1 INTRODUCTION

1.1 AISI D2 tool steel

AISI D2 tool steel is a high-carbon, high-chromium, air-hardening tool steel that belongs to the cold-work tool steel group. Globally, it finds equivalents in DIN 1.2379, EN X153CrMoV12. AISI D2 tool steel is widely used in the production of various cutting tools, such as knives, drills, reamers, and shear blades, as well as in cold-work dies, punches, and forming tools [1]. The chemical composition of AISI D2 tool steel typically includes 1.4-1.6% carbon, 0.3-0.9% manganese, 0.4-1.0% silicon, 11.0-13.0% chromium, 0.7-1.2% molybdenum, and 0.15-0.8% vanadium. This high level of carbon and chromium content provides the steel with excellent wear resistance, toughness, and edge retention, making it a popular choice for industrial applications where high durability and strength are required. These properties occur mainly in AISI D2 tool steel, where they are caused by the dissolving of alloying elements and the formation of carbides [2]. Some of the industries that commonly use AISI D2 tool steel:

1. Metalworking: AISI D2 tool steel is widely used in the metalworking industry to produce cutting tools, punches, and dies. This includes industries such as aerospace, automotive, and general metalworking.
2. Plastics: AISI D2 tool steel is also used in the plastics industry to produce molds for injection molding and die casting operations. This includes industries such as packaging, consumer goods, and automotive.
3. Woodworking: AISI D2 tool steel is used in the woodworking industry for the production of cutting tools such as saw blades, planer knives, and router bits.
4. Paper and Printing: AISI D2 tool steel is also used in the paper and printing industry for the production of cutting tools such as paper trimmers, guillotine blades, and

rotary cutters.

Some specific examples of companies that use AISI D2 tool steel in their manufacturing processes include Ford Motor Company (automotive stamping and forming dies), Boeing (aircraft tooling), and Caterpillar Inc. (cutting tools).

The current scenario of the manufacturing industry is marked by the increasing demand for high-quality, precision components, which require high-performance cutting tools to produce. AISI D2 tool steel can be heat treated to achieve a high hardness level, typically in the 55-62 HRC range. It is air-hardening, which means it can be cooled in the air after heating, making it easier to work with than some other tool steels requiring specialized quenching methods. AISI D2 tool steel also has good dimensional stability and resistance to distortion during heat treatment. Therefore, proper handling and maintenance are essential to ensure the longevity and effectiveness of tools made from AISI D2 tool steel. This material is also known for its ability to maintain a sharp cutting edge for an extended period, which reduces machine downtime and tooling costs.

On the other hand, AISI D2 tool steel is also more challenging to machine than some other tool steels due to its high hardness and wear resistance [3]. However, its low thermal conductivity, high hardness and wear resistance make it difficult to machine using traditional cutting tools such as drills, milling cutters, and turning tools. Hence, it is known as “difficult-to-cut” or “difficult-to-machine” material. The high carbon content in AISI D2 tool steel also makes it prone to cracking during machining, which further complicates the process. But grinding is the preferred machining operation compared to other machining, i.e., turning, milling, etc., for AISI D2 tool steel because it allows for precise control over the shape and dimensions of the finished product. As close dimensional tolerances, precise geometries and high surface quality requirements are more demanding for difficult-to-machine material. Grinding uses abrasive grains to remove material from the workpiece, allowing for a high degree of accuracy and surface finish.

1.2 Grinding process

The grinding process is a crucial manufacturing step used in a wide range of industries to achieve high-quality finished products with precise dimensions and surface finish. This process involves the use of abrasive grits to remove material from a workpiece, producing a smooth and even surface. Various factors, such as the selection of abrasive material, grit size, grinding speed, and coolant type, can impact the efficiency and effectiveness of the grinding process. Effective monitoring and control of these parameters are critical to ensure consistent quality and productivity in the manufacturing process.

Grinding is a major manufacturing process in modern times, and in industrialized countries, it typically represents a significant portion, about 20–25%, of the total costs incurred in machining operations [4]. However, grinding is an essential aspect of our society; without it, our current way of life would be impractical or unfeasible. Most of the objects we utilize have undergone grinding during their manufacturing process or have been created using machines that rely on abrasive operations to achieve accuracy and precision.

Abrasives have been used for machining for more than 2000 years. Abrasives were used during the first sharpening of knives, tools, and weapons. These were used to cut and make in shape to rocks or stones to construct buildings and edifices such as the pyramids. The abrasives industry plays a significant role in the development of modern technology and is now employed in a wide range of engineering applications. The Brown & Sharpe Mfg. Co. USA designed the first modern grinding machine in 1860 to finish gears, precision bearings, and parts for sewing machines [4].

However, in the twentieth century, the grinding process attained ample awareness from researchers. Now, this process has been established as highly useful and well demanding in manufacturing high-strength engineering materials. Grinding was crucial in developing bearings, transmission components, measuring equipment, astronomical instruments, micro-electronic devices such as sensitive silicon wafer plates, and cutting and forming tools like drill bits and milling cutters [5].

