Cylindrical Grinding - A Review on Surface Integrity

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Cylindrical grinding is one of the important metal cutting processes used extensively in the finishing operation of discrete components. The inherent high cutting temperature in grinding if not controlled may lead to rapid tool wear, which in turn will lead to dimensional inaccuracy. The very nature of the grinding mechanism in material removal impairs the grounded surfaces by inducing residual stress, micro cracks and other thermal damages at the machined surface. This paper is an attempt to review some of the surface integrity issues in cylindrical grinding taken up and reported by number of researchers over the years. This review may have been planned to be useful to the researchers and other professionals interested to work on grinding.

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1. Grinding- Some observations

For the production of finished components of desired shape, size and accuracy, machining is the commonly used manufacturing process. Machining process involves the usage of single or multiple point cutting tools to remove the unwanted materials from the stock in the form of chips (Komandurai, 1993). Among the various metal cutting process available, Grinding is one of the important metal cutting processes used extensively in the finishing operation of discrete components. It is a versatile and also finish machining process in the production of components requiring close dimensional tolerances, geometrical accuracies and required surface finish (Rajmohan et al., 1994). Most of the production processes are incomplete without grinding process. According to Subramanian (1999), it is a major manufacturing process, which accounts for about 25% of the total expenditure on machining operations in industrialized countries. Almost all the engineering components are processed in grinding machines at some stages of its production.

Grinding is a slow process in terms of unit removal of the stock. Hence, other methods are used first to bring the work closer to its required dimensions and then it is ground to achieve the desired finish. In some applications, grinding is also employed for higher metal removal rate. In such heavy duty grinding operations more abrasive is consumed. In these cases, the main objective is to remove more amount of material that too as quickly and effectively as possible. Thus, the grinding process can be applied successfully to almost any component requiring precision or hard machining and it is also one of the widely used methods of removing material from the work piece after hardening.

Shaw (1996) reported that Grinding is a complex manufacturing process with a large number of interacting variables, which depend on the type of grinding employed. The geometry produced in the surface grinding is influenced by many variables given as follows:

i) Wheel characteristic – Wheel diameter, grit type and size, wheel grade, structure, bond, dressing method, degree of wheel balance etc.
ii) Work characteristic – Workpiece hardness, structure, chemistry etc.
iii) Machine characteristic – Spindle and table stiffness, damping, dynamic characteristics etc.
iv) Operating conditions – Wheel speed, feed, infeed (depth of cut) grinding fluid etc.

In order to decrease the cost and increase the production rate, the grinding machine must be set to operate within the shortest possible grinding cycle time. Hence, it is often important to set the correct grinding machine parameters so as to produce parts of required quality. The selection of grinding parameters if it is done on hit and miss technique not only wastes time but also leads to an inefficient process. To over come this difficulty, Gupta et al. (2001) in their work optimized the grinding process parameters using the enumeration method. The parameters should be selected so as to result in an optimal solution. Selection of grinding process parameters is made easy by employing the “Expert system”. Shaji and Radhakrishnan (2002) analyzed the process parameters such as speed, feed, infeed and mode of dressing as influential factors on the force components and surface finish developed based on Taguchi’s Experimental design methods. Fengguo Cao et al. (2003) developed the concept of integrating neural network, grey relational analysis and genetic algorithm for the optimization of process parameters in Increased.

Explosive Electrical Discharge Grinding Process lies in the proper selection and introduction of suitable design of experiment at the earliest stage of the process and product development cycles so as obtain quality and productivity improvement.

Among the existing types of grinding processes, cylindrical grinding process is the one, which is very widely used in the finish machining of number of automobile components with surfaces of revolution. In cylindrical grinding process, the frictional resistance encountered between the work material and the tool, chip tool interface and the resistance to deformation during shearing of the chips contributes to the rise in temperature at the contact zone (Trigger et al.1951).The temperature generated is not only very high but the temperature gradients are also severe. Such temperatures of sufficient magnitude can cause adverse changes in workpiece metallurgical structure, loss in dimensional accuracy and accelerated wear [or] dulling of the tool (Des Ruisseaux and Zerkle, 1970; Takashi Ueda et al., 1985).

In addition to causing surface damage, grinding heat may cause thermal expansion/distortion in the component ground and thus adversely affect the attainable accuracy. Masuda and Shiozaki (1974) demonstrated how grinding heat in plunge surface grinding results in out-of-flatness of the finished part. Better flatness was obtained with smaller depths of cut and higher workpiece velocities. Both of them cause lesser grinding heat and with increased coolant flow rate the cooling of the workpiece is enhanced and the thermal distortion is minimized.

