Chapter 1

Introduction

1 Introduction

AISI D2 tool steel is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium as per the ASTM A681 standard [1]. It is the most widely used steel among group D steels. It has high wear resistance, excellent toughness, and good dimensional stability. As the main constituent, iron (Fe) contains alloying elements such as Cr, Mo, V, C, Si, Mn, etc. These elements play an important role in making AISI D2 tool steel resistant and tolerant to adverse working conditions. The presence of chromium in AISI D2 tool steel improves its corrosion resistance due to the tendency of Cr to form Cr_2O_3 oxide film when heated in an oxidising environment. Likewise, molybdenum (Mo) enhances the hardenability of this tool steel at elevated temperatures by the strong binding of Mo and carbides, which tighten up carbon in the Fe-C body-centred cubic (BCC) matrix. Vanadium develops hard and thermally stable carbides, which enhance the resistance against abrasive wear. Furthermore, at high temperatures, remaining alloys can maintain excellent thermo-mechanical properties such as high thermal fatigue cracking resistance, deep hardening, tempering resistance, high strength, and toughness [2]. Because of these factors, AISI D2 tool steel is a vital material for high calibre industrial applications, namely moulds, punches, dies, commercial cutting tools, gauges, components of machinery susceptible to wear, injection screws, aerospace, automobile sectors, healthcare instruments, construction, and fabrication equipment [3]. AISI D2 tool steel finds extensive application in the tooling industry. Pressure die casting dies, stamping dies, injection moulding dies, extrusion tools, cold forging dies, cold rolling tube mill dies, and shear cutting blades are the primary applications for this material [4] [5].

Typically, feedstock procured from the market for tool manufacturing is completely annealed or has a spheroid structure and is softened. This material is not directly used for die applications. Hence, proper heat treatment is essential to enhance the wear resistance and deep hardening of material for handling the molten metal during die casting. AISI D2 tool steel is a homogenous grain matrix with primary and secondary carbides, consisting of a fully hardened and tempered process [6]. After heat treatment, oxidized scale formation over the machined surface causes changes in surface properties and slight variation in dimensional tolerance. Hence, after machining it is necessary to achieve the excellent surface quality of the component. However, the machinability of hardened tool steel is very low compared to different ferrous and non-ferrous alloys. On the contrary, the high strength, rapid work hardening, and low thermal conductivity of hardened AISI D2 tool steel make it difficult to machine. Therefore, it is recognised as a “difficult-to-machine” material and possesses a machinability rating close to 30 on a scale of 100 [7]. For difficult-to-machine materials, grinding has become a more cost-effective solution than other machining techniques. Surface and profile grinding are the most often employed machining techniques in the tooling and die industry for producing excellent surface quality and high precision on cavity profiles and upper and lower die meeting sides.

Grinding is commonly employed as a final machining operation in the manufacturing of components in order to achieve good dimensional and form accuracy while maintaining acceptable surface integrity. Grinding's high order surface finish is a result of the significantly smaller chip size compared to other machining techniques. While the energy partition often runs between 60% and 85%, grinding is more likely to be referred to as a thermo-mechanical process than a mechano-thermal process. According to Malkin, grinding accounts for 20-25% of the overall expenditures incurred in machining processes [8]. This enormous expenditure led to the implementation of grinding in several manufacturing industries. In contrast to other machining operations, grinding is regarded to be a costly operation due to the increased specific energy required [9]. The greater specific grinding energy may be addressed by size effect theory. This theory proposes that, during deformation, very small grinding chips have proportionately more strength than large ones, resulting in extremely high dislocation densities in the shear zone, which increases grinding energy [10]. In addition, the grinding mechanism adds considerably to the particular energy demand. A significant percentage of the given energy is used by unwanted sliding and ploughing mechanisms as opposed to the beneficial cutting action, resulting in a higher specific grinding energy [11]. The repercussions of the above-mentioned mechanisms were mechanical, chemical, and thermal in character, causing plastic deformation even in subsurface [12]. In addition to the above, the energy requirement for plastic deformation is very high when accomplished under large strains and at higher strain rates, which thus increases the energy requirement [13].

The majority of the energy used in grinding is transformed into heat, which is absorbed by the ground sample. This is due to the rapid microchip formation caused by the high grinding wheel velocity and strain rate, which does not allow enough time for the microchip to take away a significant amount of heat from the grinding zone. This high temperature can damage the surface integrity of the ground surface, resulting in grinding burns, poor surface quality (dimensional and geometrical accuracies), uneven cracks, phase transformations, microhardness variation, and the induction of detrimental tensile residual stresses in the sub-surface layer [14]. Surface integrity can be described as the evaluation of the effect of grinding on the physical characteristics of the ground sample, which often entails the research of surface topography and sub-surface evaluation. The group of surface topography consists of surface roughness, waviness, form error, and flaws. Subsurface evaluation includes plastic deformation, residual stresses, cracks, hardness, recrystallization, and phase changes [15]. Excessive heat load in the grinding zone has a substantial effect on the aforementioned elements of the surface integrity of the ground workpiece. To overcome these concerns, grinding temperature must be reduced by proper lubrication and cooling.

Cutting fluids have been used for years to enhance grindability by decreasing the amount of heat generated at the grinding zone. The application of cutting fluids resulted in good cooling at the interface of the grinding wheel and the work material, enhanced lubrication characteristics, and decreased grinding power consumption. About 640 million gallons of cutting fluid are used around the world every year, according to estimates [16]. Yet, 85% of these machining fluids are petroleum-based cutting fluids, which are derived from the extraction of non-renewable crude oil [17]. In the surface finishing process, the grinding of "difficult-to-machine" materials may result in a 20–30% increase in the cost of cutting fluid due to the demand for large quantities of cutting fluid to remove heat from the grinding zone [18]. In addition, storing, reusing, and disposing of a large quantity of cutting fluid incurs substantial expenses. Cutting fluids are petroleum-based, nonbiodegradable oils. As a result, the disposal cost of cutting fluids may be two to four times the purchase price. In addition, expensive equipment is needed for their disposal [19]. Conversely, petroleum-based cutting fluids have the potential to have harmful impacts on both the environment and machine operators' health, including skin cancer, lung cancer, respiratory illnesses, dermatological conditions, and genetic diseases [20]. As per reported statistics, machine operators' constant usage of cutting fluid is responsible for 80% of their skin-related problems [21]. As stated by the survey of the National Institute for Occupational Safety and Health (NIOSH), more than 1.2 million machine operators across the globe are already experiencing the toxicological consequences of cutting fluid [22]. The inclusion of chlorinated chemical additives in cutting fluid generates a very hazardous dioxin environment under harsh grinding parameter circumstances of high temperature and pressure.