Common abrasive materials used in grinding include aluminum oxide (Al_2O_3), silicon carbide (SiC), diamond, and cubic boron nitride (cBN). Each abrasive material has its unique properties, such as hardness, toughness, and wear resistance, which affect the grinding performance and the resulting surface finish. Abrasive grits are bonded with specific bond material for a particular grinding wheel. Vitrified or resinoid bonds are generally used for conventional grinding wheels, i.e., aluminum oxide or silicon carbide. While vitrified, resin, and metal bonds are used for superabrasive wheels, i.e., diamond and cubic boron nitride. There are various types of grinding techniques that are used depending on the application and the type of workpiece being ground. Some of the most common grinding techniques include surface grinding, cylindrical grinding, centerless grinding, and internal grinding. Surface grinding involves grinding the surface of a flat workpiece, while cylindrical grinding involves grinding the outside or inside diameter of a cylindrical workpiece. Centerless grinding involves grinding the outside diameter of a workpiece without using a centering device. Internal grinding involves grinding the inside diameter of a cylindrical workpiece.

Grinding process removes a thin material layer from a workpiece using an abrasive wheel as the cutting tool. This wheel contains numerous micro-cutting edges (abrasive grains) that are randomly shaped, sized, and oriented, being strongly held in the circular wheels by bond material (refer to Fig. 1.1), and it is through these edges that the material is removed in the form of chips or swarf.

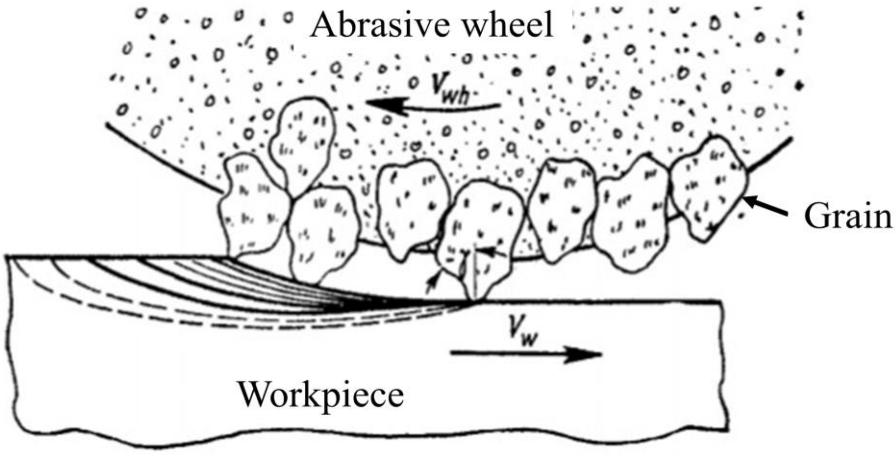

Fig. 1.1: Cutting action of abrasive grains over workpiece in grinding. “With permission from Ref. [6]”.

There are three machining mechanism: rubbing, ploughing, and cutting. Abrasive grit geometry may produce the chip formation that occurred in cutting action mode. Instead of removing chips, abrasive grits with a high negative rake angle/rounded cutting sharpness may rub or create a groove by ploughing action, which causes the workpiece material to flow laterally. In the case of rubbing mode, only low grit penetration occurs into the workpiece. In this area, the rise in force and temperature corresponding to an increase in grit penetration is extremely significant. Ploughing starts when the grit penetration is raised even further, causing the material to flow plastically. Furthermore, an increase in penetration results in the grit beginning to cut the material from the workpiece, as illustrated in Fig. 1.2. The primary factors that distinguish the cutting mechanism of a single grain from a single-point tool are:

1. The abrasive grains in a grinding wheel have an irregular geometry and are randomly distributed along the wheel's circumference.
2. The grit rake angle may vary from positive to negative. Cutting points on abrasive grains have extremely large negative rake angles, estimated to be about -60° or even

more negative [4].

3. The random position of the abrasive grains in the grinding wheel may vary.
4. Grit with favourable geometry can produce chips in shear mode. The negative rake angle with a lower shear angle has small-size chips.
5. Grinding wheels provide significant cutting marks.

