

Chapter 2

Literature Review and Objectives

2 The function of cutting fluids in grinding

Grinding is an inefficient finishing operation that consumes significantly more energy than typical machining techniques such as turning, drilling, and milling. The bulk of the energy consumed during the grinding process is turned into heat, which is distributed among the ground surface, abrasive wheel, and microchip. When hardened metal alloys are ground on traditional wheels such as Al_2O_3 and SiC , the work material absorbs around 70 to 80% of the entire heat, with the remaining portion going to the microchip and abrasive wheel [100]. This excessive heat build-up in the ground surface can result in thermal damage such as grinding burn, surface oxidation, microcrack generation, surface tempering, induction of tensile residual stress, and undesired microstructural and microhardness changes in the work surface [101]. Moreover, this high heat accumulation in the grinding zone can cause attritious wear of the abrasive grains, resulting in increased wheel wear. Mechanical friction, plastic movement of a microchip over abrasive grits, thermal or mechanical shocks, and chemical reactivity between abrasive grits and work material at extreme temperatures are significant causes of attritious wear of abrasive grits [102]. Hence, a sufficient quantity of cutting fluid should be applied to the grinding zone in order to expedite heat removal. Taylor discovered the use of water as a coolant in 1907, whereby the cutting speed could be raised by 40% when machining steel with a high-speed steel tool by using a significant quantity of water [103]. Subsequently, there was a significant progression in the effective application of cutting fluid in the machining of various engineering materials. The cutting fluid serves two key purposes in the grinding domain: lubrication and cooling. The lubrication provided by the cutting fluid assists in the

reduction of the grinding zone's frictional force. This results in a minimal size effect, which reduces the grinding process's power usage. In most cases, the size impact is a crucial phenomenon in relation to undeformed chip thickness in grinding. The power consumption per unit volume of material removed is observed to decrease with increasing chip thickness. Alternatively, increasing the downfeed produces a greater number of abrasive grits cutting edges in contact with the ground surface, which increases the grinding temperature and grinding forces in the grinding zone. Consequently, cutting fluid with a high velocity may reach the grinding zone, which minimises the force of friction between the abrasive grit and the ground surface, resulting in reduced grinding force and machining temperature. In addition, lubrication is an essential property of cutting fluid since it reduces friction along the microchip flow line, i.e., between the microchip, the grain cutting edge, and the grinding wheel bond. It decreases bond abrasion and wheel wear [104]. The heat produced at the grinding zones was dissipated and conducted to accomplish cooling during the grinding through cutting fluids. Thermal parameters such as thermal conductivity and specific heat have a significant impact on the cooling capacity of a cutting fluid. Cooling and lubrication promote grindability by decreasing wheel wear, grinding forces, surface roughness, and surface integrity. In addition to lubrication, cutting fluids help remove microchips from the grinding zone to prevent wheel loading [105].

2.1 Ecological issues of petroleum-based cutting fluids

Across the world, millions of gallons of cutting fluid were used for adequate lubrication and cooling in a variety of machining operations. The majority of these cutting fluids were derived from non-renewable crude oil or mineral oil extracts, which pose substantial environmental pollution challenges, including air, water, and soil contamination, operator health, and increased recycling, storage, and disposal costs [106]. According to reports, about 80% of occupational diseases were caused by skin contact with cutting fluids [107].

According to the International Agency for Research on Cancer (IARC), CFs derived from petroleum that include heterocyclic and polyaromatic rings are carcinogenic, and exposure to them may cause occupational skin cancer [108]. In addition, cutting fluids create a variety of major health concerns, including lung cancer, respiratory disorders, dermatological and genetic diseases, due to the presence of noxious compounds such as sulphur, chlorine, and phosphorus [109].

Owing to polymerization and oxidation, these cutting fluids were very vulnerable to chemical change. The polymerization of cutting fluids is initiated by temperature-induced processes. Cutting fluid oxidation is highly dependent on the presence of ambient oxygen. This chemical reaction modifies the viscosity, which hinders the cutting fluid's flow during machining [110]. In addition, the pH fluctuation is a key problem for water-based cutting fluids. Typically, the pH of cutting fluids should fall between 8.0 and 9.5 to prevent corrosion of machine tool components [111]. The production of carcinogenic compounds within the cutting fluid and the danger of corrosion and emulsion instability all rises when the pH level is below 8.0. The risk of skin irritation increases when the pH level exceeds 9.5. In addition, bacterial proliferation in cutting fluids greatly contributes to the presence of microbial masses and endotoxins on the shop floor. Consequently, biocides are added to the cutting fluids to inhibit bacterial development. Nevertheless, used cutting fluids containing biocides may interfere with the natural degradation process, and some municipalities have prohibited the discharge of biocides into sewage systems [112]. Several biocides were also discovered to emit formaldehyde, a potential carcinogen. These bacteria produce a biofilm over the cutting fluid, which can block filters, suction lines, and supply pipelines [110]. In order to address the environmental concerns associated with petroleum-based cutting fluids, the selection of green manufacturing techniques has become a primary focus in the manufacturing sector.

2.2 Sustainable grinding techniques

Researchers are being compelled to reduce the volume of cutting fluids due to strict international pollution standards, increased awareness of human health, and a growing focus on sustainable and environmentally friendly manufacturing, as stipulated by the ISO 14000 standard [113]. These circumstances have necessitated the adoption of sustainable concepts, including the reduction of cutting fluid usage, the effective use of biodegradable cutting fluids or vegetable oil, or even the complete elimination of cutting fluids.

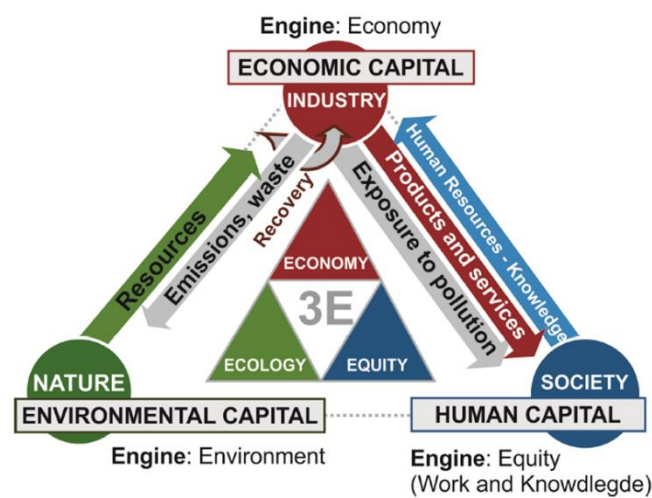


Figure 2.1 Current sustainability framework: Triple Bottom Line [114]

In manufacturing, sustainability refers to the production of goods utilising processes that minimise negative environmental impacts, conserve energy and natural resources, prioritise employee and consumer safety, and maintain economic feasibility [22]. The sustainable manufacturing paradigm has employed the 3E approach (economy, ecology, and equality) to offer solutions in this area, as depicted in Figure 2.1 [114]. The key goal of integrating sustainability into the manufacturing process is to improve the performance of economic, environmental, and social dimensions, including operator health and safety. Sustainable machining techniques refer to methods employed to enhance the machining process as a whole. This category includes dry machining, cryogenic machining, minimum quantity

lubrication machining, ultrasonic vibration assisted machining, and ultrasonic vibration assisted minimum quantity lubrication machining. Several sustainable techniques have been proposed by previous researchers to improve machinability while reducing the environmental impact. These techniques include dry machining, which eliminates the need for cutting fluids and prevents issues such as contamination, storage, disposal, and hazardous components [115]. Another technique is ultrasonic vibration assisted machining, which eliminates the use of cutting fluids, reduces thermal damage, prevents wheel loading, and improves surface integrity [25]. Minimum quantity lubrication is another technique that involves reducing the amount of cutting fluid used during machining [116]. Cryogenic machining is a technique that uses liquid nitrogen to provide high cooling capacity, which significantly improves tool life [117]. Finally, ultrasonic vibration assisted minimum quantity lubrication improves both cooling and lubrication and enhances the surface integrity of machined components [118]. The application of sustainable machining techniques can lead to a reduction in grinding forces, surface roughness, wheel loading, and improved surface integrity of machined components.

Dry machining is an effective approach to reduce the usage of cutting fluids in various machining processes, which in turn helps to lower machining costs and address environmental concerns [119]. It is a clean method that does not cause pollution to air or water resources, resulting in a reduction of disposal costs for cutting fluids. With the development of advanced cutting tool materials such as multi-layer coated carbides, ceramics, cermet, cBN, PCBN, and PCD, dry machining can be applied to turning, milling, drilling, and gear cutting on steels, steel alloys, and cast iron [106]. However, it is generally recommended to operate at lower cutting speeds and produce a lower production rate in order to extend tool life. On the other hand, higher cutting speeds are required for grinding operations to remove unwanted materials due to the continuous shearing, ploughing, and

rubbing action caused by various abrasive grits. Dry grinding poses a number of serious issues, such as the risk of overheating the grinding wheel and work material. Maximum rubbing action happens over the ground surface in dry grinding, which significantly increases the temperature, resulting in a higher level of abrasion, diffusion, and oxidation. As a result, the workpiece can experience a substantial amount of heat, which can hinder achieving close tolerances and cause damage to the superficial layer [120]. To mitigate these concerns, Sinha et al. [121] conducted a study on grinding Inconel 718 using silicon carbide (SiC) and alumina (Al_2O_3) wheels under dry conditions.

