bar pressure reduced wheel wear and increased G-ratio while generating a remarkably smoother surface than flooded grinding and significantly smoother than dry grinding.

Awale et al. [26] conducted MQL grinding on hardened H13 hot die under dry, flood and MQL and a vitrified bonded alumina wheel. They observed that the MQL technique reduces grinding force and surface roughness and obtains higher microhardness. They also found superior surface quality of ground surface as compared to dry environments. Grinding experiments were performed with respect to 6, 12, 18, and 24 μm downfeed at constant wheel speed and table feed 39.25 m/s and 10 m/min. They fixed the flow rate and pressure of MQl at 200 ml/h and 4 bar, respectively.

Arun et al. [124] conducted an analysis of centreless grinding using three different methods: wet, dry, and MQL. The objective of the investigation was to evaluate the effects of these methods on the roundness and surface finish of EN19 steel. The research findings indicate that MQL can produce a surface finish that is comparable to that achieved with wet machining while also promoting a cleaner work environment and reducing coolant consumption to a significant extent.

The MQL technique results in the release of a significant amount of oil mist into the surrounding environment, which consequently poses risks to both the operator's health and environmental pollution [29]. As such, the MQL technique cannot be deemed safe from these perspectives. However, generally, MQL has some disadvantages:

1. The MQL technique exhibits inadequate proficiency in effectively eliminating the cutting chips from the cutting zone.
2. The MQL technique generates oil mist which tends to float and contaminate the machine tool and work area. Inhalation of the floating oil mist can pose health hazards.
3. Oil mist accumulation on the interior surfaces of the machine tool or the machine shop floor may cause operational issues and accidents due to slipping.

2.2.3 Cryogenic machining

A cryogenic machining is another important sustainable technique. Uehara and Kumagai first used the term “cryogenic machining” in 1968 [125]. Cryogenically aided manufacturing techniques are proving to be safe, toxic-free, hazard-free methods that result in higher functionality of products [126]. Cryogenic cooling refers to the process of cooling materials to extremely low temperatures. Most research and standards organizations believe cryogenics begins at or below -150°C. Liquid gases such as carbon dioxide, nitrogen, and helium are substitutes for traditional oil and water-based coolants and lubricants in machining operations. After that, various varieties of cryogen have been successfully investigated in order to improve the machining properties of significant engineering materials. Recently, A liquefied gas, typically LN_2, has been utilized as an alternative to conventional cutting fluids. The use of LN_2 in the machining and grinding of different steels, titanium, and Ni-based alloys has become increasingly widespread. Nitrogen is a non-harmful, non-poisonous, non-explosive, colourless, and odourless gas that constitutes approximately 78% of the present element in the atmosphere [127]. There is no risk of contamination to the part, chips, machine tool, or operator because LN_2 immediately evaporates as it is delivered to the cutting zone and returned to the atmosphere. Thus, it eliminates requirements for maintenance, post- machining, cleaning, and disposal costs. According to Jawahir et al. [125] have suggested that cryogenic-assisted machining is gaining prominence as a process that is not only environmentally friendly but also free from toxicity and hazards. Furthermore, they propose that this method can be customized to manufacture products that offer improved functionality. Lower temperature increases the hardness and toughness of the material of the cutting tool, allowing for faster material removal rates and, as a result, higher productivity, and lower energy consumption. In cryogenic machining, a cryogen with a controlled volume flow rate is introduced into the machining zone via a nozzle. Usually, cryogens are stored in a cryogen container, known as cryogenic Dewar, as shown in Fig. 2.8. Subsequently, a specially designed pipe equipped with a nozzle is used to apply LN_2 at the grinding zone. The excellent cooling ability of LN_2 quickly absorbs heat and generates a lubricating cushion of nitrogen gas at the grinding zone [30]. As stated by Hong and Zhao [128], the application of cryogenic LN_2 not only considerably lowered the cutting temperature but also reduced the coefficient of friction and changed the surface properties of the workpiece.

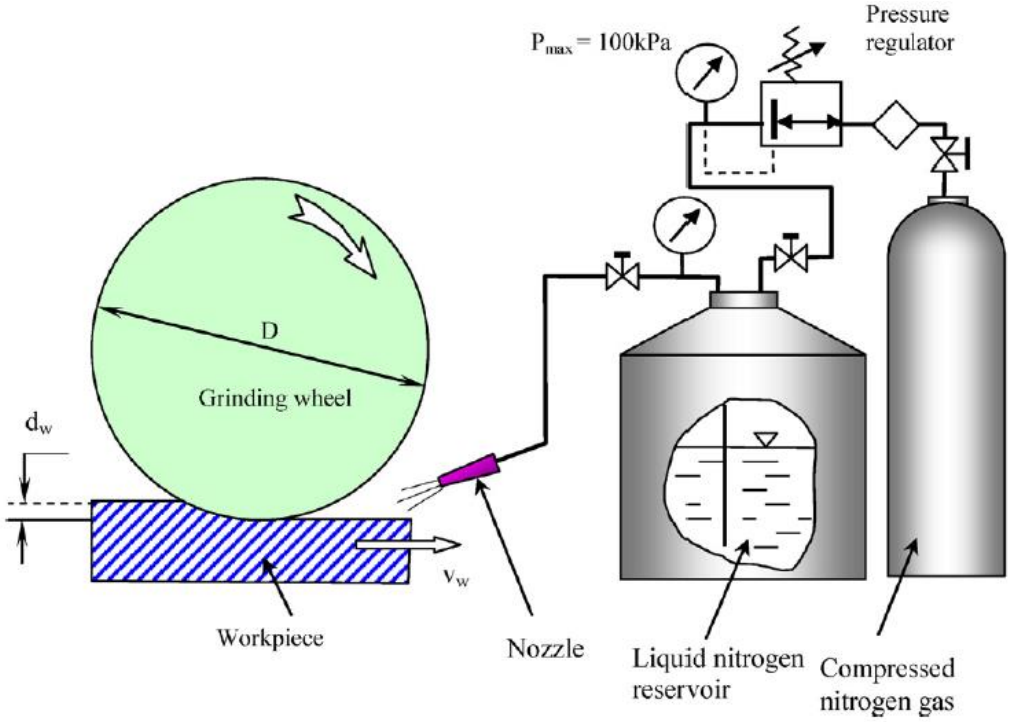


Fig. 2.8: The experimental setup using liquid nitrogen. "With permission from Ref. [129]".

Cryogenic machining is a completely clean process. It may have the following advantages [127]:

1. sustainable machining (a safer, cleaner, and eco-friendly method).
2. increased heat sink performances (low temperature at the cutting zone).
3. increased cutting tool life.
4. enhanced chip breakability.
5. reduced probability of burr formation on the machined part.

6. reduced possibility of build-up edge (BUE) formation.
7. improved machined part surface quality with the absence of mechanical and chemical degradation of the machined surface.
8. increased material removal rate (MRR) without an increase in tool wear and with decreased cutting tool changeover cost, resulting in higher productivity.
9. reduced production costs, etc.

Several methods have been utilized to use the cooling outcome of cryogenic mechanisms during machining process. Methods are categorized into cutting or contact zone cooling, workpiece cooling and indirect cooling or combining these methods [130]. Owing to the intricate nature of the machining process, particularly in intermittent operations, identifying a clear border between these methods is not possible. In addition, each method is described in the subsequently sections.

Cutting/contact zone cooling: Cryogenic coolant is the utmost recommended method for effective cooling at the cutting zone by which it is spraying the LN_2 coolant into the tool-chip-workpiece contact zone. Various methodologies have been applied to enter the coolant media into the contact zone. The foremost objective of cryogenic coolant is to extract the heat from the contact zone throughout the cutting process, cool the cutting tool, improve the properties of the cutting tool and change the coefficient of friction [131].

Workpiece cooling: The main objective of the cryogenic methods is to enhance the material characteristics of the workpiece to improve the machinability of different engineering materials. Commonly two cryogenic methods, viz. cryogenic bath, and cryogenic spray, are recommended to cool the workpiece. The workpiece is frequently immersed in a cryogenic coolant just before the cutting operation in cryogenic bath cooling.

Besides, in spray jet cooling, the cryogen coolant is sprayed over the workpiece while machining [130].