Chandrsekar et al. (1996) studied the thermal aspects of surface finishing process. In grinding, the localized abrasive workpiece contact pressures and high sliding speed produce high temperatures at the interface between an abrasive particle and the work surface, as well as in the work sub-surfaces due to frictional heating. High temperatures are the important source of damage on the machined surface. First, the transient temperature and the temperature gradient are the principle sources for residual stresses and micro cracking on ground surfaces. Secondly, the localized temperatures can cause warping of the components being machined, especially, when it is of small size and has a relatively large surface area to volume ratio. This is a serious problem in the finishing of small electronic devices such as recording heads. Thirdly, this high temperature can also lead to phase transformations in the materials being machined.

The nature of grinding damage was surveyed by Tarasov (1950), who identified three main kinds of grinding damage, namely cracking, rehardening burn and tempering burn. During grinding of hardened steel, if the surface temperature of the work piece is sufficiently high, the surface reaustenizes and is rapidly quenched. Consequently, there is a formation of brittle, untempered martensite at the surface. This type of thermal damage is also commonly referred to as workpiece burn and is highly undesirable (Tarasov, 1950; Torrance, 1978). A martensitic type of phase transformation also occurs during the grinding of toughened zirconia. Here, the transient mechanical and thermal stresses generated during grinding drives the transformation. These forms of thermal damage change the mechanical, magnetic and electrical properties of the work materials.

The local temperatures play an important role in the degradation of the abrasive particles and the bonding property of the material. The heat generated during grinding is characterized by,

i) Instantaneous concentrated source,
ii) High rate of liberation, and
iii) Very small contact period.

Heat associated with the energy expended by grinding is transported away from the grinding zone by the work piece, grinding fluid, grinding chips and grinding wheel. Of particular interest is the fraction of the total grinding energy transported to the work piece at the grinding zone, which causes the rise in workpiece temperature and possible thermal damage. For regular grinding with conventional Aluminum oxide wheels, the energy partition to the work piece typically ranges from 60-80% depending on the actual grinding situation (Malkin and Anderson, 1974; Rowe et al., 1995 and 1997). Only a few isolated attempts have been reported so far on experimental analysis of the temperature developed at the wheelwork contact zone, energy partition ratio, grain contact time and thermal damages. At this point, it appears that practical optimization strategy and reliable mathematical models are still required to analyze the thermal damage in grinding.

Field and Kahles (1971) investigated the dissipation of heat in grinding and the resulting influence on the surface integrity of the work piece. Guo and Malkin (1992) described that depending on the grinding condition the heat flux takes part mainly via the work piece and leads to a large thermal loading in the surface. This thermal load is superimposed by mechanical load causing a high temperature in the surface. This thermo-mechanical load causes some undesired alterations in the surface layer, like cracks, tempered zone or white etching areas (WEA).

Shaw and Vyas (1994) gave an impressive theoretical description of metallurgical changes in ground surfaces. Under abusive grinding conditions, the formation of heat-affected zone was observed. Des Ruisseaux and Zerkle (1970) analyzed that the heat-affected zone under abusive grinding conditions damages the ground surface of the hardened steel very frequently. A thermally damaged component may therefore incur a significant cost to the manufacturer in failing a quality standard. Thus, the thermal phenomena play a key role in the economics and mechanics of abrasive machining processes. An estimation of the amount of energy generated, work surface temperature and an understanding of their role in metallurgical changes on ground surfaces are still challenging to the production engineers (Snoyes and Maris 1978). Malkin and Fedoseev (1991) analyzed the method to predict the undesired alterations to avoid thermal damages in grinding hardened steel. In any case, the generated heat quantities in grinding are considered as a restricting factor. The invention of advanced grinding processes, which enabled the surface hardening of steel parts. was described for the first time in 1994. In such operations, named grind hardening, the dissipated heat in grinding is utilized to induce martensitic phase transformation in the surface layer of components (Brinksmeier and Brockhoff, 1997).

Better surface finish with increased hardness at the surface by utilizing the heat generated during grinding is possible under optimum operating conditions. Thus, one of the area for the researchers to concern about the unique optimal settings of grinding process parameters – Depth of cut, Number of passes, Wheel speed and Work speed for maximizing the surface hardness and minimizing the surface roughness while grinding AISI steel materials with Al_2O_3 grinding wheels.