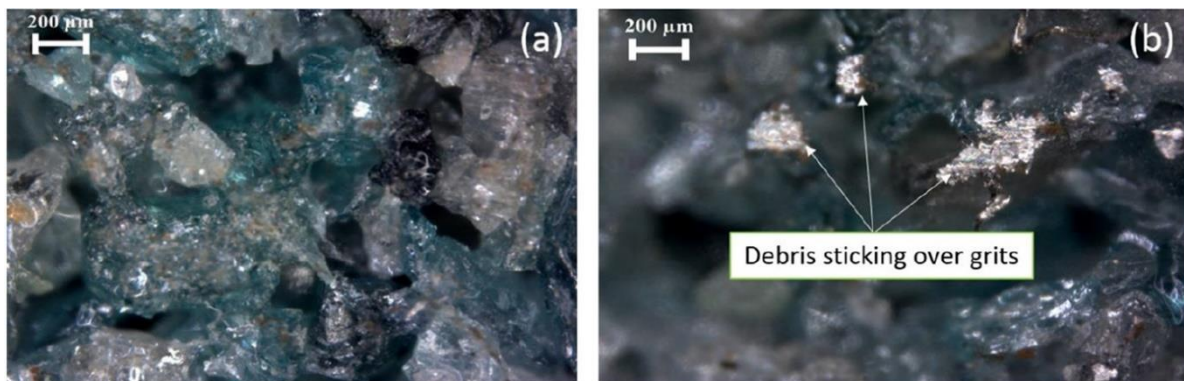


Figure 2.2 SiC wheel morphology: (a) Fresh wheel and (b) Sticking of debris over grits

[121]

The experiments employed a wheel speed of 10–20 m/s, a work feed of 3–15 m/min, and a downfeed of 5–15 μm. At a lower wheel speed of 10 m/s and a higher downfeed of 15 μm, the SiC wheel experienced significant wheel loading, as illustrated in Figure 2.2. The microchip adhesion occurred primarily as a result of the elevated temperatures generated by the cutting arcs. These high temperatures facilitated a chemical reaction between the abrasive particles and the work material, resulting in the latter adhering to the particles. Moreover, these microchips are subsequently deposited over the machined surface. Another significant sustainable machining approach is the use of cryogen in machining. Cryogenic machining refers to the machining of materials at temperatures below $-153\text{ }^{\circ}\text{C}$,

in accordance with the Cryogenic Society of America's criteria. Uehara and Kumagai initially coined the phrase cryogenic machining in 1968 [122]. As a coolant in cryogenic machining, a liquefied gas such as liquid nitrogen (LN_2), liquid carbon dioxide (CO_2), oxygen, or helium was used. According to published material, Reitz initially employed liquid CO_2 as a coolant in machining [123]. Nowadays, liquid nitrogen (LN_2) is the most popular cryogen used for chilling applications at $-196\text{ }^\circ\text{C}$. Nitrogen is the most prevalent gas in the atmosphere (78%), is odourless, colourless, non-corrosive, non-combustible, non-toxic, and has a great capacity for heat dissipation [27]. In addition, the direct release of LN_2 into the atmosphere during machining poses no hazard to the environment.

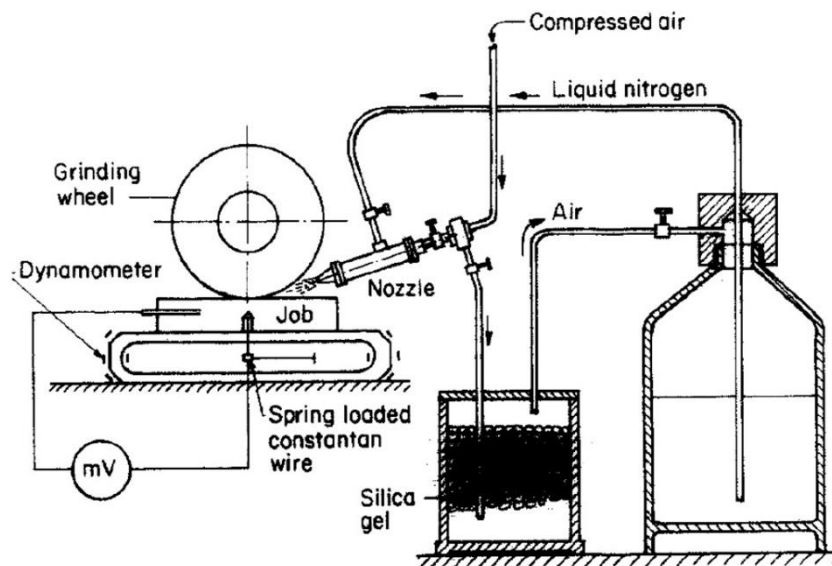


Figure 2.3 Schematic of cryogenic grinding system [124]

Via a nozzle, a controlled flow rate of a cryogen was used to enter the cutting zone in this procedure. Cryogenics were often kept in a self-pressurized tank known as a cryogenic dewar. The cryogenic grinding process is depicted in Figure 2.3. Several research groups have documented the technological benefits of cryogenic grinding. Chattopadhyay et al. [124] attempted for the first time to grind different grades of steel, including mild steel, AISI 4340 steel, and high-speed steel, in a cryogenic environment. They achieved a substantial decrease in grinding force and temperature. Paul et al. [125] investigated

cryogenic grinding of steels extensively and reported that cryo-cooling allows the wheel to retain its sharpness for a longer length of time and results in reduced wheel loading. Manimaran et al. [126] evaluated the impact of LN₂ as a cryogenic grinding coolant on AISI 316 stainless steel. They revealed that cryogenic cooling reduces grinding forces by 37% and 13% compared to dry and wet cooling, respectively. Nevertheless, this procedure has a negative impact on grindability indices and requires a substantial initial expenditure. Recently, Reddy and Ghosh [27] explored the significant concerns of LN₂ utilisation in surface grinding when an alumina wheel was used against AISI 52100 steel that had been toughened. They stated that more power consumption and surface roughness was obtained in the case of cryogenic as compared to dry, soluble oil.

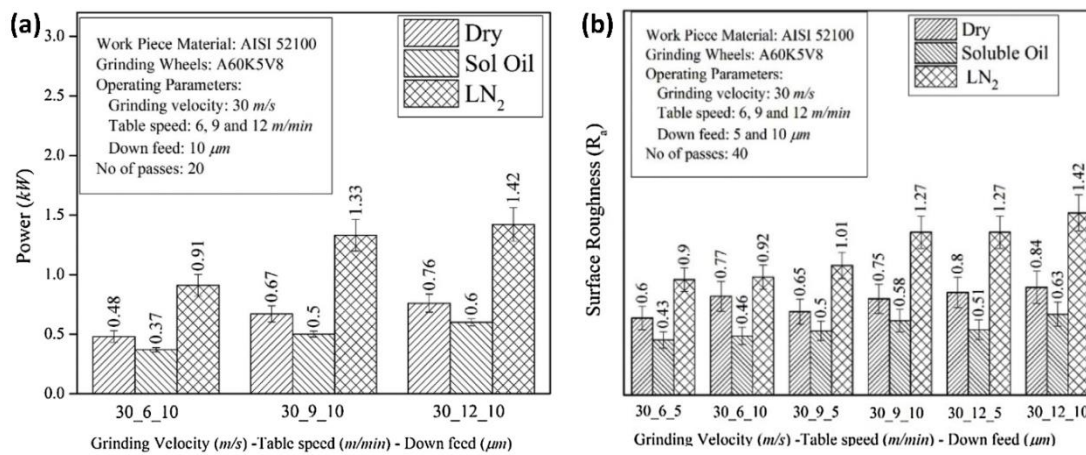


Figure 2.4 LN₂ grinding: (a) Power consumption (b) Surface roughness [27]

Figure 2.4 depicts the impact of LN₂ grinding on spindle power consumption and surface roughness. This occurs because LN₂ increases the wheel's bonding strength. Owing to a tight connection, the worn abrasive grits appeared to be preserved on the grinding wheel. During cryogenic grinding, the removal of material by these worn grits entails considerable ploughing and rubbing action on the work material, resulting in increased power consumption and surface roughness.