Indirect cooling: In this method, developed heat is dispersed by conduction across the cutting tool surface during machining. The conventional indirect cooling method is identified as a heat pipe with three parts, i.e., evaporation, adiabatic and condensation [132]. By conduction, the generated heat in the interface area between the tool and workpiece is transferred to the evaporation section, which evaporates the cutting fluids. The evaporated fluid is subsequently transmitted through the adiabatic unit to the condensation unit. In the condensation part, the vapour is cooled and then liquefied. On the contrary, adiabatic and condensation units are not required for indirect cryogenic cooling at the contact zone area due to the self-evaporation of cryogen coolant into the atmosphere after consuming the heat [133]. The cryogenic coolant is injected into a chamber that is either above or below the cutting tool. Further, this coolant absorbs heat through conduction and evaporation at the contact zone during machining. The evaporated coolant is later discharged to the air by the chamber outlet area. The fundamental goal of this approach is to freeze the tool without having the cryogenic coolant come into direct contact with the cutting zone or workpiece. In this method, the cryogenic coolant is not in physical interaction with the workpiece. As a result, the adverse impact of cryogenic coolant on the workpiece, like geometrical variation and material strength and hardness, may be reduced [134]. Therefore, the effectiveness of the method is hugely reliant on covering the material characteristics of the cutting tool.

2.2.3.1 Review of application of cryogenic cooling in grinding operation

An important focus area in grinding difficult-to-cut materials is the use of sustainable grinding processes, i.e., cryogenic grinding. Such grinding process must not have a negative impact on the product, process, or system. The innovative study effort in the enhancement of grindability of widely recognised and utilized materials using cryogenic grinding processes is discussed here.

Paul and Chattopadhyay [135], [136] discussed the effect of grinding temperatures in different types of steel, such as mild steel, high carbon steel, cold die steel, hot die steel, and high speed steel, during grinding, which can lead to reduced wheel life and induce tensile residual stresses and microcracks on the ground surface. The authors investigated the use of cryo-grinding, which involves using a liquid nitrogen jet to cool the steel during grinding, as presented in Fig. 2.9. They used the process parameters and conditions: downfeed- 10, 20, 30, and 40 µm, cutting speed-23.5 m/s, and table speed-8 m/min.

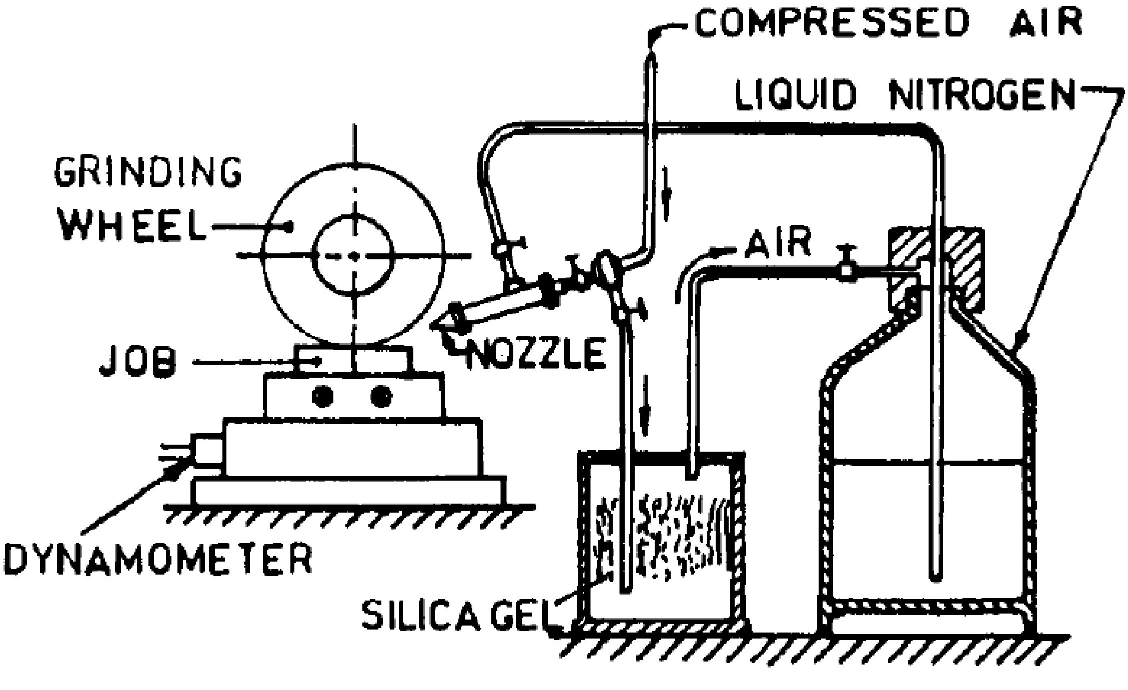


Fig. 2.9: Schematic of cryogenic grinding setup. “With permission from Ref. [135]”.

The study found that cryo-grinding resulted in improvements such as a reduction in specific energy requirements, grinding temperature, grinding forces, and residual stress. The authors suggested that cryo-grinding can be a cost-effective solution for critical components subjected to severe dynamic loading. They also recommended controlling the application of the cryogen to minimize its consumption. They further stated that cryo-cooling not only lowered the highest ground surface temperature but also reduced the depth of the heat-affected zone, which might improve the static and dynamic strength of the work materials. Furthermore, shorter lamellar chips and crushed or fractured chips were obtained in cryogenic grinding.

Fredj et al. [137] assessed the impact of cryogenic cooling on the ground surface quality of AISI 304 austenitic stainless steel. Grinding experiments were conducted under dry, soluble oil, and cryogenic cooling environments, with the latter generating the lowest grinding temperature. Although no significant differences were observed in specific grinding force components, cryogenic cooling resulted in a reduction of more than 40% in surface roughness and improvements in work hardening, residual stress, and corrosion resistance. These improvements were attributed to the reduction of the grinding temperature, which lowered the tensile residual stress, and the cryo-temperature, which reduced ground surface damage and facilitated material removal through shearing. The study also found that high work speed and low depth of cut values were favourable conditions for achieving these improvements in grindability and surface integrity.

Nguyen et al. [129] presented an innovative steel grinding-hardening technology using liquid nitrogen, which results in a hardened surface layer with a fine laths martensite structure and high hardness. The treatment also produced superior surface integrity, with compressive surface residual stresses and without surface oxidation. The use of liquid nitrogen made the grinding process environmentally friendly.

Li et al. [138] presented an evaluation of the grindability and surface integrity of a nickel-based superalloy using cryogenic cooling during grinding. Three environments were compared: dry, mineral oil, and cryogenic cooling jet. The results showed that while cryogenic cooling generated the lowest grinding temperature, there were no significant differences in the specific grinding force components. However, substantial improvements were observed in the ground surface integrity. The cryogenic cooling process not only enhanced the surface quality and surface integrity but also prolonged the wheel sharpness and reduced the pollution of the grinding fluid. Cryogenic cooling reduced the grinding forces significantly, attributed to a favourable chip formation mode, grit sharpness retention, inert atmosphere, less ploughing, and deformation. Grinding under cryogenic cooling also substantially reduced the grinding zone temperature and wheel wear due to its better effectiveness in controlling the grinding forces and specific energy.

Soni et al. [139] examined the effects of wheel speed, table feed, and depth of cut on grinding force components, specific energy, and surface roughness of a composite ceramic material (AlSiTi) using Taguchi's experimental design method. They also studied and analyzed surface and subsurface damage using scanning electron microscopy (SEM) and compared results with dry grinding. The findings provided valuable information on the grindability of the composite ceramic material, especially under cryogenic conditions. While compared to dry grinding, considerable reduction in R_a, grinding forces and specific grinding energy were found in the case of cryogenic environment. According to the SEM analysis, no notable ground surface and subsurface damage was observed under cryogenic grinding. This happens due to application of high jet LN_2, which reduces grinding zone temperature and cutting forces.

Manimaran and Kumar [140] investigated the influence of liquid nitrogen as a cryogenic coolant and its delivery pressure on grinding forces and surface roughness for the difficult-to-cut material EN31 using conventional aluminum oxide and Sol-Gel (SG) alumina grinding wheels. Results showed that the use of liquid nitrogen reduces grinding forces by 24% and 16% compared to dry and wet grinding, respectively, and surface roughness by a maximum of 43% and 26% over dry and wet grinding. The SG wheel produced the greatest reduction in grinding forces and surface roughness compared to the aluminum oxide wheel. Increasing the delivery pressure of liquid nitrogen reduced grinding forces and surface roughness by 4-8% and 3-8%, respectively.