"Ishikawa cause effect diagram" of machining is studied to identify the influential process parameters that may affect the surface integrity of grounded parts by Ramamoorthy et al., 2001 and; Harisingh et al., 2004. Taguchi's parameter design approach has been used to accomplish the objective. A special mathematical tool known as grey relational analysis can be used with response graph approach and signal to noise ratio approach for the optimization.

It is well known that physical surface properties can determine the lifetime and the function of highly loaded workpiece and components. For this reason, manufacturing industries require information about the techniques to influence the surface state of workpiece and to achieve consistent properties (Kegg, 1982). This interest has its importance due to the fact that the magnitude of the residual stress interferes on the fatigue strength of the materials (Novasaki et al., 1996). Residual stress is the most representative parameter to describe the quality of the surface (Brinksmeier et al., 1982) among various surface alterations like phase transformations, hardness variations, micro cracks, grinding burn etc.

Banerjee and Chattopadhyay (1987) investigated the control of residual stress in grinding by cryogenic cooling which results in much less tensile residual stresses. Kruszynski et al. (1991) made an attempt to predict residual stresses in grinding of metals with the aid of a new grinding parameter. Hucker (1994) showed that there was a quantitative relation between the effective work-surface temperature and the residual stress produced on ground surfaces of hardened steels. X-ray diffraction techniques were used to measure the residual stresses. It was reported that CBN grinding is found to produce compressive stress at the surface in contrast to Al_2O_3 grinding. However, Many of the researches proved that under the conditions of martensitic formation (rough grinding) compressive residual stresses are formed when ground with Al_2O_3 wheel.

Brockhoff and Brinksmeier (1997) in their comprehensive view on grind hardening found out that compressive residual stresses are existing in the White Etching Areas, which continue into the area of etchable martensite and which are compensated by low tensile residual stresses in a greater distance from the surface. Litmann and Wulff (1955) found that for hardened steels, which have been burned during grinding, the workpiece sub-surface consists of a rehardened zone near the surface and a softened tempered zone beneath it. This would suggest that the onset of burning is characterized by the formation of austenite over some portion of the workpiece sub-surface. Rehardening at the surface occurs by acicular martensite (that appears in the form of parallel needles within former austenite grains) formation as the cooler material in the bulk of the workpiece quenches the surface. This refers to phase transformation in grinding.

After grinding under ideal conditions, the ground surface will be crack free and will exhibit compressive residual stresses favourable for corrosion resistance and long life under cyclic loading conditions. In contrast, many grinding conditions are such that the surface produced suffers tensile stresses, sub-surface cracking and oxidation leading to failure in surface. In order to strike a balance between quality and strength in grounded parts it is desirable to have a control over the residual stress. This necessitates a detailed study of the free work-surface temperature, amount of heat generated and the magnitude of residual stress formed.

From time to time, it has been suggested that in the fine grinding of metals, melting of a layer of metal at the surface is involved in the material removal process. Outwater and Shaw (1952) studied the surface temperatures in grinding and reported that the total specific energy involved in a fine grinding operation is of the order of 28 Kg/m^3. In grinding, high magnitude thermal pulses of very short duration is involved. The time of heating is only a small fraction of the time required to convert a layer of steel of one-micron thickness from the crystalline to the amorphous state. So, melting does not occur on the ground surface. This has been proved through experiments and micro structural analysis by many researchers.

The main aim of the most of the investigations is the prediction of desired machining conditions to avoid thermal damages. In any case, the process parameters, wheel work contact zone temperature, amount of heat generated and dissipated, nature of residual stress are considered as restricting factors. The above said problems cause one to work and investigate the following to obtain a good surface integrity in grinding of steel components.

i. Process parameter optimization
ii. Heat generation utilization
iii. Phase transformation
iv. Residual stress formation

With this in idea, a review is made and presented in the following chapters. It is felt that it is the need of the hour and may be very useful to the researchers and other professionals interested to work on grinding.

2. An overview on the past and present of research on grindings

2.1 Introduction

Grinding is one of the most versatile methods of removing material from machine parts to provide for grinding wheel as a cutting tool. For this purpose, it is important to choose a grinding wheel of uniform grade. However, irregularity of grade changes the grinding characteristic on the working periphery of a grinding wheel locally and it affects the dimensional accuracy of work-piece (Shinichi Tooe et al., 1987).

precise geometry. Within the spectrum of machining processes, the uniqueness of grinding is found in its cutting tool. Modern grinding wheels and tools are generally composed of two materials, one is the tiny abrasive particles called grains or grits which do the cutting and the other is a softer bonding agent to hold the countless abrasive grains together in a solid mass (Fig. 1).

