Chapter 1 | Introduction

Grinding is widely used as a final machining process in the production of components to achieve good dimensional and form accuracy of the product with acceptable surface integrity. The high order surface finish in grinding is due to very small size chip which is much smaller as compared to other cutting operations. Grinding is more likely to be called as thermo-mechanical process rather than mechano-thermal process as energy partition typically ranges from 60% to 85%. According to (Malkin, 1989) out of total expenditure incurred on machining operations, grinding alone accounts for about 20-25%. This huge investment witnessed the application of grinding in various manufacturing industries. However, due to involvement of higher specific energy, grinding is rather considered as an expensive operation compared to other machining processes (Boothroyd and Winston, 1989, Kalpakjian, 1997). The higher specific grinding energy can be explained on the basis of size effect theory. During deformation very small size grinding chips have proportionally greater strength as compared to large ones as a result extremely high dislocation densities occur in the shear zone, thereby increasing the grinding energy (Boothroyd and Winston, 1989, Kalpakjian, 1997). Further, mechanism involved in grinding contributes significantly to specific energy requirement. A large portion of energy supplied is utilised in undesirable sliding and ploughing mechanism compared to the desirable cutting action which ultimately result into higher specific grinding energy (Malkin, 1984, Zhang *et al.*, 1992). The impacts of different mechanism stated above were mechanical, chemical and thermal in nature which was responsible to cause plastic deformation even in subsurface (Tonshoff and Brinksmeier, 1980). In addition to the above, energy requirement for plastic deformation is very high when accomplished under large strains and at higher strain rates and thus increases the energy requirement (Bulchar *et al.*, 1986, Hashmi and Hamouda, 1994, Zerilli and Armstrong, 1987).

Out of this high specific energy a maximum portion of this is converted into heat and gets conducted into the workpiece. Compared to conventional machining processes where most of the heat produced is carried away by the chip (~80 %) in grinding most of the heat produced is conducted into the workpiece (~70- 80%) (Griffiths, 2001). Such high heat conduction into the workpiece gives rise to high temperature which impairs the surface integrity of the ground workpiece in the form of surface burn, rehardening, residual tensile stresses of sub-surface layer and micro cracks (Snoeys *et al.*, 1986). In general surface integrity can be defined as assessment of the impact of grinding process on the properties of the ground specimen. Surface integrity includes all the parameter that affect the quality of surfaces such as surface finish, metallurgical damage, and residual stresses. The first aspect examines the roughness, lay or texture of the ground workpiece and explains orientation of the grinding scratches as it decides the fracture strength of the ground surface during real loading condition. The second aspect of the surface integrity examines the metallurgical damage which is characterized by change of microstructure, surface hardness, fracture strength, stress corrosion cracking, or the rate of wear. Phase transformation (i.e. austenizing and quenching of steel ground components.) under critical temperature history is one of the reason responsible for change in surface hardness in short it examines the nature of the altered layers below the ground surface. The third aspect of surface integrity deals with the estimation of residual stresses as is related to fracture strength, fatigue strength, dimensional stability, and is coupled with metallurgical changes of the ground specimen. Furthermore, thermal expansion of the specimen contributes significantly to inaccuracies and distortions in the workpiece. As grinding is mostly used as the end machining process on the workpiece thereby dimensional and form accuracy along with surface quality is very important (Tawakoli *et al.*, 2007).

Thermal damage is one of the important factor which limit the grinding production rate. The extent of thermal damage is related to the grinding force and temperature rise in the grinding zone. The level of heat generation and corresponding temperature rise depends not only on the grinding forces rather it is also associated with plastic deformation mechanism, work velocity and wheel speed. Grinding force plastically deform the material causing surface hardening and induction of compressive residual stresses on the other hand temperature rise reaching threshold results in change in metallurgical structure, induction of tensile residual stress, grinding burn etc. on the ground surface (Yao et al., 2014). This locked stresses has many undesirable effects on the workpiece performance usually it shortens the fatigue life; reduce dynamic and static strength, decreases resistance to stress corrosion etc. However, if the material is very sensitive it may even lead to cracks due to residual stress and localized thermal expansion (Ruisseaux and Zerkle, 1970). The residual stress generated by grinding force is generally of compressive nature whereas those generated by temperature is of tensile nature. Tensile residual stress generated by temperature phenomenon often leads the compressive residual stress due to mechanical action and thus resulting in net tensile residual stress on the ground surface.

From the preceding discussion it is worth to say that surface integrity of the ground surface determines its actual performance under real service application. Thermal damage restricts the capability of grinding process in achieving the desired production rate (Gupta et al., 1997). Heat generated and temperature rise during grinding is proportional to energy input to the process. Generally, the energy or power consumption is an uncontrollable output of the grinding process and so is temperature. Temperature related thermal damage affects the surface integrity to a large extent as is clear from the previous discussions. Therefore grinding industry demands a quick tool which can characterize the thermal damage at the rate of production in order to satisfy stringent customer requirement without scarifying product quality. Till recently, chemical inspection method was frequently used by the manufacturers due to its relatively low cost set-up. However, tighter environmental regulations restrict the use of acid etch which in turn make the process expensive as acquisition and disposal of the hazardous waste require higher initial investment. The etch method is also time consuming and tested samples attacked by acid etch need further heat treatment to avoid hydrogen embrittlement.