In traditional grinding, cutting fluids are provided at high pressure and flow rate to improve cooling and lubrication in the interface region. Nevertheless, cutting fluid can enter the elastic grinding zone, but accessing the plastic grinding zone is more difficult. The hydrodynamic boundary layer surrounding the grinding wheel creates a wedge effect between the ground surface and the peripheral surface of the grinding wheel. The minimal distance between the grinding wheel and the ground surface and the grinding wheel velocity are inversely correlated to the hydrodynamic layer's thickness. The distribution of hydrodynamic pressure is uniform over the grinding wheel's width [23] [24].

Therefore, this causes severe economic and environmental sustainability concerns. Also, current environmental laws, such as ISO 14000, have become more rigid in encouraging green manufacturing standards. This perplexing situation led to the development of novel, eco-friendly, efficient, and socially viable machining techniques for the grinding of AISI D2 tool steel. Green manufacturing involves exploring techniques that are economically sound, safe for workers and society, waste-free, and minimize negative environmental impacts [25]. By utilising such methods, organisations can ensure the sustainability of their operations and reduce the impact of their activities on the environment. In the grinding field, different environmentally friendly methods are used, including conventional dry grinding (CDG), cryogenic grinding, minimum quantity lubrication (MQL), ultrasonic vibration assisted grinding (UVAG), and ultrasonic vibration assisted minimum quantity lubrication (UVAMQL) grinding. Dry grinding is one such technology that may completely remove the usage of cutting fluid during the shearing operation and is more environmentally friendly than conventional wet grinding (CWG). Nevertheless, dry grinding as it now exists may not provide an accurate result since it generates a lot of heat, loads the wheels quickly, and affects the surface integrity of the ground surface, particularly when grinding "difficult-to-machine" materials [26]. Besides, cryogenic grinding has increased grinding wheel life and provided a great cooling effect in the grinding zone owing to shearing action conducted on work material at -196 °C using LN_2 medium. Yet, this technique has a negative impact on grindability indices. The worn-out abrasive grits appeared to be retained by the strong bond. Therefore, the removal of material in the form of a microchip includes extensive ploughing and rubbing rather than shearing, resulting in more power consumption. Cryogenic grinding produces a very rough ground surface [27]. The MQL technique is an integration of cutting fluid and compressed air to form a coolant mist that can improve the ability of fluids to reduce heat and friction in grinding. Generally, in this technique, the flow rate of cutting fluid varies in the range of 50 to 500 ml/h [28]. However, the cooling performance of MQL is not always found to be satisfactory, and it has a serious thermal problem in grinding operations due to the small amount of cooling [29] [30]. In addition, when mineral oils or synthetic oils are used as cutting fluid in MQL, the resulting aerosol contains very small particles that can pose serious health and environmental risks if they are not efficiently controlled [31]. The effect of aerosol due to atomization leads to serious risks of colon, pancreas, rectum, esophagus, and prostate cancers [32]. Hence, UVAG occupies a unique position in the machining domain and has demonstrated promising results in higher heat generation processes such as grinding.

The UVAG is a composite technique that involves conventional grinding with ultrasonic vibration, and it has been used to produce an efficient and sustainable grinding process for materials that are ‘‘difficult to machine,’’ due to the superior surface integrity, lower grinding forces, and lower heat generation [33]. In UVAG, vibrational energy produced via the ultrasonic transducer is of higher frequency in the range of 16–40 kHz and the lower amplitude of vibration in the range of 2–30 μm in the longitudinal or transverse direction toward the workpiece or the grinding wheel [34]. Another benefit of the UVAG technique is that the machining long continuous grinding chips were split into short discontinuous grinding chips with thinner, shorter morphologies, and both the work surface and the microchips remain in a dry condition that is easier to handle and dispose of [35]. UVAG is another way to make MQL grinding more efficient. The effective immersion of cutting fluids in the grinding zone in MQL grinding limits the extensive application of this technique, and ultrasonic vibration can exert a pumping effect that injects MQL cutting fluids into the interface between the grinding wheel and workpiece [36]. Furthermore, there seems to be no interference in their respective influence mechanisms. However, the combined use of both techniques, known as ultrasonic vibration assisted minimum quantity lubrication (UVAMQL), has been reported in very limited literature so far. Vegetable oil is an ideal replacement for petroleum-based cutting fluids in the UVAMQL system due to its excellent physical and chemical properties with high biodegradability and non-pollutant nature. Besides, straight vegetable oils also develop a high strength lubricant layer, which interacts strongly with the metallic ground surface, resulting in reduced friction and wear. The previous research groups adopted UVAMQL grinding with straight vegetable oil in the surface grinding of "difficult-to-machine" materials i.e., titanium alloy [37]. They reported that UVAMQL provided effective lubrication in grinding zone but insufficient work material cooling because of poor heat transfer rate of vegetable oil. The recent advancement of nanofluids and biodegradable emulsions offers an alternative to straight vegetable oils, which can be used in the UVAMQL system. The excellent heat transfer and tribological properties of these nanofluids and emulsions can provide effective cooling and lubrication in UVAMQL grinding.