Minimum quantity lubrication (MQL) is a sustainable approach that uses a very small amount of cutting fluid for lubrication and cooling at the cutting zone during machining. The term "minimum quantity lubrication" appears to have been coined by Weck and Koch in reference to ball bearing lubrication [127]. In addition, the first research on MQL machining for grinding AISI 52100 bearing steel [128]. MQL is also known as near dry lubrication (NDL) [129], cooling air and minimal quantity lubrication (CAMQL) [130], minimal quantity cooling (MQC) [131], and small quantity cooling lubrication (SQCL) [132] in manufacturing procedures. The flow rate of cutting fluid in the MQL system is predicted to be 10,000 times lower than that of traditional flood cooling systems [133]. As shown in Figure 2.5, the overall performance of MQL is influenced by several factors [25]. Intriguingly, despite the fact that MQL reduces the quantity of fluid needed to 250 ml/h [134], respiration-related health issues remain unchanged or are often worse [135]. Although there is a considerable amount of research available on the MQL technique, its cooling performance has been found to be inconsistent and sometimes inadequate [30]. Extreme pressure additives based on phosphorus/sulphur/calcium sulphonate and anti-wear additives based on zinc are utilised to improve MQL fluid penetration in machining regions [136]. When mineral oils or synthetic oils are utilised as cutting fluid in MQL, the resulting aerosol includes extremely small particles that can pose serious health consequences. The atomization action of aerosols causes substantial hazards of colon, pancreatic, rectum, oesophageal, and prostate cancers [112].

MQL performance is primarily determined by the degree of atomization of the cutting fluid into fine and tiny droplets. Hence, UVAG occupies a unique position in the machining domain and has demonstrated promising results in higher heat generation processes such as grinding.

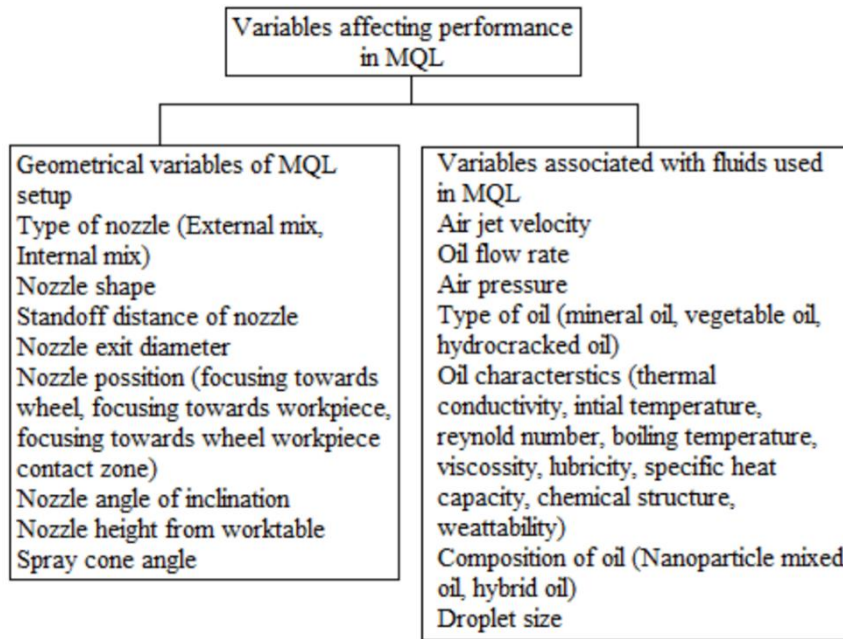


Figure 2.5 Factors influencing MQL performance [25]

2.3 Effect of UVAG parameters on surface integrity

Various characteristics of surface integrity have a significant impact on the performance of a machined component throughout its service life. These characteristics are influenced by several parameters, such as ultrasonic vibration amplitude (A_{ug}), vibration frequency (f_{ug}), grinding wheel speed (V_c), worktable feed rate (V_w), downfeed (a_p), materials, shape, geometry, wheel wear, and environment. These parameters have a considerable influence on different aspects of surface integrity. Figure 2.6 illustrates that there are multiple variables that can be modified to improve the surface integrity performance of UVAG mode. The UVAG technique, such as the conventional grinding method, uses ductile mode, brittle mode, and/or plastic flow as its material removal mechanism [137]. The rotating motion of the abrasive wheel in UVAG increases the material removal rate [138], improves surface integrity of the workpiece, decreases grinding force, and extends the life of the abrasive wheel [139] [140]. The previous research group reported that the UVAG has a material removal rate 6–10 times that of conventional grinding and around 4 times that of

ultrasonic machining [141] [142]. The UVAG can prevent thermal damage and minimize physical and chemical alterations of the workpiece surface. In addition, it can lead to a better surface quality, which can be impacted by factors such as grain size, vibration amplitude, vibration frequency, and material hardness [143] [144] [145]. According to Tawakoli and Azarhoushang [26], the workpiece's surface finish can be improved, and the grinding force can be decreased by 60–70% (in normal) and 30–50% (in tangential), respectively. Li et al. [146] conducted ultrasonic vibration assisted grinding experiment on zirconia ceramics the results obtained indicates improvement in the workpiece surface quality, and better tribological properties compared with precision grinding. Further, Wang et al. [147] observed that more downfeed and feed rate can be considered in the ultrasonic assisted grinding in comparison to traditional grinding of Titanium alloys and more uniform surfaces can still be obtained by using vibration on the workpiece in the tangential direction.

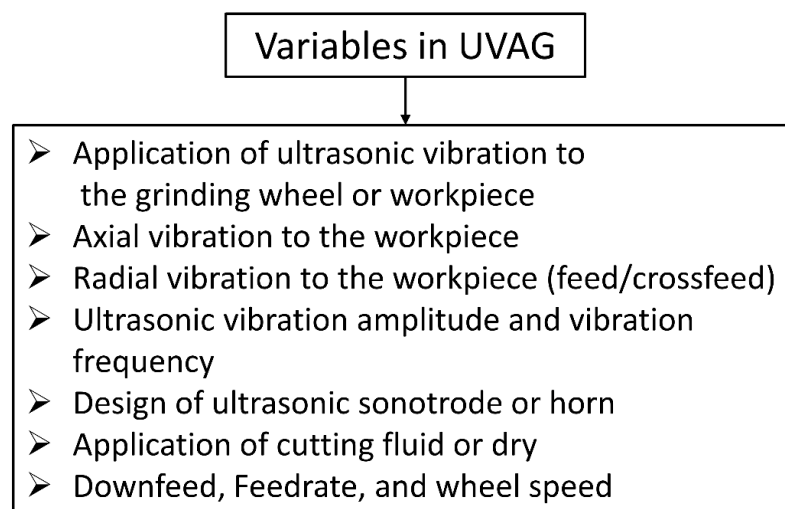


Figure 2.6 UVAG performance variables [25]

In addition, Yu et al. [148] noted that ultrasonic vibration assisted polishing of a nickel base alloys like Inconel 718 can significantly increase material removal rate, and R_a value of the workpiece surface roughness is reduced in comparison to the conventional polishing. In another experiment, Li et al. [149] experimentally demonstrated that surface roughness of

SKD61 steel was influenced by the feed rate as well as the vibration frequencies under varying grinding conditions. When vibration frequency varied from 0 to 11.4 kHz, lower surface roughness was obtained. It was reported that the UVADG of carbon steel displayed the highest decrease of 20% in surface roughness compared to the CDG and the readings of the Abbott-Firestone curve's indices i.e. heights of the peaks (R_{pk}), valleys (R_{vk}), and core roughness (R_k) under UVADG were lower as compared to CDG. [150]. Another study found that the UVADG could considerably increase the surface bearing and the fluid retention characteristics of the ground component [151]. Reduced coefficient of friction on the tool-workpiece interface and shearing layers inside the finished material and material softening because of confined localised heat induced by ultrasonic vibration at the interface region of the tool-workpiece resulting in the more effortless relative motion of them [152]. In a previous study, the frequency and amplitude of ultrasonic vibrations were shown to substantially impact the grinding force, surface morphology and surface roughness, and low amplitude and high frequency were shown to promote superior surface integrity [153]. Specifically, Mult et al. [154] reported that using vertical ultrasonic grinding caused a modest increase in wheel wear because the grinding wheel struck the ground workpiece. Furthermore, among the essential fundamental characteristics to explain the grinding mechanism is the grinding force, which represents the contact among the abrasive grits and the work material in the machining region and is closely associated with the material removal mechanism in the grinding operation and the quality of the ground surface [155]. As a result, analysis of grinding force continues to be a significant way of understanding the mechanism of ultrasonic vibration assisted grinding. According to Zhang et al. [156], the average cutting velocity in ultrasonic grinding was greater than that in conventional grinding, which is the crucial reason leading to the decrease in grinding forces. Since ultrasonic vibration assisted grinding could decrease grinding force and achieve better