Setti et al. [141] conducted grinding experiments on Ti-6Al-4V alloys under liquid nitrogen cryogenic cooling as an alternative technique. The effects of cryogenic cooling were compared with those of dry and wet (soluble oil) conditions. Results showed that cryogenic cooling reduced grinding force, improved surface finish, and caused less surface damage. Multiple regression models were created to predict normal and tangential forces in cryogenic conditions, which were validated with experimental data. The models had a maximum prediction error of less than 12% and 9% for normal and tangential forces, respectively.

Manimaran et al. [30] evaluated the effects of using liquid nitrogen (LN_2) as a coolant in the cryogenic grinding process on the grinding force and surface roughness of stainless steel 316. The experiment was conducted in dry, wet, and cryogenic cooling environments at different grinding conditions such as downfeed: 10, 20, 30, and 40 µm; table speed: 0.1, 0.125, and 0.15 m/s; wheel speed: 31.4 m/s. Results showed that using cryogenic coolant significantly reduces the grinding zone temperature, resulting in better machining performance. Cryogenic cooling reduced grinding forces by 37% and 13% compared to dry and wet cooling, respectively. It also produced surface roughness with 59% and 32% lesser values and fewer defects in surface roughness compared to dry and wet cooling. They found long leafy and sphere-shaped chips with thermal effects on edges in dry, and long lamellar and leafy chips with fewer thermal effects in wet. In the case of cryogenic cooling, short lamellar chips and some long leafy chips were seen.

Zhou et al. [142] investigated the influence of process parameters such as depth of cut, table feed, and wheel speed on response parameters, i.e., grinding force, surface roughness (R_a), and surface morphology. They used LN_2 to grind SiCp/Al composites with different volume fractions and particles size of SiC. Simultaneously, the results of the cryogenic cooling effect were compared with traditional wet grinding. According to the experiments, cryogenic cooling improved the auxiliary function of the Al matrix to SiC particles and enhanced the surface quality of the overall ground composite.

Elanchezhian et al. [143] conducted a grinding experiment to investigate the effects of using liquid nitrogen as a coolant in the grinding of Ti-6Al-4V alloy using an electroplated cubic boron nitride grinding wheel. The investigation considered input process parameters of the depth of cut and nozzle inclination angle and output response parameters of tangential and normal forces, grinding zone temperature, specific energy, and surface roughness (R_a). Results showed that using liquid nitrogen as a coolant reduced tangential force by 8% to 27%, normal force by 3% to 12%, R_a by up to 38%, and grinding zone temperature by up to 55%. The nozzle angle at 45° was found to have a significant effect on the grinding process. Surface modification and chip morphology were also analyzed.

Kumar et al. [144] discussed the difficulties and costs of machining titanium alloys, as well as methods to reduce machining costs and improve surface finish. The proposed solutions include using a novel bondless diamond grinding wheel and liquid nitrogen coolant to reduce cutting zone temperature. They achieve nanometric finishing in the grinding operation for a better surface finish under LN_2 coolant.

Sinha et al. [36] found that LN_2 during grinding improves the grindability of Inconel 718 (IN718) compared to dry and wet grinding. All the experiments were conducted by selecting the wheel speed of 10, 15, and 20 m/s, table speed of 3, 9, and 15 m/min, and downfeed of 10, 15, and 20 µm. LN_2 grinding resulted in lower grinding forces, less oxidation, minimal surface damage, and better surface integrity. They also examined the chip morphology under dry, wet, and LN_2 grinding. Furthermore, the researchers concluded that LN_2 grinding is an effective and clean method for improving the grinding performance of IN718.

Singh et al. [145] carried out grinding studies on additive manufactured Ti-6Al-4V materials using varying depth of cut and table speeds. The best grinding conditions were optimized from the regression model. The results show that cryogenic grinding significantly reduced grinding forces and heat production, resulting in reduced surface roughness compared to dry and wet grinding. The tangential and normal forces were decreased, and the surface roughness values were measured using a 3D atomic force microscopy micrograph. Cryogenic grinding was found to be the most effective in reducing surface roughness, with a decrease in values from 5.94 µm to 0.259 µm, and the values were measured as 137 nm.

The literature on cryogenic cooling provided insight into the grindability of various types of steel, ceramics, composites, titanium, and nickel-based alloy materials, which can significantly be improved using liquid nitrogen as a cutting fluid. Besides, liquid nitrogen as a coolant has all the characteristics that make the grinding process more sustainable. The high cooling capability of this cryogenic coolant can improve the grinding behaviour of AISI D2 tool steel in a more eco-friendly manner, as has been observed for difficult-to-cut material EN31 [140]. Some results under cryogenic grinding from previous articles, such as hardness, contradict our outcomes. Hardness depends on the material properties of the workpiece, microstructural transformations, grinding parameters (like wheel type, grain size, downfeed and cutting speed), and cryogenic cooling intensity.

The application condition for cooling and lubrication, which affect friction, temperatures, cutting forces, etc., significantly impact the process performance. These circumstances also impact the components' tool life, dimensional accuracy, and surface integrity. Therefore, a new aerosol technique has been developed during the past decade to lubricate the cutting zone by using small amounts of oil particles in MQL form in combination with cryogenic coolant, i.e., LN_2. Because in cryogenic machining, LN_2 has a superior cooling effect at the cutting zone, but the lubrication effect is not better than the MQL technique [125]. Thus, the application of Cryo-MQL offers the advantage in combination with cooling and lubrication effects over other sustainable techniques. The Cryo-MQL technique has been identified as an attractive method and has been explored in the material cutting field with a view to potential future applications.

2.2.4 Hybrid Cryo-MQL machining

The hybrid cooling technique is the combination of two processes to utilize the benefits of both approaches simultaneously. For instance, the combination of cryogenic cooling and MQL, called Cryo-MQL, is simultaneously referred to in much of literature [146]. Generally, Cryo-MQL technology is introduced to realize green, high-quality machining of difficult-to-cut materials due to lack lubricating capacity of LN_2 [147]. Cryo-MQL technology not only markedly lowers the temperature in the cutting zone and maintains the oil film's ability to lubricate effectively but also plays a crucial role in enhancing the workpiece's surface quality and lowering tool wear [148]. This approach employs a high-pressure jet of LN_2 and micro-lubricating oil into the cutting zone. LN_2 sublimates and absorbs a substantial quantity of heat, lowering the temperature of the cutting zone. At the same time, the lubricating oil creates a steady lubricating film on the tool/workpiece interface, enhancing the anti-friction and anti-wear properties [149]. Basically, Cryo-MQL satisfies the criteria for green and clean processing because it is pollution-free and environmentally friendly. Table 2.1 compares the Cryo-MQL with various cooling strategies and sustainability concerns.

Table 2.1: Effectiveness and application of various cooling and lubricating strategies [125].

	Effects of the cooling and lubrication strategy	**Dry (*compressed air*)**	**Flood (*emulsion oil*)**	**MQL (*Oil*)**	**Cryogenic (LN_2)**	**Hybrid (LN_2 + *MQL*)**
Primary	Cooling	Poor	Good	Marginal	Excellent	Excellent
	Lubrication	Poor	Excellent	Excellent	Marginal	Excellent
	Chip Removal	Good	Good	Marginal	Good	Good
Secondary	Machine Cooling	Poor	Good	Poor	Marginal	Marginal
	Workpiece Cooling	Poor	Good	Poor	Good	Good
	Dust/Particle Control	Poor	Good	Marginal	Marginal	Good
	Product Quality (Surface Integrity)	Poor	Good	Marginal	Excellent	Excellent
Sustainability Concerns		Poor surface integrity due to thermal damage	Water pollution, microbial infestation, high cost	Harmful oil vapour	Initial cost	Initial cost, Oil vapour

Over the past few years, the use of MQL along with appropriate cutting fluids and the application of cryogenic methods have garnered increased attention in the grinding of high-strength materials. MQL grinding is a highly efficient and effective technique for investigating material grinding characteristics, owing to its relatively lower cost, ease of implementation, and environmentally friendly nature. Cryogenic grinding is also a widely-employed and sustainable approach. MQL, cryogenic, and Cryo-MQL machining techniques represent advancements over conventional wet cooling and dry methods.