In addition to advanced sustainable grinding techniques, the surface integrity characterisation of the ground surface is also a significant factor, particularly from an economic and quality assurance standpoint. Modern grinding industries are spending substantial amounts of money on the characterization of surface integrity because it has a significant impact on the service life of the ground component. Conventional testing procedures, including microstructure inspection, X-ray diffraction (XRD), and microhardness measurement, are expensive, may compromise the ground surface, and are laboratory-based techniques that cannot be used for on-line quality evaluation of components on the shop floor [38]. Chemical inspection techniques were once widely employed in the manufacturing industries because of their inexpensive cost of setup. Nevertheless, stricter environmental rules limit the use of acid etching, which increases the cost of the process because the procurement and disposal of hazardous waste need a greater initial expenditure. Moreover, the etching process is time-consuming, and materials attacked by acid etch require additional heat treatment to prevent hydrogen embrittlement. The XRD method for determining residual stress is a more precise and quantitative method. In addition, it is more time-consuming and expensive; hence, its practical applicability is limited to incredibly small areas. However, evaluation of the residual stress profile involves removal of the surface layer through electropolishing, a destructive operation [39]. Thus, manufacturing industries continue to seek out rapid, cost-effective, dependable, and non-destructive solutions to monitor thermal damage on the production line itself [40].

The magnetic Barkhausen noise (MBN) method is a preferable alternative to conventional testing. It is a practical, dependable, and quick way for detecting large manufacturing volumes. This unique approach has already been accepted by the Federal Aviation Administration and the American Society of Automotive Engineers, and in a relatively limited period of time after its endorsement, it has been implemented by a number of industries in the automotive and aerospace sectors [41]. In addition, the Kalyani Centre for Technology and Innovation at Bharat Forge Ltd., Pune, India, uses the Barkhausen noise technique to evaluate forged camshafts. German physicist Professor Heinrich Barkhausen discovered MBN. Nonetheless, the Finnish scientist Titto was the first to attract attention to the practical applicability of the technique. MBN influence is characterised by discontinuous magnetization jumps during magnetization and demagnetization of a ferromagnetic material resulting from obstructions in magnetic domain wall propagation, elongation, and rotation [42]. During magnetization and demagnetization of a ferromagnetic material subjected to an alternating magnetic field, the magnetic domain walls move in the direction of the applied magnetic field. Crystal defects, grain disorientation, grain boundaries, contaminants, and dislocations impede the movement of magnetic domain walls [43]. This discontinuous movement of the magnetic domain wall generates Magnetic Barkhausen noise, which may be detected as a voltage pulse created in a magnetic sensor, i.e., a pick-up coil. In the past few years, the MBN method has emerged as a viable non-destructive tool for the characterization of microstructures such as phase changes [44], grain size effect [45], case hardening depth [46], and carbon content with varying composition [47]. In addition, this technique was applied to the detection of surface residual stresses generated by spiral submerged arc welding in steel [48], the monitoring of grinding burn in large bearing production [49], the fatigue and damage of rail tracks [50], and the monitoring of applied stress in rolling [51].

Ultrasonic vibration assisted grinding provides relatively better surface integrity, and the MBN technique is an effective surface characterization for in-line production. Researchers across the globe are currently working individually either on UVAG or on MBN, whereas integrating UVAG with MBN analysis may lead to efficient grinding with rapid characterization of the ground sample in terms of its surface integrity. In addition, prior researchers have not undertaken a systematic study assessing the thermal damage of AISI D2 tool steel under UVAG and UVAMQL grinding in conjunction with the MBN technique. Considering the preceding, this work integrates UVAG and UVAMQL with the MBN method and demonstrates the applicability of MBN for ground samples employing ultrasonic vibration assisted grinding.

1.1 Introduction of grinding process

The growing demand for high-quality products can be attributed to increased customer awareness and globalization in recent years. High surface quality products are necessary for many critical applications. The grinding process has the ability to produce products with high dimensional accuracy and surface quality compared to other traditional machining methods. However, machining techniques such as turning and milling of advanced engineering materials or "difficult-to-machine" materials are often linked with high machining costs and low productivity. This is due to excessive heat generation at the cutting zone, difficulties in heat dissipation due to low thermal conductivity, strain hardening, and the high chemical affinity of these materials. As a result, excessive tool wear, high cutting forces, difficulties in chip formation, increased surface roughness, and poor surface integrity of machined components are observed. Therefore, the grinding process is employed to improve the excellent surface integrity of "difficult-to-machine" materials.

Grinding is a highly effective method of material removal and abrasive machining, whereby hard and sharp abrasive grits are firmly held in circular wheels by a bonding material. As these wheels rotate at high speeds, the abrasion of the grits creates microchips that remove the material; this process is clearly illustrated in Figure 1.1. Using abrasive grits to shape metal components and stones dates back more than two thousand years. Using abrasives to sharpen early blades, tools, and weaponry. Moreover, abrasives were used to shape and cut stones for the construction of houses and pyramids. During the last few decades, abrasives have been utilised in an increasing variety of areas, and the abrasives industry is essential to the existence of a significant portion of contemporary technology. Around 1860, the

Brown & Sharpe Manufacturing Company in the United States designed and manufactured the first modern grinding machine for finishing sewing machine parts, hardened precision bearings, and gears [8]. Throughout the 20th century, however, the grinding process became an important topic of researcher interest, and it is today recognised as a very valuable and demanding technique for the production of high strength engineering materials. Currently, grinding is a significant manufacturing operation, accounting for about one-fourth of all machining costs throughout industrialised nations. Grinding played a crucial role in the production of cutting and forming tools such as drill bits and milling cutters, as well as in the development of bearings, transmission components, measuring instruments, astronomical instruments, and micro-electronic devices such as intricate silicon wafer plates [52].