integrity when the vibration direction is tangential to the workpiece, previous research revealed that the primary function was to reduce grinding chip volume owing to the interaction of abrasive grits path [34]. As theoretically, the interaction mechanism, referred to as the ultrasonic vibration impact, is primarily governed by the grinding and vibration parameters of a particular grinding wheel. Moreover, the research [90] [152] [157] revealed that ultrasonic assisted grinding could achieve almost the same decrease in grinding force and ground surface roughness, even when the grinding parameters had been substantially different, whereas vibration parameters remained constant. Cao et al. [158] found that ultrasonic vibration can be used to prevent subsurface damage to the workpiece when grinding SiC ceramics and that normal and tangential grinding forces can be reduced by up to 31% and 57%, respectively. Li et al. [159] reported that ultrasonic assisted grinding of composites produced a better consistent surface microstructure, small chips, a well-distributed depth of the machining furrow, and lower surface roughness as compared to common grinding. The ultrasonic oscillation generates various material removal mechanisms for machining various engineering material components, and those mechanisms could produce ductile zone cutting of brittle materials or modify the characteristics and behaviour of plastic materials via acoustics softening [160]. Huang et al. [161] evaluated the grinding temperature of the hardened GCr15 steel workpiece under ultrasonic assisted grinding and reported that the ultrasonic vibration produced in a 19.01% reduction in maximum grinding temperature when compared to conventional grinding. Another research group compared the ground surface roughness of TiAl intermetallic under common grinding and ultrasonic assisted grinding modes; and showed that by using ultrasonic vibration, the grinding performance could be significantly enhanced due to the route interaction between grinding wheel grits [162]. According to Zhu et al. [163], ultrasonic grinding offers the benefits of high-frequency responsiveness and reduced

cutting force; however, it also significantly contributes to increasing processing effectiveness and prolonging wheel life. Also, finishing of ceramics is a much more difficult task using conventional grinding owing to its low fracture toughness. The UVAG can create micro-fracture near the nascent surface of ceramics using small amplitude and results in negligible crack formation in the subsurface [98]. On the other hand, faster wheel loading and grinding burn issues were faced with conventional grinding of hard, superalloys and ductile material due to its low thermal conductivity and work hardening [109]. The UVAG process can minimize the interaction of wheel and work, resulting in reduced grinding force and temperature. Hence, this process can be used equally for hard, brittle, and ductile materials [164]. Furthermore, notable enhancements in ground surface quality [165], wheel life [166], material removal rate, reduction in grinding force [61], heat generation [167], and rising in the number of active grits in the cutting region by the application of ultrasonic vibration has been described [155]. In addition to that, even in dry creep feed grinding, it appears that ultrasonic vibration can replace coolant application [152].

2.4 Modelling and simulation study in grinding

In the previous decade, the significance of modelling and simulating grinding processes has witnessed a significant surge owing to the growing industrial requirements. This is substantiated by the substantial upsurge in the number of research activities and publications undertaken in this domain. In the field of international research, simulation of processes has emerged as a widely acknowledged methodology for the assessment and optimization of cutting and grinding processes. Researchers are able to selectively alter the process strategy in pursuit of improving workpiece quality or lowering machining time while ensuring high economic efficiency by comprehending the complexities of the tool-workpiece interaction during grinding. The primary analytical method focuses on creating

predictive models that are derived from fundamental physical relationships. By understanding the process and selecting relevant physical variables, mathematical equations can be used to create physical models. An understanding of the interaction between the abrasive grain and workpiece is crucial for this. The relationship between the abrasive grit and the surface of the workpiece effects the material removal mechanism and is determined by the system's tribological properties. The grinding process comprises all of these interactions, and the models must accurately depict the intricate relationships between the abrasive wheel topography, process kinematics, and workpiece properties [168]. Yoshikawa et al., [169] [170], Kassen [171], and Law et al., [172] were among the first research group to pioneer kinematic grinding process modelling. Primarily, the methods entail utilising 2-D model grits to analyse surface grinding and cylindrical grinding operations. This is done by computing the roughness or topological cross-section of the workpiece as well as chip thickness. Because of the advent of powerful computer systems in the 1980s, numerical simulations based on 3D kinematic-geometric models have been possible. These models have gotten more precise over time, helping in the optimization of various grinding methods and fostering a more thorough understanding of the process [173] [174]. To achieve effective grinding processes, it is crucial to understand and manage physical process data such as temperature, forces, and grinding energy. While kinematic models can aid in estimating forces and energy, finite element analysis (FEA) is required to model physical process data accurately [175] [176]. The FEA incorporates the use of "shape functions" or "interpolation functions" to solve differential equations [177]. This produces a system of linear equations in which the stiffness of the workpiece is dependent on both its material characteristics and geometry, and it necessitates knowledge of the thermal or mechanical load applied to the workpiece. One benefit of FEA is the ability to manage irregular meshes for complex structures, as well as the ability to locally adapt the

mesh, which is particularly useful for larger models [178]. Typically, FEA models used in grinding simulations can be categorized as macroscopic and microscopic concepts. Typically, FEA models used in grinding simulations can be classified into macroscopic and microscopic concepts [179]. The macroscopic simulation is often used to estimate the impacts of heat and mechanical surface pressure on the entire workpiece, specifically thermal distribution and shape distortion. These calculations rely mainly on thermomechanical and elasto-mechanical material properties and neglect plastic material behaviour or chip formation. On the other hand, microscopic simulation focuses on analysing the working zone and typically models only a small portion of the workpiece and a single grit that is in contact. The idea behind microscopic simulation derives from the single grit scratch test, which involves developing models equivalent to FEA models to evaluate stress and temperature during chip generation. This method considers the single grit and the workpiece to be a multi-body entity [180].

Several researchers have conducted the single grit conventional grinding experiment, to study the complex cutting action during grinding of different engineering materials. As an example, Opöz and Chen [181] demonstrated the material removal mechanics on En24T steel with a single cBN grit. Single grit grinding tests were performed by Zhao et al. [182] and Feng et al. [183] to study the grinding force and chip formation phenomena. Fu et al. [184] developed a FEA model for single grit grinding of titanium alloy and studied the impacts of downfeed on the grinding force, stress distribution, and chip formation. Sinha et al. [185] have carried out single grit grinding on Inconel 718 superalloy with alumina grit of different mesh sizes and evaluated specific grinding energy employing actual contact length. Liu et al. [186] established a FEA model of a single grit grinding to examine the mechanism of burr formation and the impact of grinding parameters such as grinding speed, downfeed, and wheel granularity on the burr formation of stainless steel employing an

alumina wheel. Sagar et al. [187] reported that the Johnson-Cook constants impact not only the highest value of equivalent plastic strain but also the distribution pattern around the shear plane, altering chip shape, and Johnson-Cook constants are interdependent in FEA simulations. Moreover, direct observation of the wheel-workpiece interaction region and material removal characteristics in single grit grinding is generally difficult. The reason is the abrasive grit and workpiece contact frequency significantly greater than the responsiveness frequency of the signal given by an instrument, the dynamic grinding forces of a single grit cannot be measured accurately [188]. However, the FEA approach may be used to model the CDG and UVADG processes and analysed the dynamic behaviour in the grit workpiece interface region. Besides, Brinksmeier et al. [178] and Tönshoff et al. [176] studied the grinding process using analytical and numerical methods. To single grit grinding model, Opöz et al. [189] and Cao et al. [190] utilized numerical simulation methods; they employed FEA model and smoothed particle hydrodynamics, respectively, to demonstrate the grinding process. Further, Farhadi et al. [191] analysed the grit workpiece interaction mechanism in UVAG using a combination of numerical simulation and analytically. They found a reduction of ground forces by 40% compared to conventional grinding.

2.5 Application of ultrasonic vibration assisted minimum quantity lubrication in grinding

From the aforementioned literature survey, it was reported that ultrasonic vibration assisted grinding and minimum quantity lubrication have independently enhanced the surface integrity indices of ceramics, glass, metals, metal alloys, and super alloy components with regards to decreased grinding forces and surface roughness. However, the combined use of both techniques, known as ultrasonic vibration assisted minimum quantity lubrication (UVAMQL). In recent years, hybrid technologies, i.e., the simultaneous use of more than

one method, have been suggested by some previous research groups as an approach to improving the effectiveness of the grinding process. Molaie et al., [118] conducted an experimental study to explore the effects of hybrid UVAG with MQL using oil-based nanofluids containing MoS₂ nanoparticles, and they analysed the outcomes in terms of normal and tangential forces, force ratios, and surface roughness. The findings revealed that the UVAG effectively reduced the grinding normal force, while MQL with nanofluids considerably decreased the tangential force. Furthermore, the hybrid utilisation of both techniques resulted in a significant reduction of forces by roughly 60%, which is a remarkable outcome. Additionally, this combined approach enhanced the surface quality of the ground material. In their research, Rabiei et al., [29] performed experiments to assess the coolant and lubricant properties of MWCNT, Al₂O₃, and hybrid MWCNT/Al₂O₃ nanofluids in UVAG with MQL grinding. They discovered that by combining the MQL technique with hybrid nano-fluid and UVAG, the grinding temperature as well as the tangential and normal forces were decreased during the grinding operation. Madarkar et al.[192] conducted an experimental investigation of the grinding performance of Ti-6Al-4V alloy using the UVAMQL grinding method, and they added 1, 5, and 10% sunflower oil to water to prepare biodegradable emulsions for grinding. After that, they compared the grinding performance of UVAMQL with dry and MQL grinding modes and evaluated surface roughness, grinding forces, and surface topography. They found that UVAMQL grinding showed smaller grinding forces and improved surface quality compared to MQL grinding mode. Another research study conducted by Molaie et al., [193] to compared the grinding performance of nano-enhanced biolubricants prepared by pure water and four types of nano-enhancers (Al₂O₃, graphite, graphene oxide, and CNTs). They found that the smallest grinding force was observed in water/graphene oxide. In further experiments, a hybrid nano-enhanced biolubricant was prepared by mixing Al₂O₃ and graphite, which

improved the grinding performance due to their different tribological mechanisms. The layered structure of graphene oxide reduces direct contact between particles and metal surfaces, forming a protective and durable friction film. However, spherical Al_2O_3 nano-enhancers produced a ball effect between friction surfaces due to their high hardness. Naskar et al. [37] carried out an experiment to assess the UVAMQL grinding process and the effect of fluid lubrication on the interaction between the grit and the surface of workpiece during the grinding of Ti-6Al-4V. Further, with an increase in fluid lubricity, the effective amplitude of vibration increases. In addition, the use of the most lubricating vegetable oil led to the lowest grinding power and the greatest compressive residual stress [37].