2.2.4.1 Review of application of the Cryo-MQL in grinding operation

Cryo-MQL machining is an emerging technology that promises to improve machining performance and reduce environmental impact. However, more research and development are needed to fully understand this technology's benefits and limitations. Researchers developed cryogenic coolant combined with MQL techniques to lower the grinding zone temperature, prevent grinding-induced thermal damage, and improve ground surface quality. It also increases the wheel life and retains the sharpness of abrasive grains.

Nowadays, many researchers are dedicating their efforts towards growing the field of cryogenic minimum quantity lubrication (Cryo-MQL) machining, especially in the turning [150], [151], [152], [153] and milling [41], [154], [155], [156] process. However, the available literature on the Cryo-MQL grinding is scarce, as presented herein.

Sanchez et al. [157] conducted an experiment on surface grinding for AISI D2 tool steel under hybrid Cryo-MQL. They used CO_2 as a cryogenic coolant. This hybrid system protects abrasive grits with a layer of frozen oil, improving the grinding wheel's longevity and the machined component's quality. Although this technique provides less cooling than traditional coolant methods, no thermal damage was observed on the workpiece. They also observed an improvement in surface roughness under Cryo-MQL.

Balan et al. [158] conducted grinding experiments with resin bonded diamond wheel on Inconel 751 superalloy in dry, MQL, and Cryo-MQL modes using Cimtech D14 oil. They used the experimental setup of Cryo-MQL system, as shown in Fig. 2.10. Fig. 2.11 shows the comparison of surface roughness with cutting velocity at different cooling mode.

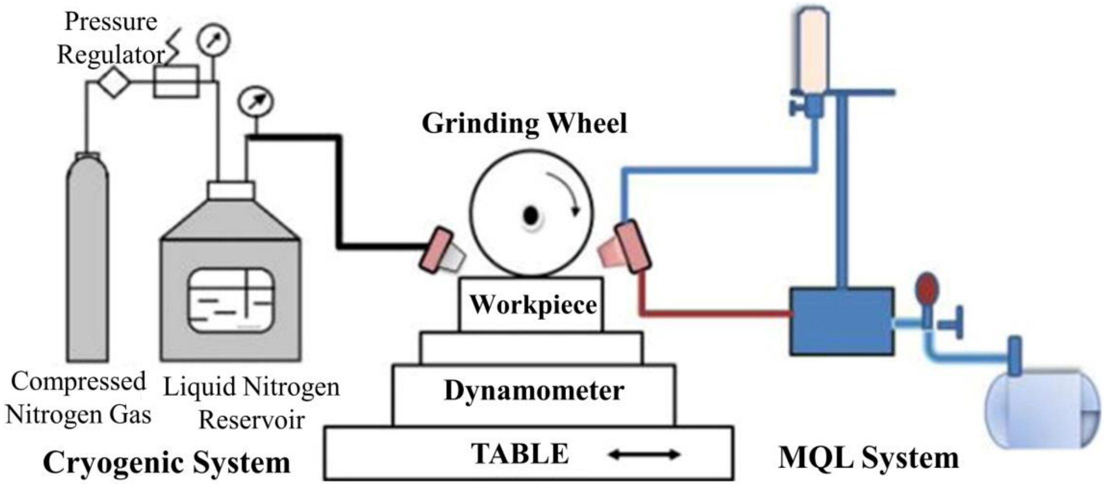


Fig. 2.10: Experimental setup of Cryo-MQL system. “With permission from Ref. [158]”.

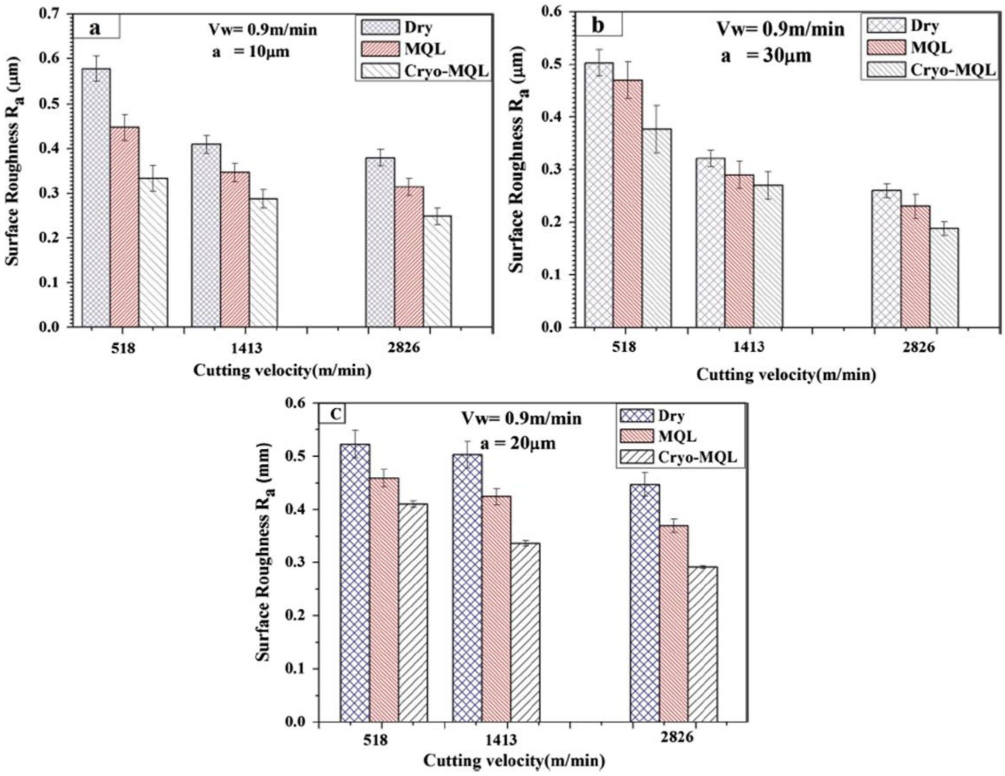


Fig. 2.11: Comparison of surface roughness at different cooling mode. “With permission from Ref. [158]".

The results showed that Cryo-MQL (using liquid nitrogen and MQL) decreased temperature, cutting forces, and surface roughness compared to MQL and dry grinding. Surface roughness decreased by 20% over MQL and 28% in dry conditions, as depicted in

Fig. 2.11. Material side flow over the ground surface was hardly seen under Cryo-MQL and MQL conditions, unlike dry grinding, which causes thermal damage. Different chip types were observed during grinding, with Cryo-MQL producing blocky chips. The specific cutting energy was 50-65% lower for Cryo-MQL than dry grinding, indicating improved process efficiency. Overall, the study suggests that Cryo-MQL can enhance the grindability of Inconel 751 superalloy.

Cui et al. [45] introduced cryogenic nanolubricant minimum quantity lubrication (CNMQL), a new approach that utilizes the heat transfer capacity of cryogenic air and the antiwear/antifriction performance of nanolubricant. They analyzed grindability for Ti-6Al-4V material based on responses such as force, temperature, surface roughness, workpiece, and debris morphology. Results show that CNMQL exhibits the lowest grinding force, grinding temperature, and surface roughness value compared with NMQL and cryogenic air cooling. The Energy ratio coefficient of the cooling medium (R_m) in CNMQL is 36.4% higher than NMQL, and the Defect ratio (D_r) value is significantly lower than cryogenic air cooling and NMQL. Cryogenic nanolubricant displays excellent grinding performance due to its higher viscosity and improved convective heat transfer capacity, which results in fewer surface defects. Therefore, CNMQL could effectively address the challenge of defect suppression in grinding titanium alloys with low thermal conductivity.

From the above-discussed literature (under MQL, cryogenic and Cryo-MQL grinding), it is apparent that in the present scenario, MQL and cryogenic grinding are getting well accepted and appreciated in cutting environments in the manufacturing industries. It is also evident that until now, MQL and cryogenic grinding has been used in the grindability improvement of various types of steel, ceramics, composites, titanium, and nickel-based alloys. However, till date, no significant and systematic research work has been reported for the grinding of AISI D2 tool steel under LN_2 and Cryo-MQL environments. It seems important to explore and investigate the grindability of AISI D2 tool steel under these sustainable grinding conditions. Therefore, it is necessary to study the grinding characteristics of AISI D2 tool steel by adopting environmentally friendly grinding techniques such as LN_2 and Cryo-MQL.