Grinding is very complex process since more interactions are involved in the grinding zone(Fig. 2)and difficult to study because of the small size of the individual chips produced by hard abrasive particles having wide range of shape, spacing and random geometry (Akira and Tadaaki , 1966; Subramanian and Ramnath , 1992).

Since grinding wheels can be classified as composite materials, the structural arrangement of the abrasive grain and binder can greatly affect their elastic properties. Brecker (1974) analyzed bond formation during firing of vitrified wheels and observed the cross section of the wheel, from which he concluded that surface tension forces are sufficient to draw the abrasive grains into direct contact.

When high accuracy of the work-piece and the automation of the grinding work are considered, it is necessary to secure the reliability and the reproducibility.

By making a quantitative energy balance, Malkin (1975) showed that the total energy in grinding could be considered as the sum of chip formation, plowing and sliding energies. Plowing refers to work-piece deformation without removal and sliding energy is associated with rubbing between the wear flats and the work-piece surface. Both the plowing and sliding energy contributions become smaller at faster removal rates, so that the minimum specific energy approaches the specific energy for chip formation.

Malkin and Joseph (1975) found that the minimum specific energy in grinding is close to the melting energy per unit volume of work-piece metal. This particular value of minimum energy was attributed to the severe constraint imposed by the highly negative rake angles and strain rates in grinding wheel where the energy reaches this maximum allowable value for adiabatic deformation.

In addition to causing surface damage, grinding heat can affect the precision, which can normally be obtained, due to thermal expansion and distortion of the workpiece. Masuda and Shiozaki (1974) demonstrated how grinding heat in plunge type grinding results in out of flatness of the finished part. Better flatness was obtained with lesser depths of cut and faster work speed, both of which may cause less grinding heat and with increased coolant flow rate, which enhance the cooling of the work-piece and minimize thermal distortion.

Malkin and Anderson (1974) investigated the fraction of the grinding energy conducted to the work-piece. From both energy partition measurements and analysis, it was concluded that virtually all of the sliding and plowing energies and half of the chip formation energy are conducted to the work-piece. Maris and Snoeys (1973) state that almost 60% of the heat energy conducted to the work-piece and this causes work-piece burn. This work-piece burn can also cause some surface quality related problems.

Surface quality consideration calls for burn-free grinding, which imposes a limitation on the allowable process parameters, thereby leading to less efficient grinding (Deivanathan et al., 1999). In order to strike a balance between quality and efficiency in grinding, it is desirable to have a technique for predicting the burn threshold in real time. In this manner, grinding can be carried out with the desired process parameters for high efficiency and at the same time, the surface quality can also be controlled. This necessitates a detailed study of the temperature developed and the consequent burning phenomena in grinding.

From the literatures, it is clear that practical optimization strategy and reliable mathematical models are still needed to analyze the temperature distribution and thermal damages in grinding.

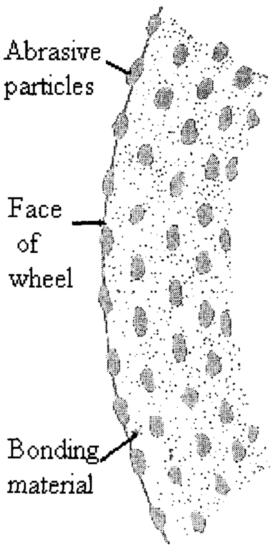


Fig. 1 Grinding wheel showing edge of abrasive grains projecting from the face

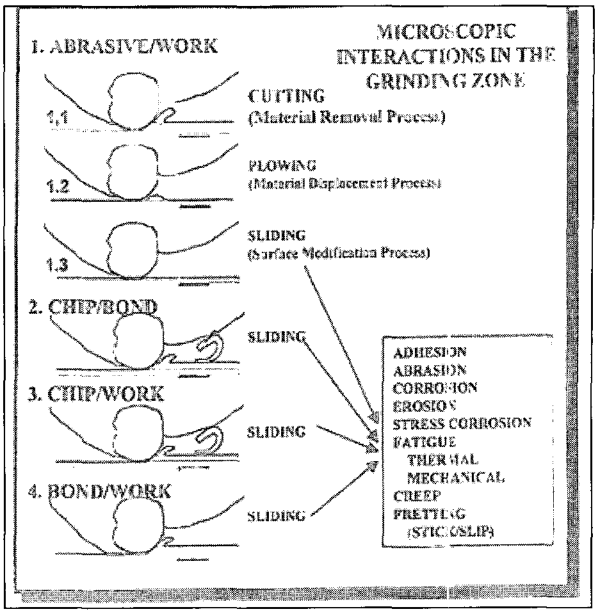


Fig. 2 Microscopic interactions in the grinding zone

2.2 Grinding principles

During grinding material is removed from the work-piece surface in the form of small chips by the abrasive particles on the grinding wheel. The material removal can be visualized by considering a single abrasive grain on the wheel (Fig. 3). As the grain makes contact with the work-piece surface, the depth of cut is zero.