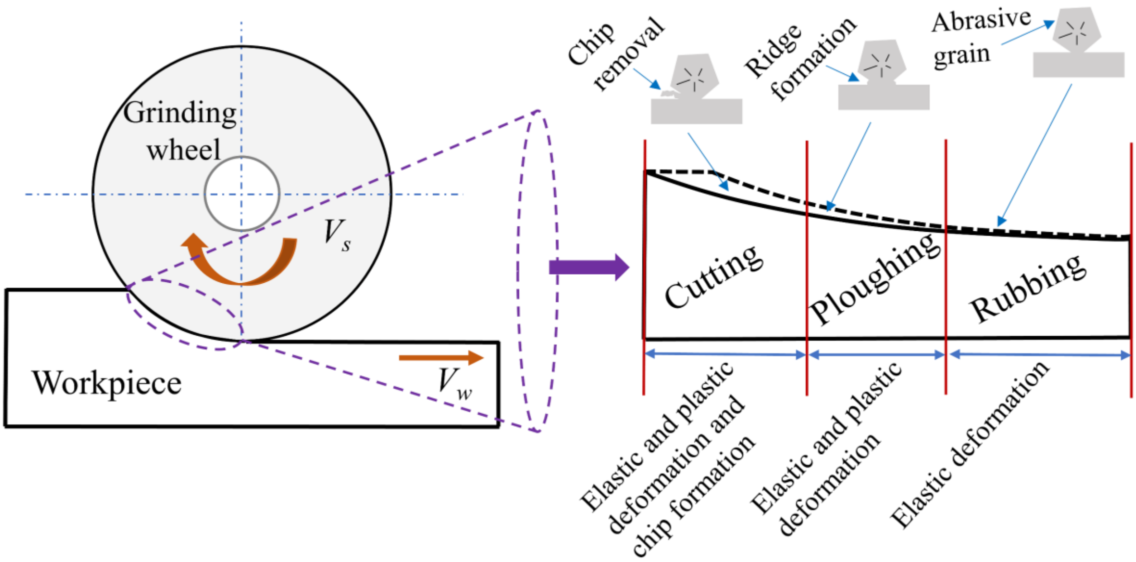

Fig. 1.2: Schematic diagram of material removal/chip formation in grinding process. “With permission from Ref. [7]”.

Grinding has several advantages over other manufacturing processes, such as turning, milling, and drilling. It can achieve high levels of accuracy and precision, which is crucial for producing high-quality components. Grinding can also remove material quickly and efficiently, making it a preferred process for large-scale production. Additionally, grinding can produce a range of surface finishes, from coarse to ultra-fine, making it a versatile technique for various applications. These benefits make grinding essential in various manufacturing sectors, including precision engineering, tool and die, automotive, aerospace, and medical [8].

Despite its many advantages, grinding also has some limitations and disadvantages. The process can be time-consuming and expensive, especially for complex workpieces with tight tolerances. Grinding can also generate a significant amount of heat, which can cause thermal damage to the workpiece, change in hardness and microstructure of the workpiece, induction of high tensile residual stresses and microcracks, affecting its strength and durability because the grinding process is characterized mainly by high specific energy requirement due to large negative rake and high cutting speed, which results in very high temperature [9]. Moreover, grinding can produce hazardous dust and noise, requiring proper safety measures to be taken.

The grinding temperature has a significant impact on the grinding process. It changes the physical properties of the workpiece and the grinding wheel, affecting the material removal rate, surface quality, and overall efficiency of the grinding operation. During the grinding process, friction between the grinding wheel and workpiece produces heat that leads to wear and tear of the abrasive wheel and deteriorates the workpiece’s surface quality in terms of poor surface finish. It may also cause residual stress to be created under the surface. Due to the relative motion between the tool and the workpiece, the tool is susceptible to three distinct elements throughout any machining process: cutting force, cutting temperature, and sliding action. After some time, the cutting tool's performance will become unsatisfactory based on these factors. Unsatisfactory performance includes dimensional precision loss, increased surface roughness, and higher power consumption.

The temperature rise during grinding can have several effects, some of which are as follows:

1. Thermal damage: A high-temperature rise during grinding can cause thermal damage to the workpiece, resulting in changes to the microstructure and reduced

material strength. This can lead to dimensional inaccuracies and reduced durability of the final product.

2. Cracks: A temperature rise during grinding can cause the formation of cracks in the workpiece, which can compromise the quality and safety of the final product. Cracks can also result in material wastage and increased production costs.
3. Surface finish: High temperatures during grinding can cause the coolant to evaporate faster, reducing its effectiveness and leading to a poor surface finish. This can result in rejected parts and increased production costs.
4. Wheel wear: Temperature rise during grinding can cause the abrasive wheel to wear out more quickly, reducing its lifespan and increasing production costs.
5. Energy consumption: A high-temperature rise during grinding can increase the energy consumption of the process, leading to increased operating costs and reduced profitability.
6. Operator safety: High temperatures during grinding can pose a safety hazard to operators, especially if adequate safety measures are not in place. This can lead to workplace injuries and increased liability costs.
7. Residual stresses: Increasing the grinding temperature can generally lead to induction of higher tensile residual stresses. This is due to thermal expansion and contraction of the workpiece and grinding wheel, as well as changes in the mechanical properties of the material being ground.

In the grinding process, the total heat generation at the grinding zone is totally adiabatic due to the rapid formation of chips at high speed; hence, the entire energy is converted to heat. Therefore, cutting fluids and coolants are essential during the grinding operation. The role of the cutting fluids and coolants is to dissipate heat from the tool and workpiece interface, preventing heat accumulation and excessive temperatures near the cutting edge.