2.3 Vegetable oil-based MQL in grinding

Industrial uses of vegetable oils provide new insights into these vital (and growing) vegetable oil products. Vegetable oils are a promising alternative to conventional cutting fluids due to their environmentally benign features, high biodegradability, non-pollutant, and cost-effectiveness [42]. Vegetable oils are extracted organically from seeds and flowers. Vegetable oils have the following characteristics: high biodegradability (>95%), low toxicity, high flash and fire points (>300°C), and lesser flammability [159]. Research on the development of bio-based cutting fluids is becoming increasingly popular, and this trend is spreading around worldwide. The usage of vegetable oil as a cutting fluid is expected to increase by 7–10% annually in the US manufacturing sector during the coming years [16].

Most of the vegetable oils available are consisting of triglycerides glycerol molecules. Triglycerides are also known by the name triacylglycerol (TAG). In triglyceride structure three long chain of fatty acids are attached via ester linkage at hydroxyl groups as shown in Fig. 2.12 (a). Natural vegetable oils are composed of fatty acids with varying chain lengths and double bonds. Thus, the ratio and the location of carbon-carbon double bonds determine the fatty acid composition. As seen in Fig. 2.12 (b), long carbon chains with one, two, or three double bonds include oleic, linoleic, and linolenic fatty acids, respectively.

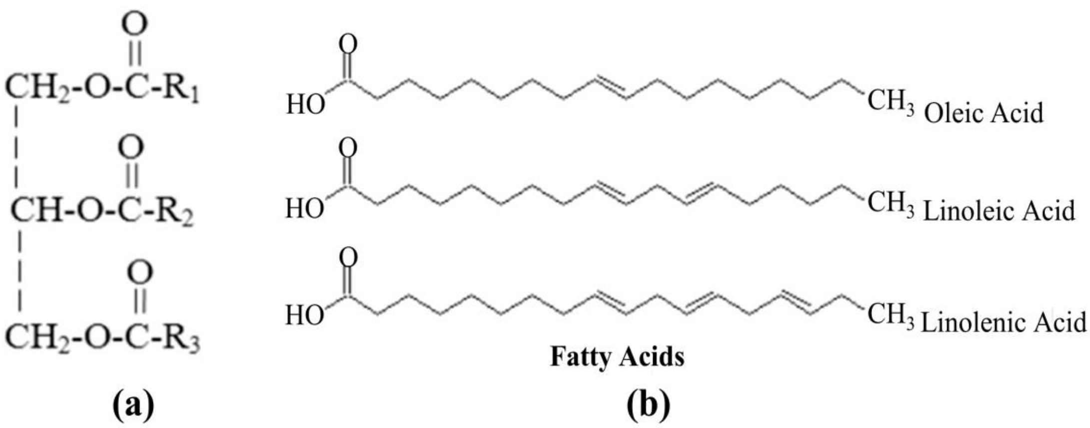


Fig. 2.12: (a) Chemical structure of vegetable oil: R_1, R_2 and R_3 are fatty acid chains; (b) Type of fatty acids. “With permission from Ref. [70]”.

Vegetable oils have fatty acids, which include 14 to 22 carbons. The presence of fatty acids in the triglyceride structure in vegetable oil provides the required lubrication by forming a high-strength lubrication film over metallic surfaces. Additionally, anti-wear and oiliness properties are also obtained by the polarity of fatty acids. Thus, the fatty acid in vegetable oil is regarded as a vital substance for lubricity [160]. In terms of scuffing load capacity, friction, and fatigue resistance, vegetable oil outperformed mineral-based cutting fluid even without the addition of additives [16].

2.3.1 Application of vegetable oils in grinding

Numerous research scholars have attempted to employ vegetable oils in MQL mode for grinding operations as a substitute for conventional cutting fluids. Here, few publications are being discussed:

Islam and Dhar investigated [161] the effects of MQL using vegetable oil, i.e., olive oil, on grinding AISI 1060 steel with a diamond grinding wheel. The results showed a reduction in surface roughness, lower grinding zone temperature and improved work-tool interaction under MQL grinding. The decrease in temperature was about 20-30%, depending on the process parameter. The temperature of the grinding process could not be effectively controlled by flood cooling with soluble oil. MQL modes also improved chip formation and surface characteristics, mainly through shearing. The surface roughness in MQL was better than in wet and dry conditions due to the reduced damage to grinding wheel grits at lower temperatures.

Emami et al. [162] performed the grinding experiment using plunge surface grinding mode on a horizontal surface grinding machine. They reduced the quantity of cutting fluid used in machining processes by evaluating four types of lubricants (mineral, hydrocracked, synthetic, and vegetable oils) for their performance in the MQL grinding of Al_2O_3 engineering ceramic material. The optimal lubricant and grinding parameters are identified for minimum cutting force, specific energy, and surface texture. Synthetic oil and hydrocracked-based oil are found to be environmentally friendly and provide satisfactory performance under MQL grinding. Hydrocracked base oil with sulfur and phosphorous additives is identified as a safe alternative to mineral oil containing zinc dialkyl dithio phosphate (ZDDP) for surface roughness in Al_2O_3 ceramic grinding. MQL lubrication not only improves machining performance but also reduces the environmental hazards associated with less amount of cutting fluids.

Changhe et al. [163] conducted an experiment on plain grinding for GH4169 nickel base alloy. The study compared the performance of MQL grinding using various vegetable oils (castor, soybean, rapeseed, corn, sunflower, peanut, and palm oil) as base oils. They found that castor oil had the lowest grinding force and that palm oil had the lowest grinding temperature and energy ratio coefficient. Viscosity significantly affected grinding force and temperature, with more viscous oils providing better lubrication but yielding higher temperatures. Saturated fatty acids were more efficient lubricants than unsaturated ones, and shorter carbon chains were better at transferring heat. Overall, palm oil was found to be the best base oil for MQL grinding, yielding specific values for tangential grinding force, normal grinding force, grinding temperature, and energy ratio coefficient.

Damasceno et al. [164] reported the outcomes of vegetable oil under MQL grinding in terms of grinding force and specific grinding energy. They found better results than conventional cutting fluid for grinding hardened AISI 4340 steel.

Jha and Paul [165] employed a cBN grinding wheel to perform grinding experiment on titanium alloy. They found that using emulsion of vegetable oil in water as the lubricant in minimum quantity lubrication (MQL) decreased grinding forces, surface and subsurface damage as compared to flood cooling during the grinding process. This enhancement resulted from the mist's ability to penetrate the grinding area effectively.

Awale et al. [166] carried out a grinding experiment on AISI H13 die steel using an alumina wheel as a cutting tool with grinding wheel specification of “AA-54-K-5-V-6”. They compared the lubricating properties of four vegetable oils: castor, groundnut, sunflower, and soybean oil, at a downfeed of 8, 16, 24, and 32 µm. The experiments showed castor oil provided the best lubrication, including a smooth surface, low force ratio, and high antifriction ground. In addition, the lower viscosity of the soybean oil enhanced the wettability of the lubricant in the grinding zone.

2.4 Nanofluid-based MQL in grinding

The term "nanofluid" refers to a particular kind of suspension made up of nanoparticles (NPs), typically less than 100 nm, dispersed in a base fluid like water, alcohol, oil, refrigerant, etc. [167]. A newer class of thermally enhanced fluids known as nanofluids (NFs) has emerged due to recent developments in nanotechnology. NFs have superior thermo-physical properties, i.e., higher thermal conductivity, dynamic viscosity, convective heat transfer coefficient, and lower wettability than the base fluid. These NFs properties result in superior cooling and lubricating, which makes them beneficial in a wide range of heat transfer applications, including but not limited to fuel cells, micro-channel applications, engine cooling in the automotive sector, magnetic sealing, chemical reactors, and various manufacturing processes [168], [169].