2.5.1 The necessity of eco-friendly cutting fluid in grinding

Various types of cutting fluids have been utilized in hybrid MQL grinding, including synthetic, semi-synthetic, soluble oil, and straight oil [194]. However, the use of petroleum-based cutting fluid in hybrid MQL grinding is not advisable as it can create an atomized mist of cutting fluid in the air, which may cause chronic bronchitis, eye irritation, and lung cancer in workers [195]. In addition, inhalation of gram-negative bacteria and mycobacterium immunogenum found in petroleum-based mineral oils can result in an asthmatic response among machine operators [196]. Cutting fluids derived from biological sources that are environmentally friendly, sustainable, and easily biodegradable are a desirable alternative to cutting fluids made from petroleum [197]. The biodegradability of a substance is a crucial aspect of its eco-friendliness. A biodegradable material can be broken down by microorganisms through biochemical processes. During primary degradation, the original molecule of a recyclable substance is dissolved, leading to the development of CO_2 and biomass during ultimate degradation. Ultimate biodegradability is important as it ensures that the organic component can be safely reintegrated into the

natural carbon cycle [198]. For this reason, vegetable oil is a preferable choice as a cutting fluid due to its easily biodegradable nature.

2.5.2 Vegetable oils as a cutting fluid in sustainable grinding

Vegetable oils have emerged as a promising option for eco-friendly lubricants due to their sustainability and renewability. Compared to petroleum-based cutting fluids, vegetable oils are biodegradable, less toxic, and more environmentally friendly, making them the most viable alternative [199]. This has led to increased interest in vegetable oils as a potential replacement for traditional lubricants. Triglycerides are the molecular structure of vegetable oil, which consists of glycerol. The ester linkage at the hydroxyl groups of glycerol combines with three continuous chains of fatty acids in triglycerides. The fatty acids present in vegetable oil contribute to the formation of a continuous chain and several unsaturated double bonds. The fatty acid components oleic, linoleic, and linolenic are represented by long carbon chains with one, two, or three double bonds, respectively [106]. According to Shashidhara et al. [107], vegetable oils typically contain 4–12 types of fatty acids. The proportion of these fatty acids is primarily influenced by weather and geography. Table 2.1 provides information on the application of vegetable oil as a base stock in various manufacturing industries, where it is being used as an alternative cutting fluid [200]. In the MQL grinding process of hardened AISI 4340 steel, Damasceno et al. [201] discovered that substituting conventional cutting fluid with vegetable oil leads to decreased grinding force and specific grinding energy. The impact of MQL on alumina ceramics was examined by Emami et al. [202] using four types of lubricants: mineral, hydrocracked, synthetic, and vegetable oil. The study revealed that during MQL grinding, vegetable oil demonstrated a remarkable reduction in grinding force, specific energy, and surface roughness.

Table 2.1 Vegetable oil based lubricants used in industry application [200]

Vegetable oil	Application
Canola oil	Hydraulic oil, tractor transmission fluids, metal working fluids, food grade lubes, penetrating oils, chain bar lubes
Castor oil	Gear lubricants, greases
Coconut oil	Gas engine oils
Olive oil	Automotive lubricants
Palm oil	Rolling lubricants, grease
Groundnut oil	Chain saw bar lubricants, air compressor-farm, grease
Sunflower oil	Light color paints, diesel fuel, resins, enamels
Linseed oil	Coating, paints, lacquers, varnishes, stains
Soybean oil	Lubricants, biodiesel fuel, metal casting, printing inks, paints, coatings, detergents, plasticizers, hydraulic oil
Joboba oil	Grease, cosmetic industry, lubricant application
Crambe oil	Grease, intermediate chemicals, surfactants
Tallow oil	Steam cylinder oils, soaps, cosmetics, lubricants, plastics

This was attributed to its efficient cooling properties and the formation of a robust lubricating layer that decreased friction force during the grinding process. In their study on the GH4169 alloy, Wang et al. [203] tested seven types of vegetable oils, including castor, soybean, corn, peanut, palm, rapeseed, and sunflower, during MQL grinding. Their findings showed that using castor oil in MQL grinding resulted in the best surface quality, lowest specific energy, and minimum surface roughness value. They attributed these positive outcomes to the higher viscosity index of castor oil, which provides better lubrication stability across a wider range of operating temperatures. Additionally, the

researchers observed that the surface quality and specific energy trend differed among the different vegetable oils tested, with castor having the best performance, followed by palm, peanut, sunflower, soybean, rapeseed, and finally, maize. Moreover, compared to flood grinding, MQL grinding only increased the G-ratio by 39.6%, and its corresponding value was 19.25. In their study, Li et al. [204] examined the impact of seven different types of vegetable oils, including castor, soybean, rapeseed, corn, sunflower, peanut, and palm oil, on the energy ratio coefficient and grinding temperature during MQL grinding of the nickel-based alloy GH4169. The energy ratio coefficient represents the ratio of energy transferred to the workpiece to the total heat flux density generated by the grinding wheel's input energy in the grinding zone. The researchers found that the use of palm oil resulted in a lower energy ratio coefficient and grinding temperature due to its superior heat extraction capacity compared to the other vegetable oils. Typically, vegetable oils with a higher viscosity provide better lubrication performance, but they also significantly reduce the heat exchange capability. In their study, Silva et al. [205] utilised a vitrified-bonded alumina wheel to perform plunge cylindrical grinding on hardened AISI 4340 steel. They carried out the grinding process under both flood and MQL conditions, using a combination of synthetic and soybean oil. The researchers focused on analysing the residual stress levels at various stages of material removal. Their findings showed that MQL grinding using the synthetic/soybean oil mixture produced significantly high levels of compressive residual stresses.

After conducting a literature review, it has been established that vegetable oils possess excellent lubricating properties that can enhance both the surface quality of a ground surface and the grindability indices. However, using straight vegetable oil in Minimum Quantity Lubrication grinding for materials that are challenging to machine and generate significant heat in the grinding zone can result in greater thermal damage to the ground

surface due to the poor heat transfer of vegetable oil. To improve both cooling and lubrication performance, some researchers have opted to use an emulsion of vegetable oil and water as a cutting fluid in MQL grinding. In their study, Ruzzi et al. [206] used a mixture of vegetable oil and water as MQL oil while performing surface grinding on hardened AISI 4340 steel. As a result, they achieved an improved surface finish and a reduced roundness error of the ground surface. In a recent study, Jha and Paul [207] evaluated the efficacy of a mixture of vegetable oil and water as a cutting fluid in MQL grinding of Ti-6Al-4V. The emulsion was composed of 5% vegetable oil and 95% water, with a volume ratio of oil to water of 1:20. To enhance the stability of the oil in water, a non-ionic surfactant was incorporated into the mixture at a concentration of 1.6%. This surfactant creates a monolayer around the oil droplets, which attracts positively charged hydrogen ions from the water droplets. Their findings indicate that using an oil/water emulsion in MQL grinding results in improved surface topography with lesser thermal damage and reduced grinding force and surface roughness. Additionally, this method leads to the development of a small amount of compressive residual stress in the ground surface due to its superior lubrication and cooling abilities.

2.5.3 Nanofluids as a cutting fluid in sustainable grinding

According to Gupta et al. [208], liquids commonly used as cutting fluids, such as water, oil, and ethylene/propylene glycol, do not have good thermal properties compared to solids. To enhance heat transfer during cutting, researchers have developed a new type of cutting fluid called nanofluid (NF). This is achieved by adding metallic, non-metallic, ceramic, or carbon nanoparticles that are smaller than 100 nanometers to a conventional cutting fluid [209]. Nanoparticles such as Ag, Au, Cu, SiO₂, TiO₂, Al₂O₃, MoS₂, graphite, diamond, and carbon nanotubes are often used to create NFs [210]. These NFs possess superior thermo-physical properties, including higher thermal conductivity, convective heat transfer

coefficient, viscosity, and thermal diffusivity when compared to traditional cutting fluids [211].