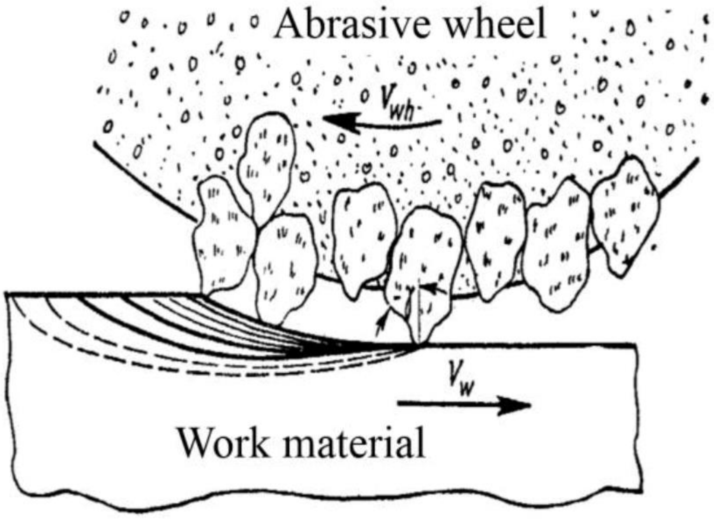
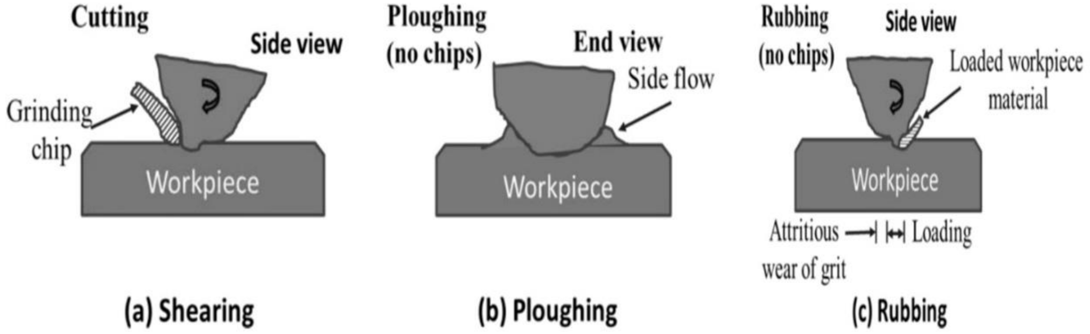


Figure 1.1 Cutting action of abrasive grits over work material [8]

1.2 Mechanism of material removal in grinding

In the grinding process, material removal actually takes place by the cutting action of hard abrasive grits of varying shape, size, and geometry. As seen in Figure 1.2, microchip generation in grinding is caused by a combination of shearing, ploughing, and rubbing operations in ductile materials. Shearing is the cutting operation responsible for the production of microchips and ultimately material removal. Ploughing is the displacement of the work material sideways or in front of the abrasive grits by a high negative rake angle of randomly oriented abrasive grits, whereas rubbing is the slide of worn-out or round grits across the surface of the work material without metal cutting. Rubbing is an entirely frictional process that converts more energy into heat [53]. In the grinding process, a large number of hot, microscopic chips are generated and frequently deposited in the inter-grit area, which alters the grit geometry so that a greater number of grits become blunt, resulting in ineffective material removal. Hence, the specific energy needs of grinding are significantly higher than those of traditional machining techniques. In addition, cutting fluid plays a crucial role in the grinding process by removing heat from the cutting zone.



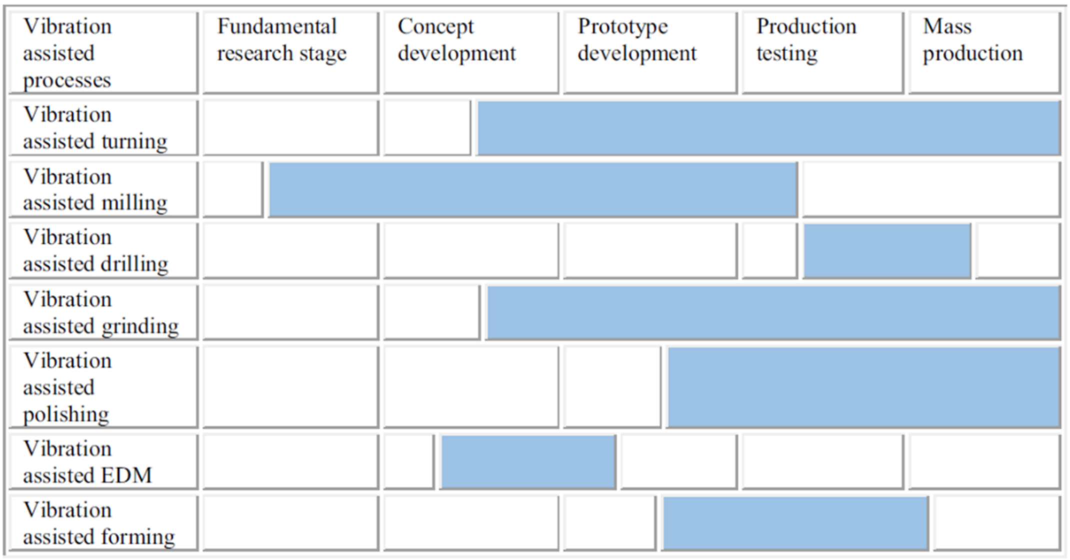
(a) Shearing (b) Ploughing (c) Rubbing

Figure 1.2 Schematic representation of the grinding mechanisms [52]

1.3 Fundamentals of ultrasonic vibration assisted grinding (UVAG)

Ultrasonic wave resembles a harmonic wave that propagates at a frequency of greater than 20 kHz, which is above the usual hearing range of human. These ultrasonic waves can propagate in a solid, liquid and gas medium that depends on their natural elastic characteristics as well as densities [54] [55]. The ultrasonic vibration produced by the harmonic wave excites little displacements of the particles of the medium from their equilibrium position. The developed mechanical vibration can propagate like a wave travelling to different sections of the medium. The ultrasonic wave and its propagation can affected by various parameter like frequency, pressure, wavelength, velocity, power and amplitude [55]. The frequency of the ultrasonic wave is the number of complete oscillations that an individual molecule undergoes per second. The intensity of ultrasonic vibration is determining by ultrasonic amplitude and frequency, that is, the measure of energy passing through the area per unit of time. The most vital criteria to accomplish adequate supply of mechanical vibration for the processing of the materials. It is necessary to render reliable contact among the oscillation component of the ultrasonic generator and media such as sonotrode or horn, tool or workpiece holder, ultrasonic probe and ultrasonic vibration setup [56]. The thought of implementing ultrasonic oscillation to enhance the process performance was formed an early as the 1920s by Wood Loomis [57]. After then, the application of ultrasonic vibration in various manufacturing processes has been widely considered. As compared through different low frequency vibrations, ultrasonic vibration holds a much higher frequency than a manufacturing system's natural frequency. Thus, ultrasonic vibration can support or enhance the system's stability without adding harmful low frequency vibrations in the manufacturing system [58] [59] [60]. The implementation of high frequency vibration with low amplitude on the tool-workpiece interface, which results in making the process discontinuous [61]. Therefore, compared to traditional machining, the materials removal mechanism is different principally due to the difference in cutting characteristics.