The eddy current method came as an alternative to the nital etch method and remove some of its shortcomings however, similar to nital etch this method is also suitable to characterize grinding burn caused due to metallurgical transformation. Eddy current method is best suited to characterize thermal softening or hardening due to thermal damage but is insensitive to residual stress (International Organisation for Standardization, 1995 and American National Standard, 1992).

X-ray diffraction method of residual stress determination is quite trusted and quantitative method on the other hand it is very slow and costly method and is applicable on very small areas in realistic application. Further, assessment of residual stress profile require removal of surface layer using electro polishing technique which makes the process destructive and rather time consuming (Society of Automotive Engineers, 1980).

Magnetic Barkhausen noise established itself as the best alternative to the grinding industry to detect thermal damage at the cost of production. It is a fast, reliable and practical method to detect high production volume .This method has already been recommended by Federal administration of Aviation and American society of automotive engineers and in a very short span of time since its endorsement, it has been adopted by several industries in the field of automotive and aerospace(Ogden,1991).

Barkhausen noise also known as Magnetic Barkhausen noise is discovered in 1919 by German Physicist Prof. Heinrich Barkhausen. However Finnish scientist Titto in 1970s was the first to draw the attention of the method in industrial application. Magnetic Barkhausen noise (hereafter named as MBN) technique is the measurement of noise like signal, generated when an external continuously changing magnetic field is applied to a ferromagnetic specimen. A clear understanding of the magnetization process of the ferromagnetic specimen were possible with the effort of French scientist Pierre Weiss who in 1907 shows that in order to minimize magnetostatic energy ferromagnetic materials divide itself into magnetic domains. Felix Bloch showed that each magnetic domain is separated from its neighbours by finite frontier called domain walls or bloch walls (Daveci, 2016, Kleber and Barroso, 2010).

In the absence of external magnetic field the direction of these magnetic domains are random resulting in zero net magnetization. However, under externally applied magnetic field domains with the direction close to the applied magnetic field increases their size at the cost of less favourable domain which leads to increase in magnetization of the specimen. Once the applied magnetic field is increased enough there exist only one domain inside the ferromagnetic specimen in a direction parallel to the applied field which corresponds to saturation magnetization (B_s), beyond which any further increase in magnetic field will result in little or no change in magnetization (Daveci, 2016).

Magnetic Barkhausen noise (MBN) results owing to discrete changes in magnetization as moving domain wall under applied external field overcome microstructural features such as impurities, grain misorientation, crystal defects, grain boundaries and dislocations or even applied or residual stress as these acts as a local pinning sites and hinder the movement of domain wall and hence affects the MBN. Microstructural features mentioned above the both pinning strength and mean free path of the displacements of domain wall motion during magnetization hence is sensitive to MBN (Ktena et al., 2014, Moorthy et al., 2003, Gurruchaga et al., 2010, Monlevade et al., 2012, Blaow et al., 2005). Generally two types of domain walls exists i.e. 180° domain wall and 90° domain wall in a ferromagnetic material depending upon their crystallographic arrangement. Domain walls which separate the opposite magnetic moments are termed as 180° domain wall while walls positioned at $90^{\circ}$to each other are called 90°domain walls. MBN occurs mainly due to 180°domain wall as its mobility is higher as compared to 90° domain wall. However as large number of variables affects the MBN, only relative comparison can be established between different materials states. Hence calibration needs to be performed against standard microstructural state for a given ferromagnetic sample (Blaow et al., 2005). MBN emissions were detected as a voltage pulses in a search coil placed on the surface of the specimen (surface

Barkhausen) or wrapped around the specimen (encircling Barkhausen) (Mitra et al., 1995). In the last decade non-destructive MBN technique came forward as a potential NDT tool for the characterization of microstructure (Altpeter,1996, Clapham et al.,1991, Rajkumar et al.,2010, Viswanath et al.,2010), grain size (Ktena et al.,2014, Rievera et al.,2001, Yamaura et al.,2001, Zergoug et al.,2000), residual stress (Maugin and Sabir, 1990, Rautioaho et al.,1986, Zerovnik et al.,2010) applied stress (Kivimaa et al.,1993, Krause et al.,1996, Rautioaho and Karjalainen,1988, Stevens,2000, Stewart et al.,2004) , carbon content (Jiles,1988, Thompson and Tanner,1993, Thompson and Tanner,1994), case depth (Moorthy and Shaw,2010, Santaaho et al., 2010).The parameters that were frequently used to quantify the Barkhausen signals were number of events per magnetizing cycle, rms voltage, peak to peak voltage, MBN energy, peak position, width and height of MBN profile (Mitra,1995).The dependence of MBN on above mentioned mechanical properties enables the wide spectrum application of the technique to the manufacturing industry which includes automobile, aerospace, heat treating industry where it can be used to sort defected component, to control microstructure, to assess service life and in service damage of the component.