1.3 The role of cutting fluids and coolants in grinding process

In industry, the general method of controlling high temperatures at the cutting zone is by using cutting fluids and coolants. Often, the grinding performance has been improved using suitable cutting fluids and optimizing the grinding parameters. Cutting fluids are used to assist in grinding to enhance grindability by minimizing the heat generated at the grinding zone. In terms of performance, it significantly extends grinding wheel life while improving surface quality and dimensional accuracy. Effective cooling and lubrication are the keys to controlling wheel wear and achieving better surface quality. Over 640 million gallons of cutting fluid are utilized annually worldwide [10].

In the early days of grinding, water was used as a cutting fluid to cool the grinding wheel and workpiece [11]. However, this was ineffective, and the water quickly became contaminated with metal particles, resulting in corrosion and rusting of the machine parts. To overcome these problems, various types of cutting fluids were developed in the early 20th century. Mineral oils were initially used, but they were found to be ineffective in preventing rust and corrosion. Later, sulfurized, and chlorinated oils were introduced, which had improved cooling properties and could also protect against rust and corrosion. During the mid-20th century, synthetic cutting fluids were developed, which had superior lubricating properties and could also provide better surface finish. These cutting fluids were based on esters, polyalphaolefins, and other synthetic chemicals.

Water-based cutting fluids were introduced in the 1960s and 1970s, offering several advantages over oil-based cutting fluids. These included better cooling properties, lower cost, and reduced environmental impact. In recent years, cutting fluids have become more specialized, with specific fluids being developed for different grinding applications. For example, some fluids are designed for high-speed grinding, while others are better suited for grinding hard metals such as tungsten carbide. Today, the role of cutting fluid in grinding is critical to achieving high-quality surface finish and prolonging the life of the grinding wheel. The right cutting fluid can improve grinding performance, reduce wheel wear, and improve workpiece quality.

Grinding the difficult-to-cut material in the surface finishing process may raise the cutting fluid's cost by 20-30% of the overall production cost due to the need for large amounts of cutting fluid to extract heat from the grinding zone [12]. Costs associated with the procurement, use, disposal, and cleaning of the machined components for difficult-to-cut materials are four times as high as those associated with cutting procedures for other materials [13]. Cutting fluid expenses accounts for roughly 16% of total manufacturing costs [14]. Additionally, a large amount of cutting fluid is related to a significant storage, recycling, and disposal cost. However, this high usage can lead to significant issues such as worker illnesses such as skin cancer, lung cancer, respiratory diseases, dermatological and genetic diseases, environmental contamination like water and soil, and increased machining costs [15]. Reported data points out that the continuous utilization of cutting fluid causes 80% of skin-related issues among machine operators [16]. The toxicological consequences of cutting fluid are already having an impact on more than 1.2 million machine-handling employees worldwide, according to research by the National Institute of Occupational Safety and Health (NIOSH) [17]. At high heat and pressure under severe grinding parameter circumstances, the inclusion of chlorinated chemical additives in cutting fluid creates a highly hazardous dioxin environment.

With ongoing research and development, the use of cutting fluids in grinding is ineffective with an increase in the cutting speeds and at higher speeds [18]. These problems occurred mainly due to the stiff boundary layer of the air around the grinding wheel. Generally, a stiff air boundary layer (hydrodynamic boundary layer) was developed ahead of the grinding zone due to the wedge effect between the peripheral surface of the grinding wheel and the workpiece surface. The reason was that hydrodynamic pressure is inversely proportional to the minimum gap between the grinding wheel and the workpiece [19], [20]. There is a strong need to develop innovative technologies that would eliminate or minimize the usage of cutting fluids in manufacturing. The technique should be more effective in performance, eco-friendly, and socially viable. Many sustainable techniques for machining have been successfully implemented, including dry machining [21], minimum quantity lubrication (MQL) machining [22], cryogenic machining [23], cryogenic minimum quantity lubrication (Cryo-MQL) machining [24].

In dry machining, no coolant or cutting fluid is used to cool and lubricate the grinding zone area, making it more cost-effective and eco-friendlier. However, due to the absence of cutting fluid, more heat is generated at the grinding zone area during the grinding operation. Excessive heat generation is a leading suspect in the deterioration of the ground surface quality of "difficult-to-machine materials" such as AISI D2 tool steel, titanium alloys, nickel-based alloys, composites, and ceramics. The adverse effects caused by the greater temperature may be mitigated by employing the proper technique during grinding [25]. In contrast, the MQL approach is frequently employed in grinding since it can lubricate and cool the grinding zone with a small amount of cutting fluid consumption. Minimum quantity lubrication uses a little amount of oil carried by high-pressure air [26]. The MQL with vegetable oil can significantly enhance the cutting process [27], [28]. Concerning operator health and environmental pollutants, the MQL approach is unsafe due to the emission of harmful gas during the cutting process [29]. A common alternative technology is cryogenic machining, which uses liquid nitrogen (LN_2) coolant to produce a safe environment and harmless effect on health during operation [30].