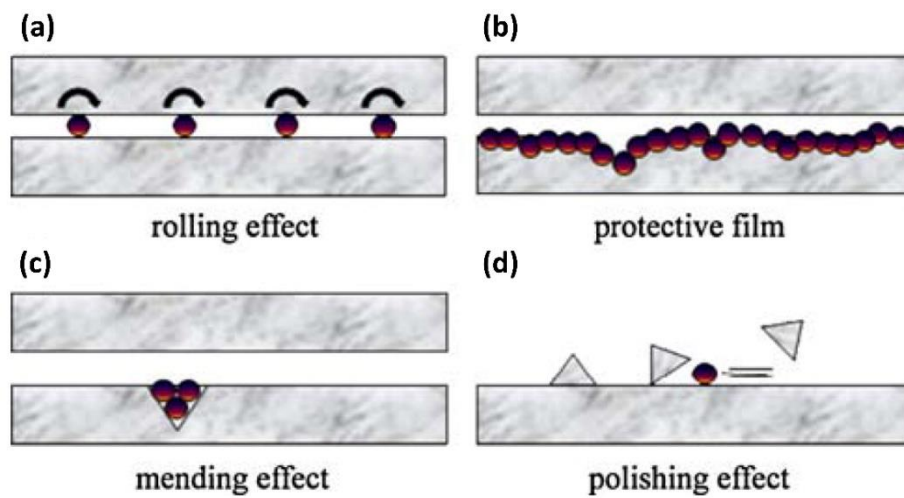


Figure 2.7 Lubrication mechanism of nanofluids in machining [212]

Extensive research has been conducted on the functioning of NFs, which can lead to decreased friction and wear. A study by Li et al. [212] examined four lubrication mechanisms to explain the enhanced lubrication capability of NFs, which include the rolling effect, protective film effect, mending effect, and polishing effect. These mechanisms are illustrated in Figure 2.7. The rolling effect mechanism involves the movement of spherical nanoparticles between two friction surfaces, resulting in a shift from pure sliding friction to rolling friction. The presence of small spherical nanoparticles can enhance the extreme pressure performance and increase the load carrying capacity of NFs [213]. In the protective film mechanism, spherical nanoparticles have the ability to create a thin protective film between two surfaces, which reduces friction and wear. When the nanoparticle size is similar to the film thickness, the mechanism resembles that of ball bearings. On the other hand, when the film thickness is less than the nanoparticle size, a transfer film may be formed. This means that if the surface area of the spherical nanoparticles directly contacts the friction surfaces, the thin protective film effect will be

more prominent [214]. The mending effect mechanism involves depositing nanoparticles of any shape onto surfaces experiencing friction or filling in surface grooves.

Table 2.2 Lubrication mechanism of nanoparticles [215]

Nanoparticles	Lubrication mechanism
Graphite	Nanoparticles act as ball-bearing spacer
CNT MNCNT	Formation of protective file, deposition of MNCNTs on the worn surface
Diamond	Nanoparticles plowing on the worn surface
Ag	Synergic effect of the particles and base lubricant
Cu	Nanoparticles fill scars and grooves, formation of physical film
Al ₂ O ₃	Formation of self-laminating protective film, friction mode change: from sliding to rolling action
CuO, ZnO	Nanoparticles acting as rolling medium film formation
TiO ₂	Formation of lubricating film via chemical reaction and physical mechanism, third body rolling effect
MoS ₂	Shear formation of nanoparticles Tribo-film formation
SiO ₂	Nanoparticles acting as rolling particles, shearing of nanoparticles, particles filling and polishing effect
Graphite	Nanoparticles act as ball-bearing spacer

This helps to balance mass loss and create a multilayer lubrication film between the two surfaces in contact. The end result is a reduction in surface roughness and asperity contact [216]. The process of polishing involves the use of hard nanoparticles, such as abrasives, to act as a polishing agent, which can reduce surface roughness and improve the surface topography of rubbing surfaces [217]. Table 2.2 outlines the lubrication process of various

nanoparticles in the context of machining [215]. Furthermore, the stability of nanofluids is a cause for concern, as they tend to become unstable over time, which can affect their thermo-physical properties such as thermal conductivity [218]. Therefore, it is necessary to choose the appropriate method for suspending NFs in order to prevent the nanoparticles from clustering and agglomerating. One way to address this issue is to use surfactants, which are additives that have a high surface energy that can help to homogenise and conglomerate the nanoparticles. By adding a small amount of surfactant (10 weight percent of nanoparticle) to a low interfacial tension base fluid, the coagulation tendency of the nanoparticle can be increased. Proper probe sonication after the addition of surfactants can also help to address these issues to some extent. To assess the stability of NFs, several approaches have been developed, including sedimentation analysis, pH testing, dynamic light scattering, and zeta potential measurement. The sedimentation technique is the most cost-effective and easy-to-use approach for determining the stability of NFs. This technique involves the settling of nanoparticles in the base fluid and is influenced by both buoyancy and frictional forces [219]. In this method, photographs taken over time can be used to perform visual analysis of NFs. If NPs remain suspended for an extended period, it indicates a minimum sedimentation effect, suggesting that the NFs are stable. The stability of nanofluids can be assessed through pH measurements using a pH meter, which gauges the hydrogen-ion activity present in water-based NFs. In this process, the glass electrode and reference electrode are submerged in the NFs to establish an electrical circuit. A potential difference is created and detected by a voltmeter [220]. If the pH value of NFs is significantly different from the isoelectric (IE) point of nanoparticle dispersion in the base NFs, then the nanofluid is considered more stable. The IE point refers to the pH value at which a nanoparticle possesses no net electrical charge or is electrically neutral. Table 2.3 outlines the IE points of various nanoparticles. The stability of various concentrated

Al₂O₃/water nanofluids was evaluated by Choudhary et al. [221] using the pH-dependent isoelectric point (IEP) method. In recent times, several researchers have utilised various nanoparticles in eco-friendly grinding fluids owing to their outstanding thermo-physical characteristics, ability to transfer heat effectively, and potential to decrease the coefficient of friction and wear impact.

Table 2.3 Isoelectric point of various nanoparticles [221] [222]

Nanoparticles	IE point	Nanoparticles	IE point
Al ₂ O ₃	~ 9.1	SiC	~ 4.9
SiO ₂	~ 2-3	Graphene	~ 3-4
MoS ₂	~ 6-6.5	TiO ₂	~ 5.98
TiO ₂	~ 5.98	MNCNT	~ 4.5
CuO	~ 10	Ag	~ 2.85

In their research, Kalita et al. [223] investigated the impact of MoS₂ based on vegetable oil on specific energy, coefficient of friction, and G-ratio during the MQL grinding of EN24 steel. They performed grinding trials using soybean oil with different concentrations of MoS₂, ranging from 2% to 8%, and grain sizes between 70 and 300 nm. Their findings indicate that using 8% concentrated MoS₂ resulted in a 50% improvement in the G-ratio and a reduction of 41% and 53% in the specific energy and coefficient of friction, respectively. Zhang et al. [224] used MoS₂ nanoparticles (50 nm) with vegetable oils in MQL grinding of AISI 1045 steel. They found the best grinding performance with MoS₂ added to soybean nanofluid, which increased viscosity and thermal conductivity, improving lubrication and cooling in the grinding zone. The researchers recommend a 6 vol.% MoS₂ concentration in soybean oil as the optimal lubricant condition for grinding AISI 1045 steel. Recently, Jia et al. [225] created nanofluids by blending varying volume percentages of

MoS₂ nanoparticles (2%, 4%, 6%, 8%, 10%) with a mixture of soybean and castor oil to surface grind the Ni-based alloy GH4169 under MQL mode. Their findings indicated that the use of 8 vol.%-based nanofluids produced the best results, which included lower grinding force, specific energy, and grinding temperature. Additionally, they discovered that excellent surface topography was achieved, with no wear marks present on the microchip surface under the same grinding conditions. Wang et al. [203] reported in their MQL grinding investigation of 440C steel using an alumina wheel that they utilised various NFs, such as palm oil mixed with MoS₂, Al₂O₃, and SiO₂ and their findings revealed that the friction coefficient of NFs based on Al₂O₃ decreased by 19.3% when compared to pure palm oil. Hosseini et al. [226] conducted surface grinding of tungsten carbide grade YG8 using MoS₂, graphite, and Al₂O₃ nanoparticles in MQL grinding. The researchers added 1-3 wt. % of different nanoparticles to sunflower oil to prepare the respective NFs. The findings showed that MoS₂ and Al₂O₃ nanoparticles resulted in lower grinding forces and surface roughness compared to graphite-based NFs. This is because the former two NFs formed a robust protective tribo-film over the ground surface. Wang et al. [227] conducted MQL grinding tests on the GH4169 alloy, utilising six distinct nanoparticle types: MoS₂, SiO₂, diamond, CNTs, Al₂O₃, and ZrO₃. These nanoparticles were added separately to palm oil, which served as the base lubricant, at a concentration of 6 wt.%. Their findings revealed that spherical Al₂O₃ nanoparticles exhibited superior lubricity, while nanodiamonds were reported to provide better polishing of the work surface. In a recent study conducted by Dambatta et al. [228], a combination of SiO₂ nanoparticles and canola oil was utilized in the surface grinding of Si₃N₄ ceramic. The experiment yielded results indicating a significant decrease in grinding force and surface roughness when using a 2 wt. % SiO₂ nanofluid. The researchers also observed that SiO₂ contributed to friction reduction and the formation of a tribofilm between the rubbing surfaces.