UVAG is a sustainable hybrid manufacturing technology that offers multiple benefits, including reducing the negative environmental impact of coolant, lowering manufacturing costs, and improving surface integrity. The process of UVAG employs the vibratory energy generated by an ultrasonic transducer to create a vibratory impact on either the workpiece or the wheel [62]. High-frequency vibrations ranging from 16–40 kHz and low amplitude vibrations ranging from 1 to 30 µm are superimposed on the movement of the wheel or workpiece [25]. The UVAG process has demonstrated significant improvements in reducing grinding forces, thermal damage, wheel wear, surface roughness, and noise [63]. It has demonstrated immense potential in the machining of "difficult to machine" materials. During the machining of "difficult-to-machine" materials, ultrasonic vibrations are being combined with various traditional machining techniques in order to improve the performance of the process. A few hybrid techniques like UVAG have made significant progress and are currently employed in the industry for the mass production of components. The UVAG may be observed being used at many phases of product development, from concept development to mass manufacturing. The UVAG technique has achieved popularity in industry because of its better accuracy and capability of producing nearly flawless surfaces. The advancements in hybrid ultrasonic machining processes are depicted in Figure 1.3 [64].



Vibration assisted processes	Fundamental research stage	Concept development	Prototype development	Production testing	Mass production
Vibration assisted turning		▨	▨	▨	▨
Vibration assisted milling	▨	▨	▨	▨	
Vibration assisted drilling				▨	▨
Vibration assisted grinding		▨	▨	▨	▨
Vibration assisted polishing			▨	▨	▨
Vibration assisted EDM		▨	▨		
Vibration assisted forming			▨	▨	▨

Figure 1.3 Advancements in hybrid ultrasonic machining processes [64]

Ultrasonic vibration was first used in machining in the 1950s; since then, it has been used in different machining processes to machine different kinds of super-hard materials [62] [65] . Also, in the early 1980s, the challenges faced in machining "difficult to machine" materials led researchers to investigate the potential use of ultrasonic grinding as an alternative machining technique. This was motivated by findings that demonstrated a significant increase in tool lifespan when using ultrasonic grinding to machine materials such as stainless steel, glass, or ceramics, and increased tool lifespan provides a cost-effective benefit while the machining process[66] [67].

1.3.1 Ultrasonic vibration assisted grinding system: basic elements, classifications, processing principle, and kinematics

An adequately designed ultrasonic vibration system performs an essential role in ultrasonic vibration assisted grinding. The basic elements of a standard ultrasonic vibration assisted machining system consist of an ultrasonic generator (power supply), controller, transducers or actuators, booster, and horn or sonotrode and work or tool holder. A transducer converts electrical energy to mechanical vibrations, which are then passed through the booster. The booster transforms the vibration amplitude delivered by the transducer to the amplitude value required by the horn. The booster is connected between the transducer and horn to achieve variations in amplitude that cannot be achieved by the horn alone.

1.3.2 Ultrasonic: power supply

The most significant component found in the ultrasonic grinding system is an ultrasonic generator. The ultrasonic generator is used to convert the alternating current from a lower frequency (50/60 Hz) to a higher frequency, almost 20 kHz [34]. More accurately, the power source of the ultrasonic machine tool is described as a high-performance sinus generator that allows users to control both the frequency and power of the signal produced. UVAG systems with high accuracy, dependability, and application are advantageous for UVAG technology advancement in the manufacturing sector. The focus of the study is on ultrasonic power supplies and vibration systems [68]. The ultrasonic power supply requires continuous amplitude control and automated frequency monitoring, among other things. The vibration devices' resonance frequency changes as the load and wheel wear vary. The ultrasonic auxiliary system operates in an untuned condition in the lack of a feedback mechanism. Because the ultrasonic power supply's output is primarily transformed into heat, the amplitude of the ultrasonic vibration system is considerably decreased, if not eliminated. The ultrasonic vibration aiding effect vanishes. The ultrasonic power supply must be managed and adjusted for the system to function correctly. Hence, some articles regarding this perspective have been reviewed in this section. To ensure continuous vibration amplitude, the research [69] employed a phase-locked loop piezoelectric transducer. When compared to the traditional approach, the phase-locked loop technique exhibited an improvement in constant current. Then, to eliminate cross talking between the two directional vibrations, a unique feedback control mechanism was created to stabilise the ultrasonic elliptical vibration [70]. Gao et al. [71] showed that the vibration amplitudes and phase differences are considered constant, and the average resonance frequency of this control system is effectively pursued. A sensor-less approach for tracking and controlling the frequency and amplitude of ultrasonic vibrations while machining is described as an alternative to employing vibration sensors. Since the natural frequencies of ultrasonic vibration actuators change with different cutting load disturbances during machining, this approach prevents the amplitudes of supplied vibrations from deviating from the intended reference values. Furthermore, the load impact on the vibration effectiveness of the giant magnetostrictive rotary ultrasonic machining system was investigated to study the influence of load effect on amplitude stabilization [72]. Because of the load, the giant magnetostrictive rotary ultrasonic machining system actual resonance frequency raised and diverged from the ultrasonic power supply's resonant frequencies, resulting in a drop in the giant magnetostrictive rotary ultrasonic machining system absolute ultrasonic amplitude. Moreover, Zhao et al. [73] investigate a dynamic model and the impacts of thermo-mechanical stress on the ultrasonic vibration system's vibrational properties. When the static stress increased, it was discovered that the ultrasonic amplitude raised at first, then reduced. The heat impact was also considered when the static load increased, and the ultrasonic frequency followed the same trend as the ultrasonic amplitude.