The word “cryo” is a Greek word that signifies cold. Hence, cryogenics means operating in a low temperature (below -150 °C) environment [31]. Stable gases similarly hydrogen, neon, helium, oxygen, nitrogen, and atmospheric air as cryogens, on the other hand, have a normal boiling point below -180 °C. These gases have a broad category of uses such as medical, automotive, electronics, aerospace, and manufacturing, mainly for cooling purposes. It is typically referred to by the term LN_2 and is manufactured industrially through fractional distillation of liquid air. Nitrogen gas (melting at -210.01 °C and boiling at -198.79 °C) is sufficient in air, composed wherein 78.03% by the volume of the air. It is an unsavory, odourless, colourless, harmless gas and naturally recycled without harming the environment [32]. These properties of LN_2 have made it a favoured coolant. In metal cutting, the primary function of cryogenic cooling is extracting heat effectually from the contact zone, which minimizes cutting temperature, changing the frictional properties between tool and chip, and altering the properties of the tool and workpiece [33]. In order to make cryogenic machining more cost-effective, using liquid nitrogen must be minimized by applying it carefully and strategically to the cutting area. The benefits of cryogenic cooling include longer tool life, less cutting force, better surface quality, enhanced chip breaking and handling, superior dimensional accuracy, increased productivity, and lower manufacturing costs. Hence, it will be helpful to the summary of information on cryogenic cooling for better assessment of the subject in the machining process [34], [35], [36]. Fig. 1.3 shows the schematic diagram of cryogenic cooling system. A flat spray nozzle, nitrogen gas cylinder, pressure gauge, pressure regulator and dewar are clubbed with stainless steel piping to fabricate a low-cost cryogenic setup. The earlier research articles studied the cryogenic technique with LN_2 coolant in machining “difficult-to-cut” materials. They observed that LN_2 coolant is more effective in cooling than the lubrication effect [37], [38], [39].

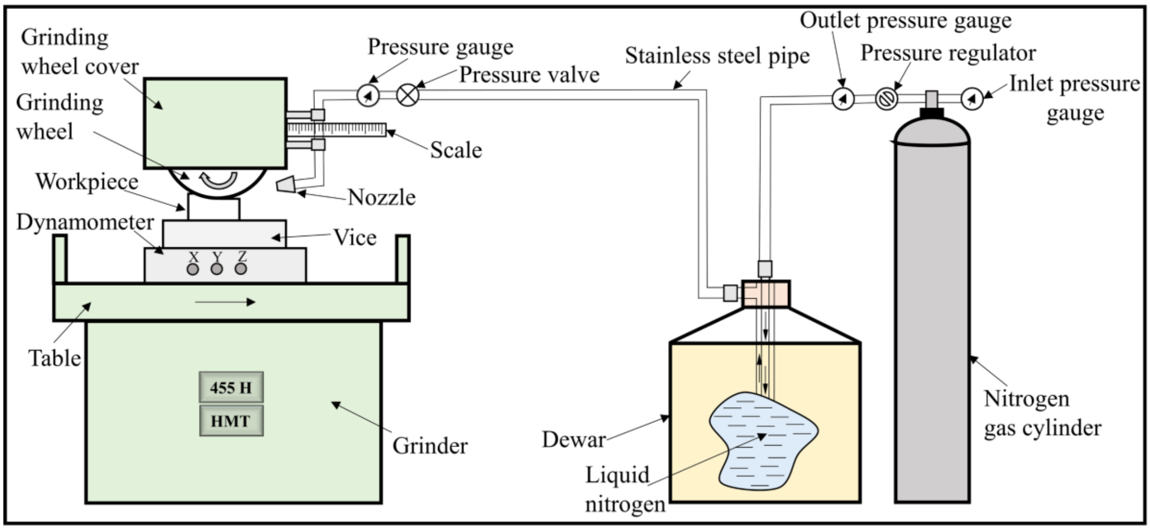

Fig. 1.3: Schematic diagram of indigenous cryogenic grinding experimental setup. "With permission from Ref. [40]".