2.6 Magnetic Barkhausen noise analysis

Currently, precision manufacturing industries are investing large sums of money in analyzing surface integrity, as it greatly impacts a product's lifespan. Commonly used conventional testing methods to assess the surface integrity of ground components include metallographic inspection, X-ray diffraction, scanning electron microscope, and microhardness measurement. However, these methods are restricted to laboratory settings and cannot be employed for real-time testing due to their high initial costs and lengthy analysis time [38]. In order to determine the depth profile of residual stress, electrolyte polishing is required to remove a layer, which can result in changes to the stress profile [229]. Additionally, obtaining clear diffraction peaks in XRD and consistent indentation sizes in microhardness can be difficult for samples with irregular geometries or oversized dimensions. However, the magnetic Barkhausen noise (MBN) technique has emerged as a cost-effective and time-efficient alternative for the grinding industry to detect grinding damage at production rates, making it a viable solution for reducing production costs [230].

The Barkhausen noise phenomenon was identified by Professor Heinrich Barkhausen, a German physicist. The initial observation of Barkhausen noise was made by detecting the sound produced in headphones connected to a pickup coil wound around a ferromagnetic substance as it became magnetised over time [231]. The MBN technique was first employed in an industrial setting for material characterization by Tiitto [232]. Through the efforts of the French scientist Pierre Weiss, magnetic domain theory made it feasible to comprehend the magnetic behaviour of ferromagnetic materials. According to the theory of magnetic domains, ferromagnetic materials minimise their magnetostatic energy by dividing themselves into separate magnetic domains. These domains are separated from each other by boundaries known as domain walls, which have a finite width [233]. There are typically two types of domain walls that exist in ferromagnetic materials, namely 180°

and 90° domain walls, which are determined by the crystallographic arrangement of the material. The 180° domain wall is more mobile than the 90° domain wall, making it possible for MBN generation. A 180° domain wall occurs when the domain walls are parallel to each other, while a 90° domain wall occurs when the domain walls are perpendicular to each other [234]. Ferromagnetic materials are composed of magnetic domain walls with varying magnetic orientations that cancel out each other's magnetic fields. When an external magnetic field is applied to the material, the magnetic domain walls that are most closely aligned with the applied field will grow at the expense of the other walls. As a result, the material becomes magnetised [42]. Figure 2.8 illustrates the impact of an applied magnetic field on the magnetic domain wall of a ferromagnetic material.

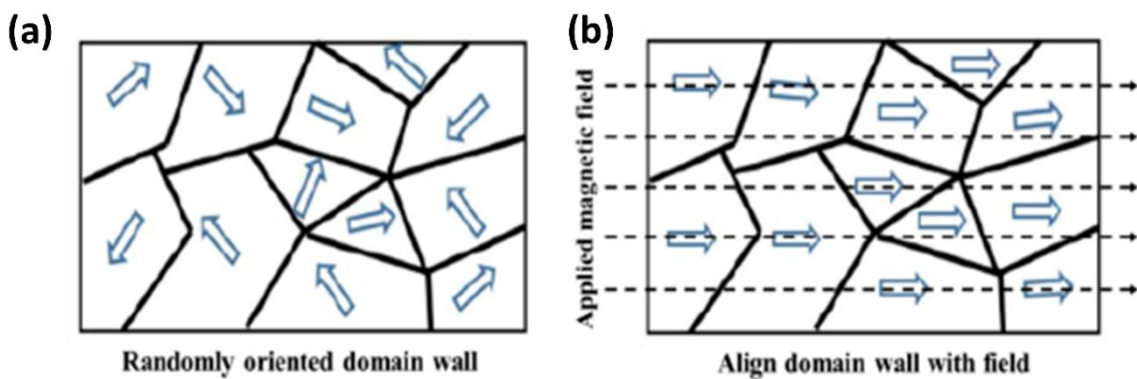


Figure 2.8 Effect of external magnetic field on ferromagnetic material

When a ferromagnetic material is subjected to a maximum magnetic field, the magnetic domain wall aligns with the applied field direction, resulting in saturation magnetization. Beyond this point, any further increase in the magnetic field will have a small or no effect on the magnetization [235]. The ability of a ferromagnetic material to develop a magnetic field is referred to as permeability, and a material with a higher permeability has better conductance for magnetic lines of force. When the magnetic field strength is reduced after reaching saturation magnetization, the magnetization of the material also decreases, but the

path followed during magnetization is different from that during demagnetization. The difference in these paths is known as the hysteresis loop. Even when the strength of the applied magnetic field is reduced to zero, there is some remaining magnetization in the material, which is referred to as remanence. When the applied field strength is increased in the opposite direction, the magnetization of the material decreases further until it reaches zero. This specific strength of the applied field is referred to as coercivity. If the applied field strength is further increased in the opposite direction, the magnetization of the material again reaches its saturation point, but in the opposite direction. This variation in the magnetic field in both positive and negative directions results in the creation of a hysteresis loop [236], as shown in Figure 2.9 (a).

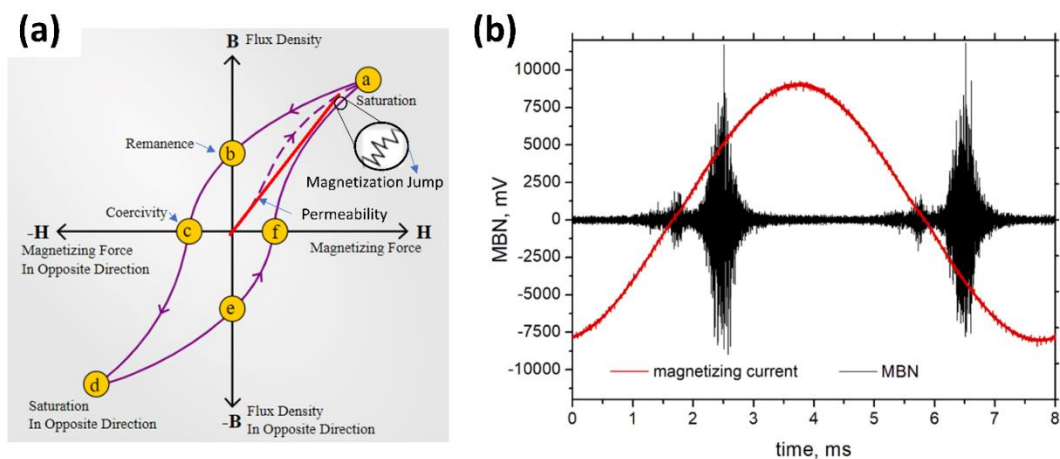


Figure 2.9 (a) Hysteresis loop formation, (b) Barkhausen noise signal

A constant magnetic field applied to a ferromagnetic material result in a smooth hysteresis loop. However, this does not accurately reflect the jerky and abrupt movements of domain walls within the material caused by the presence of pinning sites. The strength of these sites determines the extent to which they hinder the motion of the magnetic domain wall. Pinning sites arise due to material inhomogeneities such as grain boundaries, impurities, phase formation, and crystal defects [236]. When a material has pinning sites that resist magnetic fields, an external magnetic field can be applied to overcome these sites, causing the

material to suddenly break away from them. This results in a rapid change in magnetization and generates many small voltage spikes in a coil, known as Barkhausen noise signals. When amplified, these signals create a cracking noise that is audible through an earphone and is referred to as Barkhausen noise [237]. Figure 2.9 (b) illustrates the Barkhausen noise signal produced by ferromagnetic materials.

2.6.1 Principle of magnetisation

The generation of the Barkhausen noise signal is mainly contributed by three types of magnetism, which are irreversible discontinuous domain wall bowing, irreversible discontinuous domain wall translation, and irreversible discontinuous domain wall rotation. A more elaborate explanation of these mechanisms is given below [238].

- (I) The phenomenon of domain wall bowing can be observed when a material is subjected to a low external magnetic field. Initially, all domain walls in the material expand elastically. However, after a certain point, the deformation of the domain walls becomes permanent, leading to an irreversible expansion. This continuous expansion, without any increase in the external magnetic field, causes abrupt changes in magnetization and generates a signal known as the Barkhausen noise.
- (II) The movement of domain walls is the primary cause of Barkhausen jumps and occurs when a domain wall is released from its pinning sites under the influence of a strong magnetic field. In ferromagnetic materials, these pinning sites are created by inclusions and localized residual stresses that arise from imperfections in the crystal structure.
- (III) The rotation of domain walls occurs when a material is subjected to a strong magnetic field, causing them to shift from their original easy axis to the nearest crystallographic axis aligned with the field direction. This is due to the magnetic energy overpowering the domain wall's anisotropy energy. Despite removing the

magnetic field, the moments remain aligned along the new easy axis and do not revert to their original orientation. This sudden change in magnetization, resulting from the switching of moments between easy axes, generates a Barkhausen noise signal.