1.3.3 Ultrasonic transducers

Being an energy output system, transducers convert electrical energy into vibrational mechanical energy to stimulate the vibration stage. This provides to the range of ultrasonic frequency and vibration amplitude and the precision of the movement of the vibration stage. At present, there are two kinds of transducers, specifically, piezoelectric and magnetostrictive transducers are primarily chosen for vibration systems. This segment presents comprehensive information of specific transducers, including their pros and cons. Piezoelectric transducers are broadly utilised, particularly in high power applications (refer to Figure 1.4). Piezoelectric transducers utilise the novel piezoelectric characteristics of piezoelectric ceramics to change high-frequency electrical energy into vibrational mechanical energy for ultrasonic vibration amplitude. In comparison with different kinds of transducers, they have the features of economical cost, simplistic fabrication, miniature size, quick response, significant control accuracy, the absence of magnetic and electrical fields. Furthermore, a non-electromagnetic barrier enhances system durability and drives adaptable designs of oscillation tools.

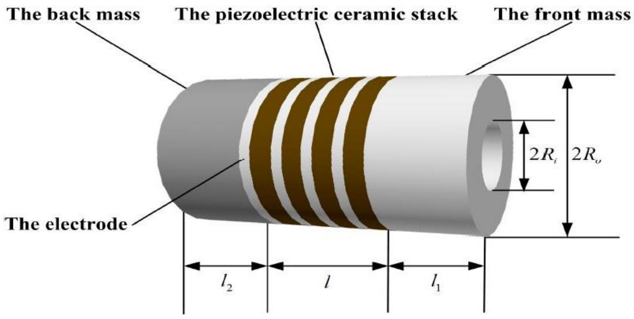


Figure 1.4 Diagram of a sandwich piezoelectric ultrasonic transducer [74]

Different kinds of piezoelectric transducers, such as sandwiched, flat plate, rod, and bimorph types, have been produced for various purposes [74] [75]. Analyzing parameters like displacement yield, stiffness, and frequency response, sandwiched kind piezoelectric transducers composed of several parts of piezoelectric ceramic plates, which attached in series mechanically and electrically joined in parallel are normally kept in real oscillation systems. Piezoelectric transducers can convert electrical energy into vibrational energy at 96% efficiency and therefore do not need cooling. [76]. The technology of ceramic piezoelectric transducers was not fully developed until the mid-1960s. The magnetostrictive transducer was the highly powerful and reliable ultrasonic transducer available and was used in every ultrasonic vibration system. When ferromagnetic materials are magnetized by applying the electrical current to the electromagnetic coil, an expansion happens, which result in vibrations at the applied frequency. However, the magnetostrictive transducer is a reliable source for ultrasonic vibration. Nevertheless, the primary disadvantage of the energy conversion efficiency is only 20% to 35% due to eddy current losses[76]. Hence, water cooling is required to displace excess heat from the transducer, which makes it bulky. The magnetostrictive transducer is typically used in ultrasonic vibration devices that need lower frequency and higher vibration amplitude [77].

1.3.4 Ultrasonic boosters and horn or sonotrode

The booster is implemented basically to amplify the amplitude of vibrations generated at the end of the transducer and further transmit them to horn or sonotrode, and it is made of aluminium or titanium. To operate the booster successfully, it must be either one half of a wavelength of material (from which it is fabricated) or multiples of this length. Usually, it is a half wavelength. Further, Kumar et al. [78] stated that the booster, also known as an amplifier, is an optional component of the ultrasonic system assembled between the transducer and the horn. The primary purpose of the booster is to either enhance or de-amplify the amplitude at the horn's end, based on the application. Different boosters provide an appropriate gain ratio based on application. There is six standard colour codes classification of boosters to distinguish them easily [79], as shown in Figure 1.5 the colour of body and colour of the ring for aluminium and titanium boosters, respectively.

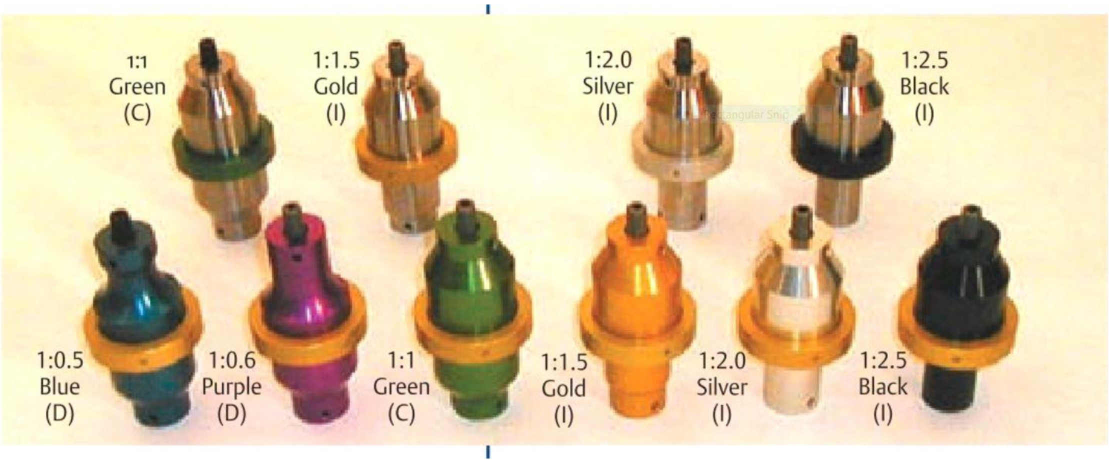


Figure 1.5 Classification of the booster based on seven colour codes and their gain ratio (upper row: titanium and lower row: aluminum) (D = amplitude decreasing; C = coupling, no change; I= amplitude increasing) [79]