To compensate for the significant effect of cooling and lubrication, operator's health issues, and environmental problems, the combined processing of cryogenic and MQL techniques (Cryo-MQL) is being studied. Cryo-MQL is a new eco-friendly method that produces superior outcomes with minimal quantities of cutting fluids or lubricants [41]. This method of machining combines the benefits of both cryogenic cooling and effective lubrication to improve the quality and efficiency of machining operations. A hybrid Cryo-MQL sustainable lubri-cooling technique has also been proven to enhance tool life and surface integrity in difficult-to-cut materials such as AISI 304 stainless steel, Inconel 718, Ti-6Al-4V alloys, etc., where high temperatures produced during machining, results in poor surface quality, diffusion, and adhesion wear and tool life limitations. Vegetable oil is a perfect substitute for cutting fluids in the MQL technique due to its superior thermo-physical properties, high biodegradability, and non-pollutant nature [42]. Recently, vegetable oil-based nanofluids have been developed as a promising cooling lubricant for machining. Nanofluids (NFs) are colloidal mixtures of nanomaterials, such as nanotubes, nanowires, and nanoparticles (NPs), in a base fluid. Nanofluids have enormous potential for enhancing lubricant tribological characteristics [43]. The nanomaterials can increase the thermal conductivity of the NFs, thus improving the cooling performance [44]. Therefore, improvements in surface quality and tool life, as well as a decrease in cutting forces and tool wear, were found [45], [46].

1.4 Background of the present research work

Nowadays, to stay competitive in the global market, it is essential to maximize the efficiency and effectiveness of the grinding process while avoiding issues such as thermal damage to the product, rapid wear of the grinding wheel, and long conditioning time of the wheel. For difficult-to-cut materials, the thermal damage caused by grinding can be seen in the form of oxidation on the surface, metallurgical phase changes, and the induction of unfavorable residual stresses [47]. Grinding at a high temperature can cause the abrasive grains to break down quickly, leading to fast wear on the grinding wheel and a decrease in the surface finish quality. Ultra-precision surface finishes can be achieved by grinding with superabrasive wheels [48]. Although these wheels are expensive, the complexities of truing and dressing them make their usage time-consuming, significantly raising the cost of production. Hence, the conventional abrasive wheel may be a cost-effective option for grinding difficult-to-cut materials since it is much cheaper than a superabrasive wheel. Conventional abrasive wheels continue to be the preferred alternative for grinding industries, partly because of their cheaper abrasive cost but primarily due to their ease of use. Dressing can easily give the conventional wheels desired forms, and such forms are essential for manufacturing industries. Hence, there is a chance to develop a suitable grinding process that allows for the utilization of cost-effective conventional wheels when grinding AISI D2 tool steel in an economically sound way.

The grinding process efficacy has been improved using suitable cutting fluids in wet cooling mode. However, the additional cost of cutting fluids makes the process economically non-viable. Also, many cutting fluids harm operators, machines, and materials. Water-based cutting fluids may cause staining, corrosion and produce microorganisms, leading to severe irritation and diseases like skin irritation, rashes, and asthma for the operators [49]. Additionally, the manufacturing industries are supposed to adhere to the provisions of ISO 14000 standard and zero-waste in manufacturing to minimise the negative environmental impact [50]. This concern motivates researchers to explore coolant-free or dry machining in more detail. However, in its current state, dry machining presents significant challenges for high-strength materials like AISI D2 tool steel. These challenges include generating excessive heat and rapid tool wear. Therefore, there may be more realistic solutions than dry machining since it has significant limitations. This situation has driven the development of alternative techniques that promote the minimization of cutting fluids. These environmentally friendly and sustainable approaches include cryogenic, MQL, and hybrid cooling [51]. These techniques have been implemented in turning, drilling and milling processes but have not been thoroughly investigated in the grinding of AISI D2 tool steel. Based on the economy and ecology, cryogenic cooling finds a unique position in the machining domain and has shown encouraging results in higher heat generation processes like grinding. A suitable coolant is used during cryogenic grinding. The cryogenic coolants are in the form of supercooled liquefied gases such as LN_2. However, in grinding, LN_2 captured a significant dominance, especially in the machining of steel, Ti, and Ni alloy, due to its inert behaviour and extraordinary heat dissipation capability [52]. In recent years, the use of LN_2 in grinding has increased because of its non-polluting and user-friendly nature. LN_2 can be directly discharged to the environment, which makes its application easy and economical [53]. The MQL offers another environmentally friendly approach to grinding. In the MQL technique, a small amount of coolant is mixed with compressed air and delivered to the grinding zone in mist form via a nozzle [54]. Nowadays, nanofluids are very demanding in manufacturing processes due to their better properties. The recent scenario presents the better cooling and lubrication effect under Cryo-MQL technique during the grinding operation. Cryo-MQL grinding is a hybrid cooling technique that combines the cryogenic cooling with MQL for grinding processes. A very few research articles are available in the grinding of AISI D2 tool steel under Cryo-MQL technique.

Apart from this, in modern manufacturing industries, significant investments are being made to accurately characterize surface integrity as it plays a critical role in determining the service life of ground components. The surface integrity of a ground component refers to the state of its surface after the grinding process has been completed and encompasses a range of characteristics such as surface roughness, residual stress, microcracks, and surface defects. Various analytical techniques are employed, such as microscopy, X-ray diffraction (XRD), and spectroscopy, to provide detailed insights into the surface characteristics of ground components. It is most likely to be time taking, costly and laboratory-based [55]. Hence, many manufacturing industries find a unique instrument, which can inspect the sample during online production.