Depending on the kinds of NPs employed in the synthesis process, there are four main forms of NFs: (i) metal based NFs (NPs: Cu, Ag, Au etc.), (ii) metal oxide based NFs (NPs: TiO_2, Fe_3O_4, ZnO, Al_2O_3 etc.), (iii) carbon based NFs (NPs: Graphene, GO, CNT etc.), and (iv) hybrid/mixed metal based NFs (Al_2O_3–MWCNT, Ag-MWCNT, MWCNT-Fe_3O_4, etc.) [167]. The selection of NFs for any application should consider the improvement in their physical characteristics and stability. Due to the benefits of NFs, they are widely used and experimented with in machining difficult-to-cut materials. NFs are prepared by mixing the NPs in the base fluid using two distinct methods: (i) the two-step method and (ii) the one-step method. Most of the time, the two-step method is used to prepare the NFs. This method is cost-effective and easy to implement. The main problem with this method is that it is challenging to stop particles from agglomerating. The frequent application of ultrasonication and stirring is the most often employed to control agglomeration. Another way to stop particles from agglomeration is to add various surfactants/dispersants in base fluid during the preparation of NFs. Several investigators have also developed a two-step procedure without the use of surfactants or polymers to create stable nanofluids [170], [171]. The two-step NFs synthesis method has two different steps of preparation: (i) preparation and drying of NPs, and (ii) dispersion of NPs in the base fluid using chemical (electrostatic, steric, and electrosteric) and physical (ultrasonication, magnetic stirrer, and high-pressure homogenizer) methods. On the other hand, in the one-step method, NPs are prepared and dispersed in the base fluid simultaneously by liquid chemical method or physical vapor deposition technique. This approach results in NFs with less agglomeration. This approach avoids the numerous intermediate stages of drying, storage, and dispersion of NPs [172]. Usually, the one-step method is used in the preparation of metallic NFs. The major drawback of this method is the synthesis method, which is expensive.

Besides, the stability of the NPs remains a matter of concern. It means the capacity of a suspension of nanoparticles in a liquid medium (base fluid) to maintain uniform dispersion over an extended period of time. Most NFs become unstable over the passage of time, which consequently influences their thermo-physical characteristics, i.e., thermal conductivity [173]. In order to prevent the clustering and agglomeration of the NPs, the appropriate NFs suspension methods must be chosen. Some of these problems can be fixed by using proper probe sonication after adding surfactants/dispersants to NFs. Because the rate of NPs agglomeration mostly determines the stability of the NFs. To determine the stability of NFs, a pH meter instrument is used to measure the hydrogen-ion activity in water-based NFs. The Derjaguin–Landau–Verwey–Overbeek (DLVO) theory says that NPs tend to be unstable, form clusters, and precipitate when the pH is equal to or close to the isoelectric point (IEP) [174]. Choudhary et al. [175] examined the stability of various concentrated Al_2O_3/water NFs using the IEP-based pH method. They also studied the pH effects and sonication time for the stability of NFs in detail. The stability was also investigated by using sodium dodecyl sulphate, a surfactant, regarding the time elapsed after the preparation of NFs.

2.4.1 Application of nanofluids in grinding

The application of NFs in grinding has gained significant attention due to their potential to enhance heat transfer and lubrication properties during the machining process. The NFs are engineered fluids containing nanoparticles suspended in a base fluid, such as water or oil, offering unique thermal and tribological characteristics. This can effectively reduce grinding temperatures, which is critical for maintaining workpiece integrity and prolonging tool life when used as grinding fluids. Recently, many researchers have published more research articles on NFs per year due to their excellent properties, as shown in Fig. 2.13.

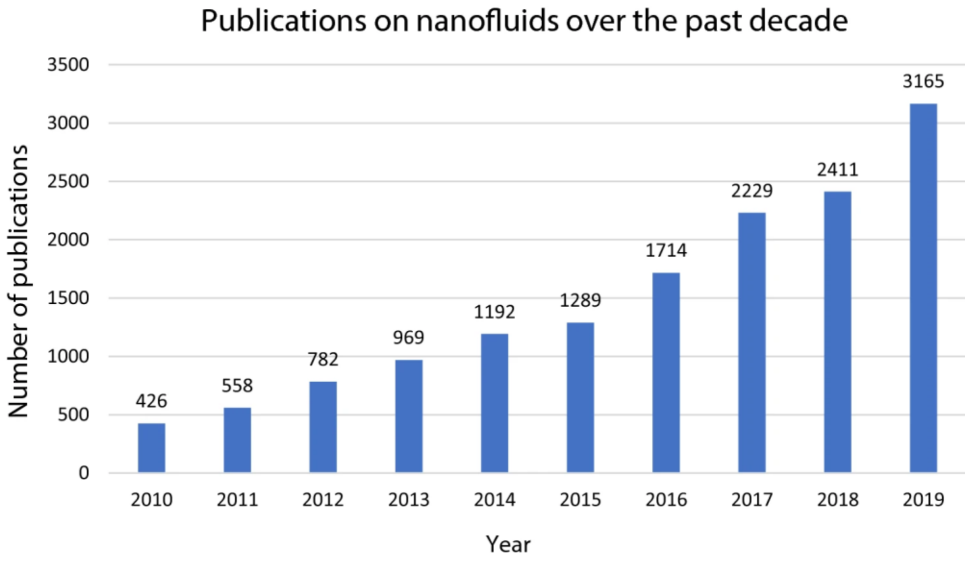


Fig. 2.13: NFs-related publications in the past decade. “With permission from Ref. [176]”.

Research in this area continues to explore the optimal types and concentrations of nanoparticles for specific grinding applications, aiming to maximize efficiency while minimizing environmental impact. Overall, the application of NFs presents a promising avenue for advancing grinding technology toward higher precision, productivity, and sustainability.

Shen et al. [177] investigated the wear and tribological properties of cast iron under dry, wet, and MQL grinding. They compared the outcomes of Al_2O_3 and diamond NFs in the MQL process with pure water. The experimental results depicted that high-concentration NFs improved the G-ratio, reduced grinding forces, improved surface roughness, and prevented thermal damage. MQL grinding also significantly lowered the grinding temperature compared to dry grinding.

Mao et al. [178] studied the effect of water-based Al_2O_3 nanofluid with the MQL approach while grinding hardened AISI 52100 steel. Results indicated that Al_2O_3 nanofluid significantly reduced the grinding forces, decreased the grinding temperature, reduced surface roughness, and improved the ground surface morphology compared to pure water-based MQL grinding. These improvements are attributed to the excellent convection heat transfer and thermal conductivity properties of the Al_2O_3 nanofluid.

Zhang et al. [179] conducted a grinding experiment for 45 steel materials under vegetable oil-based NFs MQL mode with MoS_2 NPs. They used liquid paraffin and distinct vegetable oils such as soybean, palm, and rapeseed oil as cutting fluids. The grinding performance was evaluated by measuring the grinding force and surface roughness under different concentrations (2%, 4%, 6%, and 8%) of MoS_2 in the base oil. They found the better surface finish and lowest grinding force in the case of MoS_2-added soybean NFs under MQL grinding. This happened as MoS_2 increased the viscosity and thermal conductivity of NFs, improving the grinding zone's lubricating and cooling effect. They also recommended that the 6 wt.% concentration of MoS_2 in soybean oil as it provides the best lubricant condition for 45 steel material during grinding.

Wang et al. [180] discussed the lubrication mechanism of Al_2O_3 NPs between the grinding wheel (WA80H12V) and workpiece (nickel-based alloy GH4169). They observed that better results were obtained regarding lubrication than palm oil, enhancing wheel life, anti-friction and anti-wear properties (refer to Fig. 2.14). They also found that the Al_2O_3 NFs provide superior tribological properties and are advantageous for industrial applications concerning economics and ecology.

Virdi et al. [181] used Al_2O_3 NPs with different vegetable oil, i.e., Palm and groundnut oil, as a cutting fluid under MQL grinding of Inconel 718. Al_2O_3 NPs with different concentrations of 0.5 and 1% wt. were mixed in both oils to make NFs. Results revealed that the nanofluids Minimum Quantity Lubrication (NFMQL) with 0.5 wt.% Al_2O_3 NPs had low grinding energy, the highest G-ratio, and a lesser coefficient of friction than pure MQL and flood grinding. NFMQL with 1 wt.% of Al_2O_3 had a less surface roughness value. Because of the rolling effect of NPs, there is less friction between the wheel and the workpiece. This, along with NFMQL's better cooling performance, makes it possible to remove more material faster. NFMQL made from vegetable oil improved tribological performance and could help the industry in terms of the economy and environment.