The boosters are available for different range of vibration amplitude. The gold colour code booster is employed for slightly higher amplitude (one-inch diameter or larger), and the green, purple, blue colour code booster used for small components. The silver and black colour code boosters are known as a high gain booster. Further, Paktinat and Amini [80] implemented a booster to increase and transfer the mechanical vibrations to the horn for ultrasonic assisted drilling operation.The ultrasonic transducers produce the vibration with a resonant frequency of approximately 20 kHz and higher. The displacement of the generated ultrasonic vibrations is incompetent for the fulfilment of the machining operation. To subdue those issues, the amplifying waveguided components of the ultrasonic vibration assisted machining devices are combined with the transducer to obtain the required vibration amplitude range. The waveguide concentrating equipment recognised as ultrasonic horn or sonotrode is attached to the end of the transducer. The horn transmits the longitudinal ultrasonic vibration to the workpiece or cutting tool to achieve the expected machining operations. The machining characteristics of ultrasonic system devices basically depends upon the proper design of the horn [81]. Consequently, the horn has to design and manufactured for oscillating at the resonance frequency, and the influence of significant horn dimensions on natural frequencies and mode shapes is investigated by model analysis using the finite element analysis (FEA). Adopting FEA, different ultrasonic horn configurations can be designed and optimized at a specific oscillation frequency. The different types of horn profiles are used in the ultrasonic vibration assisted machining process, such as stepped, tapered, exponential and cylindrical [82] [83] . Lately, the Bezier horn profile has also been reported in the literature [84] [85]. The materials used to fabricate ultrasonic horn have good wear resistance and suitable acoustic properties to transfer the ultrasonic waves efficiently. The ultrasonic horn is commonly fabricated by using titanium based alloys [81] [86], steels [87] [88] and aluminium alloys [82] [89]. The selection of the horn profiles and their materials depends on the ultrasonic vibration assisted machining processes for which they will be used.

1.3.5 Classification of UVAG system

The UVAG process can be categorised into two modes: ultrasonic vibration superimposed on the grinding wheel or on the workpiece. Based on which mode is used to vibrate the grinding wheel or workpiece, the UVAG technique can be classified as either a one-dimensional (1D) or two-dimensional (2D) UVAG process. The effectiveness of ultrasonic grinding is substantially greater when vibration is superimposed on the workpiece, owing to changes in the mechanical characteristics of the material, such as decreases in yield points, strength, and resistance to plastic deformation [90]. The term 1D-UVAG refers to a phenomenon where ultrasonic vibrations are applied either parallel or perpendicular to the rotational axis of a grinding wheel [91]. Research has indicated that the 1D-UVAG process's operational and performance features are significantly impacted by the orientation of the oscillations. These oscillations can either be transverse or longitudinal, following the feed direction. The type of vibration along the wheel's axis is known as 1D axial-UVAG, while the perpendicular vibration is referred to as 1D vertical-UVAG. According to research [91] [92] , the axial type has been shown to yield better surface roughness and fewer deformations on the workpiece surfaces compared to the vertical type [93]. According to reports, the grinding forces decreased when 1D vertical vibrations were introduced during the grinding process [94] [95]. Previous researchers have reported that the 1D axial UVAG exhibits superior performance in terms of accuracy and tolerances when compared to the 1D vertical-UVAG [96] [97]. Also, the 1D axial UAG demonstrated a significant increase in tool wear and a decrease in surface quality [95].

The 2D-UVAG method involves the use of two-axis vibration to induce an elliptic or circular shape on the workpiece [98] [99]. The elliptical-UVAG, also known as 2D-UVAG, employs the simultaneous activation of ultrasonic vibrations of the workpiece material in two horizontal directions. The setup functions in such a manner that vertical vibrational movement is combined with the horizontal linear motions of the 1D-UVAG. As the workpiece moves in the cutting direction, it undergoes a repetitive motion characterized by a series of ellipses that overlap each other, and this motion is created by the workpiece material displaying a small circular or elliptical shape of movement. The complexity of the motion required by the 2D-UVAG system leads to a more intricate and expensive design compared to the 1D-UVAG system [62]. Also, the initial setup cost for the 2D-UVAG system is considerably high, making the 1D-UVAG system more economically viable [94]. Therefore, the 1D-UVAG system remains more preferable and cost-effective [37].

1.3.6 Kinematics of abrasive grits during UVAG

It is crucial to examine the abrasive grits and workpiece's motion for analyzing the mechanism of UVAG. In UVAG, there are three types of movement: rotational motion of abrasive wheel, worktable feed rate motion, and ultrasonic vibration along the longitudinal feed direction. The repetitive back and forth motion of the workpiece due to ultrasonic vibrations amplitude, which is longitudinal to the feed direction and takes it to sinusoidal path of the abrasive grit on the workpiece surface. The representation of a ground surface can be approximately described by peaks and valleys of the surface. In the UVAG mode the active abrasive grit come into contact side by side with the peaks. UVAG quietly and with comparatively lower forces changes and wipes out those peaks. Though, during conventional grinding the active abrasive grit must drive the material ahead and this material is sustained by the material blocks standing before it, in the process of chip formation. This is the reason why ultrasonic vibration assisted grinding produces less plastic deformation than conventional grinding. As Figure 1.6 (a-b) represents the schematic of UVAG grinding and motion of the single active abrasive grit in different grinding domains on workpiece surface. As demonstrated in Figure 1.6 (b), the path of conventional grinding is linear, while ultrasonic grinding pursues a sine waveform path due to the ultrasonic vibration on the workpiece.