2.6.2 Application of magnetic Barkhausen noise in grinding

Several researchers have employed different signal parameters like RMS, peak, and peak position of MBN to characterise the mechanical and metallurgical properties of ground components. Gupta et al. [230] were likely the first to use the MBN technique in the grinding field to assess varying degrees of grinding thermal damage in steel. They investigated the relationship between microhardness and residual stress on the MBN signal, specifically peak voltage and peak width. Moorthy et al. [239] conducted a study on the changes in residual stress of case carburized En36 steel caused by grinding using the MBN method. They utilised both the high and low magnetic frequency ranges of MBN to detect the carburizing depth of 0.55 and 0.8 mm subjected to different levels of thermal damage. The authors observed that the high frequency MBN signal profile exhibited a single peak, indicating changes in residual stress near the ground surface (<10 μm depth). Conversely, the low frequency BN profile displayed two peaks and clearly reflected the changes in residual stress in the subsurface (<50 μm depth).

Vashista and Moorthy [240] observed a comparable pattern of MBN signal profiles, with both single and double peaks, when they studied the impact of various heat treatment processes on the microstructure of high-carbon 42CrMo4 and low-carbon 18CrNiMo5 steel. Similarly, Vashista et al. [40] examined the residual stress, grain refinement, and microhardness variation during surface grinding of AISI 1060 steel utilising the MBN technique. Their findings demonstrated a linear correlation between the peak and RMS values of the MBN signal and residual stress, with a correlation coefficient of

approximately 0.92%. They also noted that an increase in tensile residual stress resulted in grain elongation and changes in microhardness due to plastic deformation on the ground surface. Earlier, Jiles [237] discussed the impact of grain size on the MBN signal, indicating that as the grain size decreases, the number of pinning sites increases, resulting in higher Barkhausen jumps but with a smaller amplitude. In their study, Moorthy et al. [241] proposed that a larger grain size would cause a shift in the peak position of the MBN envelope towards a lower applied field strength. Santa-aho et al. [242] conducted experiments involving the grinding of gear teeth made from case-hardened 18CrNiMo7-6 gear steel and observed changes in MBN that indicated thermal damage in the form of microhardness and residual stresses. They discovered that an increase in material hardness led to a higher dislocation density, which restricted the motion of domain walls and resulted in a lower MBN signal. Similarly, Srivastava et al. [101] reported a decrease in RMS MBN value with an increase in microhardness for IS 2062 steel that had undergone dry grinding, due to the hindrance of the motion of domain walls resulting from plastic deformation. In their research, Deng et al. [243] investigated how the hardness of commercial carbon steels is affected by tempering temperature using MBN parameters such as peak value and RMS. They discovered that the formation of soft phases, such as bainite, reduced hindrance to domain wall motion and rotation, resulting in higher peak and RMS values of the MBN signal. Additionally, they found that an increase in the surface roughness of the sample led to a decrease in the peak and RMS values. This occurred because higher surface roughness widened the spacing between domain walls, making their movement and rotation more difficult. Vashista and Paul [244] proposed a new approach to evaluating the surface integrity of ground hardened AISI 52100 steel by processing the MBN signal with three unique parameters: event, count, and threshold. These parameters were introduced to address the problem of the poor sensitivity of the MBN signal. They found that the MBN

parameters, event, count, and threshold, showed a linear correlation with the residual stress of the ground sample with poor micro-magnetic response. In another study, Neslusan et al. [49] demonstrated the advantage of the MBN technique in real industrial applications related to the grinding of large bearing rings. They found that the two-peak MBN envelope was due to the inhomogeneity of the carbide distribution at elevated temperatures, which were generated in the bearing due to high grinding heat. Recently, Lasaosa et al. [245] used the MBN signal to measure the thickness of the hardened layer induced during cylinder grinding of a ball screw shaft. They detected the thickness of the hardened layer in the range of 150–2500 μm by analysing the position of the first peak of the MBN profile. Additionally, they identified the ground burns near the top surface by analysing the position of the second peak of the MBN profile.

From the literature on UVAG, UVAMQL, and MBN techniques, it has been confirmed that the use of vegetable oils and nanofluids as eco-friendly cutting fluids has the potential to reduce the grinding temperature and enhance the lubrication properties during grinding. They can improve the grinding performance and surface integrity of finished components in terms of grinding force, specific energy, surface roughness, negligible variation in microstructure, and microhardness. In grinding, most of the work with straight vegetable oils has been carried out on different engineering materials. Also, there is a lack of work regarding the use of nanofluids based on vegetable oil and oil-water emulsions during the grinding of hardened tool steel. On the other hand, the MBN method is an efficient surface characterization for in-line production. So, there is some research gap to use a combination of UVAG, UVAMQL, with MBN, which may lead to efficient, eco-friendly grinding with fast surface characterization of AISI D2 tool steel.

2.7 Gaps in literature and Motivation of current research

Sustainable machining is an emerging area to make the grinding process more economical and environmentally friendly. However, previous work, as discussed in the literature, reflects the importance of UVAG, UVAMQL, and MBN techniques for improving grindability and surface integrity characterization, respectively. A significant research gap exists in the field of ultrasonic vibration assisted grinding (UVAG) and ultrasonic modulation-assisted quenching grinding (UVAMQL) for "difficult-to-cut" materials like AISI D2 tool steel. There is a lack of literature on modelling and simulation work for UVAG using single alumina abrasive grit and its experimental validation. Moreover, no experimental investigations have been conducted to evaluate the impact of UVAG and UVAMQL grinding on the surface integrity of AISI D2 tool steel. Furthermore, very limited research has been reported on the utilization of eco-friendly cutting fluids, such as vegetable oil and nanofluids, during UVAMQL grinding of "difficult-to-machine" materials like AISI D2 tool steel. Additionally, no experimental studies have been carried out to assess the lubrication performance of emulsion of vegetable oil-water and oil-water-based nanofluid in UVAMQL grinding. Finally, there is no available literature on the application of the micro-magnetic Barkhausen noise technique to qualitatively evaluate the thermal damage of ground AISI D2 tool steel following UVAG and UVAMQL grinding. Based on the literature review, the following objectives have been framed for the present work on the eco-friendly grinding of hardened AISI D2 tool steel:

(I) Modelling and simulation study of ultrasonic vibration assisted grinding of AISI D2 tool steel with single alumina abrasive grit. This research objective will cover the following topics:

- To investigate real-time multiphysics domains such as chip morphology, temperature field, equivalent stress, and strain parameters, which are essential for engineering

applications for conventional and ultrasonic assisted grinding cannot be performed experimentally because of the tiny-affected region and speedy action of the abrasive grit. Therefore, the finite element analysis (FEA) simulation is used for such investigating.

- Ansys explicit dynamics module simulates the grinding processes and compares the results with experimental findings.

(II) Experimental investigation on ultrasonic vibration assisted grinding of AISI D2 tool steel with an alumina wheel. This research objective will include the following:

- Evaluation of grinding performance in terms of grinding force, force ratio, specific grinding energy, and grinding temperature.
- Measurement of grinding temperature by a high-speed infrared thermography camera.
- Evaluation of surface integrity in terms of surface roughness, bearing area curve, surface topography, microchip morphology, and microhardness.

(III) Experimental study on UVAMQL grinding of AISI D2 tool steel with an alumina wheel using four different eco-friendly lubricants, i.e., soybean oil, soybean oil-deionized water emulsion, Al₂O₃ NFs -0.5 wt.%, and Al₂O₃ NFs -1 wt.%.

The following investigation would be included:

- Different emulsions and NFs stability through the sedimentation technique.
- Evaluation of nanofluid dispersion stability using a pH test.
- Measurement of thermal conductivity by transient hot-wire method.
- Measurement of surface tension of different lubricants by using Pendant drop shape method.

- Studying the effect of different eco-friendly lubricants on grindability indices, surface integrity, surface functional parameter, and grinding temperature.
 - Measure wettability of lubricants through a goniometer.
- (IV) Surface integrity characterization of the ground surface using the magnetic Barkhausen noise (MBN) and hysteresis loop (HL) techniques.
- Evaluation of grinding temperature effect on surface integrity of ground samples using conventional characterization techniques such as microstructure and microhardness of the ground surface.
 - Qualitative assessment of thermal damaged ground surface under different environments using MBN and HL techniques.
 - To establish a possible correlation between the state of microhardness of the ground surface with the RMS value of the magnetic Barkhausen noise as well as permeability and coercivity derived from the hysteresis loop.