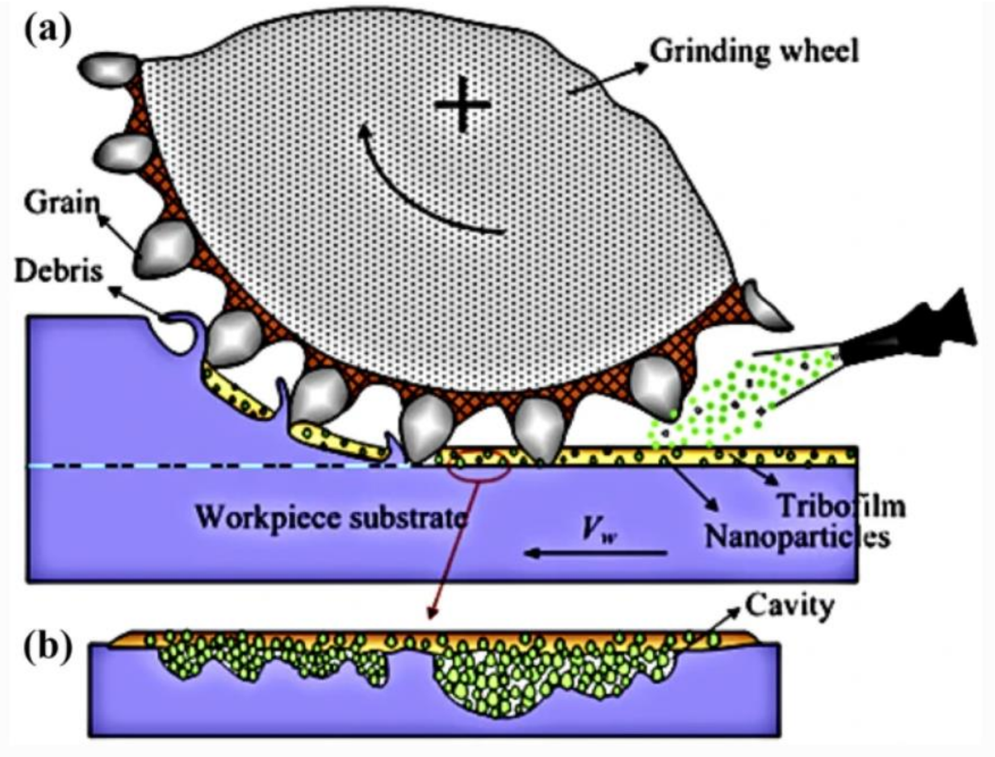


Fig. 2.14: Lubrication mechanisms formed in the cutting zone. “With permission from Ref. [180]”.

According to the research articles previously mentioned, there is an opportunity to improve the grindability of AISI D2 tool steel by using environmentally sustainable Al_2O_3 nanofluids in minimum quantity lubrication grinding.

2.5 Magnetic Barkhausen noise technique

The MBN is an online monitoring, non-destructive method for evaluating ferromagnetic materials' surface quality and integrity. This technique is more helpful for industrial applications, including quality control, material characterization, and failure analysis, since it may reveal details about the material's microstructure, mechanical characteristics, and stress state. Fig. 2.15 illustrates the industrial application of MBN analysis [182]. The MBN technique is a good substitute for conventional testing, i.e., metallographic tests, X-ray diffraction (XRD), etc. This technique produces precise outcomes in a few minutes without creating a hazardous environment, and the instrument is cost-effective, reliable, and conveniently transportable. Therefore, the MBN technique is widely adopted in the automotive and rail industries as well as quality inspection laboratories for qualitative assessment of surface stresses in pipelines [183], fatigue monitoring of rail tracks [184], detection of the thermal damage during grinding [185], and detection of residual stress of welded samples [186].

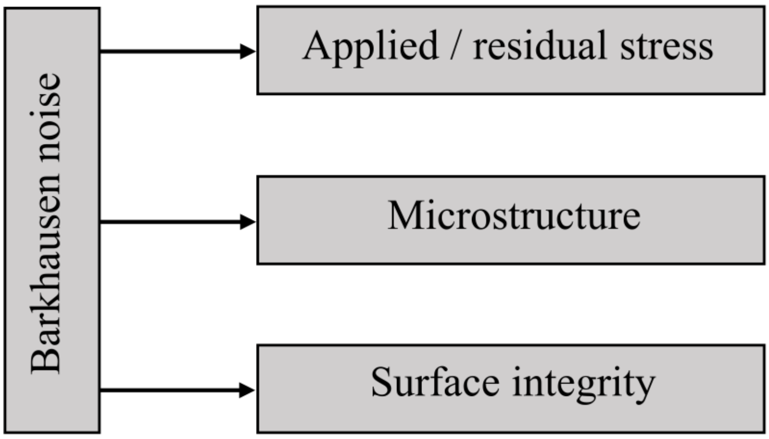


Fig. 2.15: Measured analysis in industrial application by MBN technique.

Heinrich Georg Barkhausen, a German scientist, found out about the Barkhausen noise effect. This effect was discovered, which supported the magnetic domain theory of ferromagnetism. The magnetization of ferromagnetic materials like iron changes in tiny discontinuous jumps by changing the magnetic field, which can be heard as sound in a loudspeaker connected to a coil of wire surrounding the iron material. It was later determined that the movement of the magnetic domains in the iron caused these jumps. Through the research work of French scientist Pierre Weiss, magnetic domain theory has provided a clear explanation of the magnetic nature of ferromagnetic materials. The microstructure of ferromagnetic material is characterized by regions known as domain. In ferromagnetic materials, there are usually two domain walls: 180° and 90°. These two types have different crystal structures. As a result of their increased mobility when compared to 90° domain walls, 180° domain walls are more suitable for producing MBN signal among them. A 180° domain wall results from parallel domain walls, whereas a 90° domain wall results from perpendicular domain walls [187]. When a ferromagnetic material is magnetized, domain walls aim to align in the direction of the applied magnetic field (refer to Fig. 2.16).

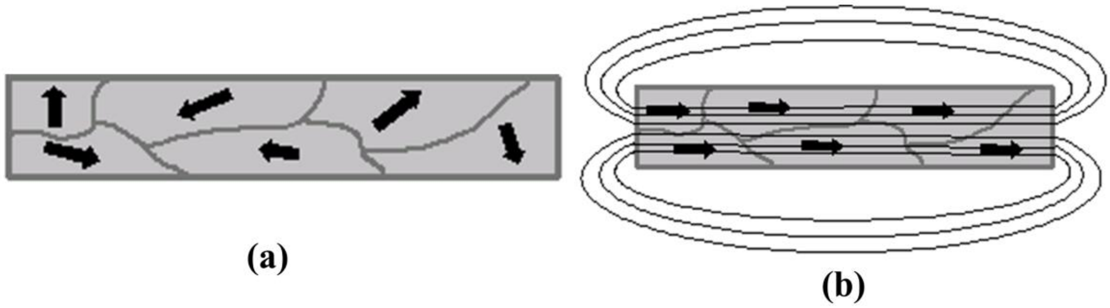
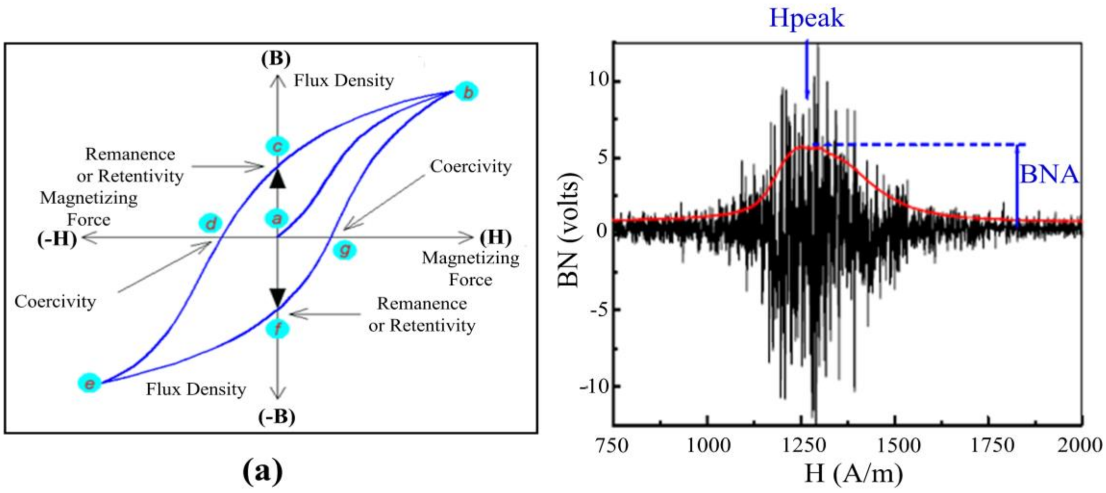


Fig. 2.16: (a) Random orientation; (b) Aligned domain.