Magnetic Barkhausen noise (MBN) technique is a non-destructive characterization tool. It can be easily used to evaluate surface integrity for ferromagnetic materials such as all types of steel. The MBN technique provides certain advantages, such as deep penetration, less energy consumption, faster measurement, and portability of equipment [56]. The Federal Aviation Administration and the American Society of Automotive Engineers have already acknowledged this technique. Various industries have used it in the automotive and aerospace fields relatively quickly after its endorsement [57]. Besides, the MBN technique is used for the inspection of forged camshafts at the Kalyani Centre for Technology & Innovation (KCTI), Bharat Forge Ltd., Pune, India. H. G. Barkhausen discovered magnetic

Barkhausen noise. He provided the first proof of the discontinuous nature of magnetic domain wall movement in the presence of an external magnetic field. In the 1960s and 1970s, researchers began using MBN to study stress's effects on magnetic materials. MBN analyzer works on the eddy current effect. Generally, the MBN signal is generated by the irreversible domain wall movement during the magnetization of the workpiece. When a ferromagnetic material is magnetized, domain walls strive to align in the direction of the applied magnetic field. This movement was restrained by lattice imperfections such as grain boundaries, dislocations, and precipitates [58]. An increased magnetic field is applied over a pinning wall to eliminate the obstacles. The accelerated jumps of the domain wall over the pinning wall give immediate magnetic flux fluctuations, called Barkhausen noise [59]. Last decades, many researchers utilized the MBN technique to qualitatively evaluate the characterization of microstructure like phase transformation [60], grain size effect [61], case hardening depth [62], and carbon content with different compositions [63]. Besides, this technique was utilized to detection of surface residual stresses generated at the weld joints by spiral submerged arc welding in steel [64], monitor the grinding burn in large bearing production [65], fatigue and damage of rail tracks [66], and monitor applied stress in rolling [67].

1.5 Brief overview of the present research work

AISI D2 tool steel is a well-accepted and widely utilized material in various engineering applications. Due to its properties, the machining of this material faces challenges in the grinding process. In order to enhance the widespread adoption and economic feasibility of AISI D2 tool steel, it is imperative to substantially enhance its grindability. This can be achieved by using the proper low-cost conventional grinding wheels for grinding AISI D2 tool steel. AISI D2 tool steel exhibits low thermal conductivity and high strength, causing an increased amount of heat to be generated during the grinding process. It is crucial to remove this heat rapidly to protect both the ground surface and the grinding wheel from excessive thermal exposure. Therefore, this study aims to enhance the grindability of the material through sustainable techniques, such as cryogenic coolant. The insufficiency of cryogenic coolant in providing adequate lubrication effect during the grinding of high-strength materials like AISI D2 tool steel has been observed. Therefore, it is necessary to investigate the viability of a hybrid cooling system (i.e., Cryo-MQL technique) that enhances the cooling and lubricity properties of the coolant after a small addition of ultra-fine particles. As a result, this work also discusses the application of MBN technique to enhance the surface integrity of AISI D2 tool steel. Additionally, the MBN technique is utilized for surface characterization in-line production, allowing for real-time monitoring of surface quality, and identifying any defects or irregularities.

It is concluded that the use of cryogenic and Cryo-MQL techniques, along with the MBN technique for in-line surface characterization, can significantly improve the quality and efficiency of grinding operations. Previous research studies have not yet systematically explored the evaluation of thermal damage in AISI D2 tool steel subjected to cryogenic and Cryo-MQL grinding while simultaneously utilizing the MBN technique. Thus, the current research study presents a novel approach, and the work aims to validate the applicability of the MBN technique for ground samples

1.6 Outline of the thesis

This study focuses on developing the cryogenic cooling and Cryo-MQL setup for the surface grinding process, investigating the influence of cryogenic cooling by liquid nitrogen and MQL by different lubricants with alumina grinding wheels, and comparing the advantage of cryogenic cooling and Cryo-MQL over dry, wet, and MQL grinding. This thesis regarding results and discussions is categorized into three sections. The first section deals with developing a cryogenic cooling setup for grinding and evaluating the grindability indices during dry, wet, and cryogenic environments. The second section also deals with developing a Cryo-MQL grinding experimental setup and further the performance evaluation of the grinding of AISI D2 tool steel under MQL and Cryo-MQL environments. The third section deals with the ground surface's surface integrity using the magnetic Barkhausen noise technique. The ground samples were obtained under dry, wet, cryogenic, MQL and Cryo-MQL environments.