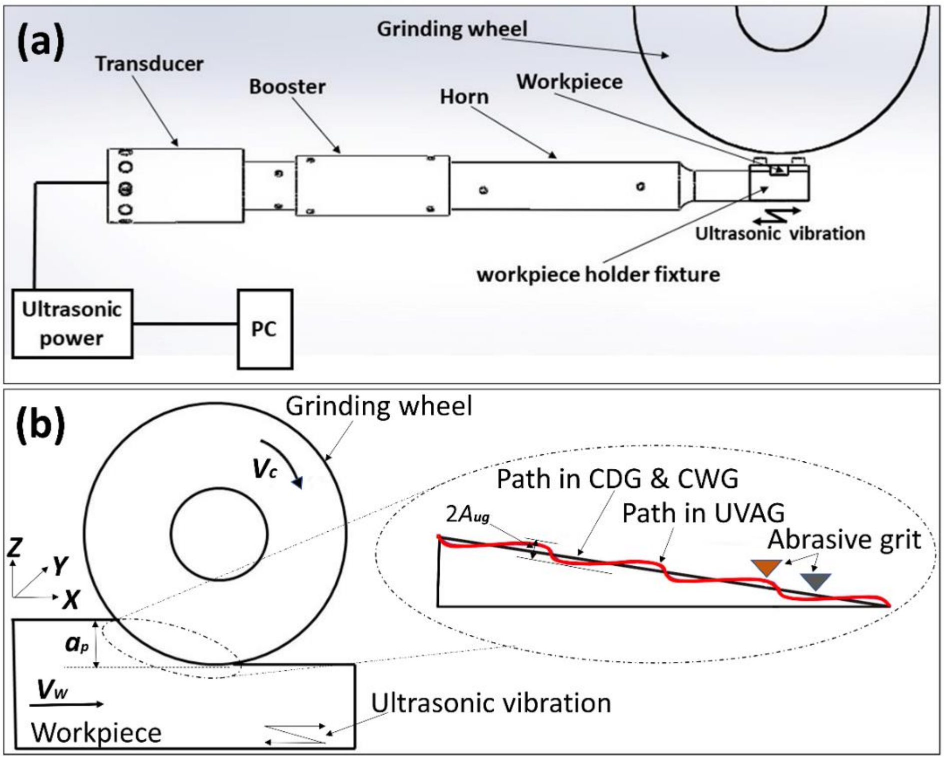


Figure 1.6 (a) Schematic of UVAG grinding,
(b) Kinematics of abrasive grit in different modes of grinding

The direction of ultrasonic vibration is tangential to the worktable feed rate. The ultrasonic vibration assisted grinding process has a periodic reciprocating motion, which results in the discontinuous cutting action of abrasive grits. The velocity component of the abrasive grain under a UVAG mode can be shown mathematically from equations (1.1) and (1.2):

$$V_{c_x} = (-1)^{n'} \times V_w + V_c \times \cos(\omega \times \tau) + 2\pi f_{ug} \times A_{ug} \cos(2\pi f_{ug}\tau + \beta_0) \qquad (1.1)$$

$$V_{c_y} = V_c \times \sin(\omega \times \tau) \qquad (1.2)$$

Where, n' = 0 for down grinding and n' = 1 for up grinding. Further, V_{c_x} and V_{c_y} are the horizontal and vertical components of abrasive grain velocity in UVAG at time τ. The ultrasonic vibration amplitude is A_{ug}, and the vibration frequency is f_{ug}. The grinding wheel's linear and angular speeds are V_c and ω. The worktable feedrate V_w and initial phase angle β_0.

1.4 Thesis organization

The thesis is comprised of eight chapters, with the Introduction serving as Chapter 1.

Chapter 2 discusses the literature review, which has been split into seven sections. The first section emphasises the significance of the grinding process, particularly in the domain of manufacturing. It covers details of the literature dealing with the surface grinding of "difficult-to-machine" materials using different grinding wheels. Further, it covers a detailed discussion about the mechanism of material removal, the function of cutting fluids, and the ecological issues of petroleum-based cutting fluids. The second section includes sustainable grinding techniques such as dry, cryogenic, MQL, UVAG, and UVAMQL grinding. The third section deals with the modelling and simulation of the grinding process. The fourth and fifth sections of the literature review address UVAG and UVAMQL grinding. The sixth section of the literature review emphasises the necessity of non-destructive characterization techniques for the assessment of the surface integrity of ground components. It also briefly talks about the Barkhanusen noise and hysteresis loop techniques that were used to predict the different mechanical properties such as hardness and microstructure.

After a thorough study of the literature, the last section of this chapter is the research objective.

Chapter 3 goes into detail about the work materials used for this study and the whole process used to choose the best grinding wheel for grinding the surface of AISI D2 tool steel. Further, details about the indigenously developed UVAG system for single alumina abrasive grit, UVAG system, and UVAMQL system on the wheel head of surface grinding using an adjustable fixture are also included, as are details of the machine tool, abrasive wheel, dressing parameters, and instruments used for grindability indices and surface integrity characterization, such as a grinding force dynamometer, a grinding temperature measurement unit, a surface roughness tester, a SEM, an AFM, an optical microscope, and microhardness. In addition to that the lubricating properties of cutting fluid, such as wettability, thermal conductivity, stability, viscosity, and its measuring equipment, have been discussed. Finally, calibration of ultrasonic vibration assisted grinding experimental setup.

Chapter 4 mainly focuses on the Modelling and simulation study of dry ultrasonic vibration assisted grinding of tool steel. In this chapter, a two-dimensional finite element model (FEM) of single grit ultrasonic vibration assisted dry grinding (UVADG) and conventional dry grinding (CDG) of AISI D2 steel has been developed, which taken into account the influence of longitudinal ultrasonic vibration on the workpiece with variable downfeed. The effects of ultrasonic vibration and downfeed on the chip formation mechanism, temperature field, grinding force, and equivalent stress and strain were evaluated by analytical and simulation methods. The validation experiment compared the simulated and experimental grinding forces in both grinding modes to verify the reliability of the finite element model results. The validation results demonstrate that the finite element model can accurately describe single grit UVADG and CDG grinding.

Chapter 5 mainly focuses on the experimental work related to the surface grinding of AISI D2 tool steel under UVAG mode with varying vibration amplitude and downfeed. The grinding characteristics obtained have been compared with those obtained in the cases of conventional dry and wet grinding. This chapter covers the details of the grindability indices and surface integrity evaluated in terms of grinding forces, force ratio, specific energy, surface roughness, 2-D and 3-D surface topography, bearing area characteristics, grinding temperature, microchip morphology, microstructure, and microhardness analysis.

Chapter 6 discusses an experimental study into UVAMQL grinding of AISI D2 tool steel with an alumina wheel using eco-friendly cutting fluids. It talks about how different lubricants, like straight vegetable oil, biodegradable emulsions, and nanofluids, can be used to make cooling and lubrication better. The chapter talks in detail about the procedure adopted in characterising the prepared emulsion and nanofluids. The methodology followed for experimentation. Finally, the improvement in surface integrity using UVAMQL mode has been indicated by the obtained results in terms of grinding force, surface roughness, surface functional parameters, ground surface topography, microchip morphology, and grinding temperature.

Chapter 7 presents the novel non-destructive methods such as magnetic Barkhausen noise (MBN) and hysteresis loop (HL) in the surface grinding operations. It describes a qualitative assessment of a thermally damaged ground surface under various grinding modes. MBN and HL results, such as root mean square (RMS), permeability, coercivity, the MBN envelope, and the HL profile, were associated with surface characteristics, i.e., microhardness, under various grinding modes.

Chapter 8 contains the conclusions and the scope for future work.