The maximum applied magnetic field to the ferromagnetic material forces the domain wall to align itself in a parallel direction to the applied magnetic field, corresponding to saturation magnetization, beyond which any further increase in a magnetic field will result in a small improvement or negligible magnetization [188]. The ability of a ferromagnetic material to support magnetic field formation within the material is known as permeability. Greater permeability implies greater conductivity for magnetic force lines. Further, after reaching the saturation magnetization point, a drop in magnetic field intensity causes a decrease in the material's magnetization. Still, this decreasing magnetization path differs from the increased magnetization path. The difference in the magnetization and demagnetization path is known as the hysteresis loop. The material properties are also characterized by hysteresis loop parameters such as permeability, remanence, and coercivity, as presented in Fig. 2.17 (a). A smooth or stable hysteresis loop may be achieved by applying a steady magnetic field, but this may not be true for movements of the domain wall, which behaviour is jerky and discontinuous. It is mainly due to the presence of pinning sites in the material. The pinning sites hinder the magnetic domain wall movement due to the availability of impurities, phase formation, grain boundaries, and crystal defects in the ferromagnetic material [189]. An increased magnetic field is applied over a pinning site to eliminate the hindrance. The accelerated jumps of the domain wall over the pinning sites give immediate magnetic flux fluctuations, called Barkhausen noise signals [190]. This signal received from ferromagnetic materials is depicted in Fig. 2.17 (b).



(a)

(b)

Fig. 2.17: (a) Hysteresis loop of a ferromagnetic material; (b) Barkhausen noise signal. “With permission from Ref. [191]”.

2.5.1 Literature related to application of magnetic Barkhausen noise in grinding

Implementing an in-process monitoring system for surface layer conditions is deemed essential for achieving a significant increase in productivity and process stability during grinding operations. Because of this need, a measuring device has been developed to assess the Barkhausen noise signal in-process. Consequently, using MBN techniques, manufacturers can obtain instantaneous feedback on the ground surfaces quality as well as the heat treatment process. Since MBN is a surface technique, its ability to characterize materials constantly challenges the signal's penetration depth. More previous literature characterized the metallurgical and mechanical properties of ground samples by the MBN technique, and their findings are discussed below:

Gupta et al. [192] investigated the thermal damage on the ground surface of steel material by the Barkhausen technique. They observed that the outcomes of changes in microhardness and residual stresses were obtained faster than the conventional method.

Jiles [193] studied the influence of grain size on the Barkhausen noise signal. Smaller grains have more pinning sites, leading to larger Barkhausen jumps but smaller amplitudes as the grain size decreases under the same applied field conditions.

Moorthy et al. [194] analyzed the impact of changes in residual stress due to grinding on MBN signal in case-carburised En36 steel material. The low-frequency magnetic Barkhausen emission (MBE) profile was found to have two peaks, with the first peak remaining unchanged by grinding and the second peak rising and shifting to a lower field. This observed modifications to the microstructure as well as residual stresses. The high-frequency MBE profile showed a single peak, showing variations in surface residual stress but not at penetration depth than 10 µm. In general, Moorthy et al. [195] also provided useful data for selecting a Barkhausen effect signal for a specific application. However, the faster high and medium Barkhausen noise measurement techniques are more appealing in industrial practice.

Vashista et al. [196] compared two methods for examining the surface integrity of AISI 1060 steel ground with alumina wheels: XRD and MBN. They experienced that the MBN technique was a faster and more efficient way to examine surface integrity. The study found that the downfeed, work speed and abrasive grit size significantly influenced surface integrity measures such as microhardness, grain elongation, grain refinement, and residual stress. Their research has demonstrated a linear correlation between MBN parameters (RMS) and residual stress, with a correlation coefficient of about 0.92.

Santa-Aho et al. [197] studied the feasibility of causing controlled thermal damage on calibration samples for the MBN method of assessing gear grinding burns and assessing this damage with the same method. They observed a linear link, with an increase in RMS value leading to a rise in the change in residual stress value.

Čilliková et al. [198] evaluated surface damage of 100Cr6 bearing steel (in-ring shape) under different grinding environments. They observed a linear correlation in the characteristics of magnetic BN signals and grinding outcomes, such as microstructure and residual stresses.

Lasaosa et al. [199] studied the MBN signal to estimate the hardened layer thickness induced during grinding. The first peak location of the MBN profile measured the thickness of the hardened layer (range between 150 and 2500 μm with error ±200 μm). The second peak location of the MBN profile detected the grinding burns at the surface regarding the tangential magnetic field.

Srivastava et al. [200] studied the effect of the BN signals to detect grinding burns on hardened IS 2062 steel under dry and wet conditions. The poor magnetic response was observed due to higher carbon content in ground-hardened steel and a non-linear relationship between peak shift and RMS value of Barkhausen noise. On the other hand, the hysteresis loop's average permeability demonstrated a strong link with peak shift, with a correlation coefficient of almost 0.8149.

Shrivastava et al. [201] conducted grinding tests on AISI D2 tool steel with an alumina wheel under dry and flood conditions. They analyzed the ground sample by the MBN technique. They discussed the linear correlation between response and process MBN parameters (RMS and Peak). They found an increasing trend in the value of MBN parameters with a decrease in downfeed and an increase in magnetic field intensity. They also reported that the magnitude of the MBN parameter decreases with an increase in the hardness of the ground sample.

Heinzel et al. [202] also employed the multiparameter MBN approach for in-line inspection of the grinding burn of case-hardened steel. They reported that a significant in-process improvement was observed in terms of an almost 37% reduction in the inspection time of ground samples.

Therefore, the above literature on the MBN technique has proved that the MBN technique is a unique surface characterization for in-process monitoring.

2.6 Research gap

Based on the literature reviewed, it has been confirmed that cryogenic cooling provides several benefits in grinding difficult-to-cut material. Some literature reported that AISI D2 tool steel is a more demanding engineering material due to its good physical and mechanical properties. Because of low thermal conductivity and high strength, this material is challenging to grind. In order to increase the applications for AISI D2 tool steel, the grindability of this tool steel must be significantly increased through the appropriate selection of grinding wheel, optimal grinding parameter selection, and cooling conditions. According to the preceding discussions and cited literature, the following research gaps related to grinding of AISI D2 tool steel:

1. Few experimental investigations have been conducted on grinding AISI D2 tool steel using an alumina wheel.
2. Very few research works have been introduced on grinding performance improvement of AISI D2 tool steel using cryogenic grinding with LN_2 coolant.
3. Almost no work in cryogenic using Al_2O_3 nanofluids grinding of AISI D2 tool steel has been found in the available literature.
4. No literature on the MBN technique for cryogenic and Cryo-MQL grinding of AISI D2 tool steel has been found.

2.7 Objectives of the present work

The objective of this work is to investigate the effects of cryogenic cooling by LN_2 in grinding AISI D2 tool steel with alumina wheel under dry, wet, cryogenic, MQL and Cryo-MQL environments on the resulting grinding force, surface roughness, bearing area curve analysis, ground surface topography, microchip morphology, grinding temperature, microstructure, and microhardness. The study has the following objectives:

1. To develop a cryogenic cooling and Cryo-MQL setup for the surface grinding process.
2. To assess the effectiveness of alumina grinding wheels for the grinding AISI D2 tool steel under cryogenic cooling and Cryo-MQL, as well as their impacts on cutting temperature, grinding force, specific grinding energy, force ratio, surface roughness, surface topography, chip morphology, microstructure, and microhardness.
3. Based on the preliminary experiments, optimization of grinding parameters such as downfeed, table feed rate, LN_2 delivery pressure, mist flow rate, air pressure, nozzle angle, and stand-off distance under cryogenic and Cryo-MQL grinding was conducted to enhance grinding performance.
4. To investigate the impact of table feed rate and LN_2 delivery pressure on the forces, specific grinding energy, surface roughness, grinding temperature, and microhardness during the grinding process.
5. Experimental investigations for Cryo-MQL grinding performance of AISI D2 tool steel using different eco-friendly lubricants, i.e., vegetable oil, vegetable oil-based deionized water emulsion, and nanofluids with 0.5 and 1 wt. % concentration of nanoparticles.
6. To assess the thermal damage of the ground surface under various downfeed using the MBN technique for grinding AISI D2 tool steel in dry, wet, cryogenic, MQL, and Cryo-MQL conditions.