The current work is organized into five chapters. The introduction and the related literature review are presented in Chapters 1 and 2, respectively. These chapters provide a broad view of the current research trends of cryogenic cooling, Cryo-MQL, and MBN techniques used in machining. The development of cryogenic cooling and Cryo-MQL experimental setup is discussed in Chapter 3, and this chapter also discusses the detailing of the magnetic Barkhausen noise analyzer and all instruments which are used in the characterization of ground samples. Chapter 4 presents the performance evaluation in grinding the AISI D2 tool steel work material under dry, wet, cryogenic cooling, MQL and Cryo-MQL environments. Also, this chapter presents the characterization of the ground sample using the MBN technique. The conclusions of this research are presented in Chapter 5, along with suggestions for future work.

Chapter 1: This chapter provides an overview of the work material and grinding process. It highlights the detrimental effects of temperature rise in the grinding process and discusses the limitations of conventional cooling methods. Moreover, the chapter emphasizes the necessity of implementing cryogenic cooling and Cryo-MQL in grinding operations. By reducing the temperature and enhancing lubrication, these advanced cooling techniques can significantly improve the grinding performance, increase the tool life, and enhance the workpiece quality. The chapter thus underscores the importance of adopting modern cooling methods for effective grinding operations in various industries.

Chapter 2: This chapter reviews the research articles according to the drawbacks of conventional cooling and details discussion about sustainable techniques, i.e., dry, MQL, cryogenic and Cryo-MQL. The grinding studies on work materials like AISI D2 tool steel are also reviewed. Furthermore, eco-friendly vegetable oil and nanofluids are studied in MQL and Cryo-MQL grinding processes. The literature review's last section emphasizes the importance of non-destructive characterization approaches for evaluating the surface integrity of ground components. The Barkhausen noise and hysteresis loop methods that were utilized to forecast various mechanical properties, including hardness, are also briefly discussed. In the last, the chapter concludes by addressing the research gaps and objectives of the present work.

Chapter 3: This chapter explains the experimental methods and grinding conditions on the AISI D2 tool steel using the Al_2O_3 grinding wheels. This chapter also gives information about the workpiece materials, grinding wheels, and grinding environments. The construction and working principle of the developed cryogenic cooling setup and Cryo-MQL setup are also introduced here. This chapter also deals with the novel magnetic Barkhausen noise technique. The equipment used to investigate the grinding force, grinding temperature, 2D surface roughness, 3D surface roughness, bearing area curve analysis, 2D and 3D topography (SEM and AFM images), chip morphology, microstructure and microhardness is also discussed.

Chapter 4: This chapter is divided into three sections, i.e., Sections 4.1, 4.2, and 4.3. Section 4.1 discusses the outcomes of grinding AISI D2 tool steel in dry, wet, and cryogenic cooling environments. An analysis of the experimental data related to microstructure, microhardness, grinding temperature, forces, specific grinding energy, force ratio, surface roughness, surface modifications, bearing area curve analysis, and chip morphology is done. The effect of variations in coolant delivery pressure and table feed rate affects grinding forces, specific grinding energy, surface roughness, surface functional parameters, grinding temperature, and microhardness are investigated. In conclusion, the effect of LN_2 cooling and coolant delivery pressure on the grinding of AISI D2 tool steel is compared to that of dry and wet machining.

In section 4.2, the grinding experiments were carried out on AISI D2 tool steel under MQL and Cryo-MQL environments. The lubricants' friction coefficient, grinding force, specific grinding energy, surface roughness, bearing area curve analysis, ground surface topography, microchip morphology, and grinding temperature were analyzed over the ground surface. Here, eco-friendly MQL lubricants (i.e., vegetable oil as base fluid, biodegradable emulsion, and nanofluids) and cryogenic LN_2 coolants provide better lubrication and cooling effects at the grinding zone during operation. This chapter presents a detailed description of the characterization of prepared emulsion and nanofluids and thermo-physical properties of lubricants in terms of thermal conductivity, dynamic viscosity, surface tension, density, pH value, and wettability. Also, the measuring equipment used in the present experimental research work is discussed in this chapter. The methodology involves preparing emulsions using different lubricants, such as vegetable oil, and adding nanoparticles to create nanofluids. The emulsions and nanofluids are analyzed by measuring their physical properties. This study's findings suggest that using eco-friendly lubricants can lead to improved performance and reduced environmental impact in various industrial applications.

Section 4.3 presents the novel application of the MBN technique to assess the thermal damage of a ground surface of AISI D2 tool steel work material under different environmental conditions, i.e., dry, wet, MQL, and Cryo-MQL environments at higher downfeed. It outlines various BN and HL parameters such as root mean square (RMS), peak, MBN envelope, average permeability, coercivity, and hysteresis loop (HL) profile.

The BN and HL outcomes are linked to surface properties, such as microhardness, via correlations, providing a qualitative assessment of the damage caused by thermal processes.

Chapter 5: This chapter presents the conclusions on the effect of grinding AISI D2 tool steel using alumina grinding wheels under dry, wet, cryogenic, MQL, and Cryo-MQL environments. The outcomes obtained from the MBN technique for ground samples also concluded. It also identifies potential directions for future study.