As the wheel and work-piece revolves, the depth of cut increases to a maximum, some where along the arc of contact of the wheel and the work-piece and then reduces again when the chip is dislodged from the work-piece. Since the wheel speed is considerably higher than the work speed, the maximum value of depth of cut is reached almost at the point where the wheel leaves the work-piece. This depth of cut is termed as the grain depth of cut.

In Fig. 3, when the grain is at P it is just contacting the work-piece and the depth of cut is zero. In unit time T, the grain will advance to position R. In the same unit time T, the point R on the work-piece would have come to position S. The point S will be very near to the point R, since the rotation of the wheel is much faster than the work. The chip section removed is represented by PRS. The maximum depth of cut represented by SU is the maximum chip thickness per grit (or) the grain depth of cut (g_d).

The length traversed by the abrasive grain PR in unit time

$$T = PR = V_s T \text{ or } T = PR/V_s \tag{1}$$

Where,

V_s = Surface speed of the wheel in m/s.

The length traversed by the point R on the work-piece in unit time

$$T = RS = V_w T \tag{2}$$

Where,

V_w = Surface speed of the work in m/s

Maximum chip thickness per grit

$$SU = RS \sin(\theta + \phi) \tag{3}$$

Where θ and ϕ are the angles subtended at the centers of the grinding wheel and the work-piece by the point R.

Therefore,

$$SU = V_w T \sin(\theta + \phi) \tag{4}$$

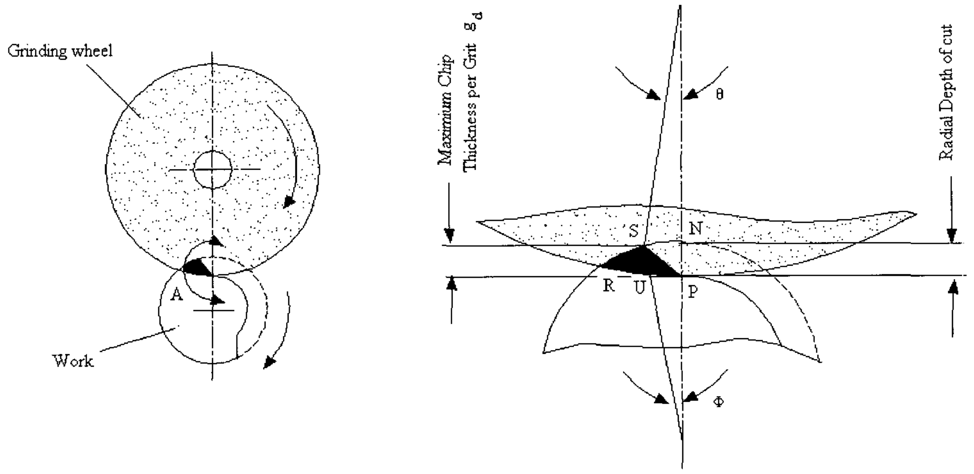


Fig. 3 Grinding principles

If there are Z numbers of grains in unit length, the number of grains in length PR of the grinding wheel is given by PR x Z

Maximum chip thickness per grit,

$$g_d = \frac{SU}{PR.Z} \tag{5}$$

$$g_d = \frac{SU}{PR.Z} = \frac{V_w T}{PR.Z}[\sin(\theta + \phi)] \tag{6}$$

Substituting for T

$$g_d = \frac{V_w}{ZV_s}\sin(\theta + \phi) \tag{7}$$

The wheel can be made to cut harder or softer by reducing or increasing the grain depth of cut. It can be seen from the Equation (7) the following are clear.

i) Work speed – By increasing the work speed, the grain depth of cut increases and the bond wears out faster and the wheel appears softer. When the work speed decreases, the wheel appears to be harder.

ii) Wheel speed – By reducing the wheel speed the grain depth increases and the wheel appears softer. By increasing the wheel speed, the wheel appears harder (Arabatti et al., 1996).

2.3 Grinding parameters

The success of any grinding operations depends on the proper selection of various grinding parameters, like wheel speed, work speed, transverse feed, and infeed area of contact, grinding fluids, balancing of grinding wheels etc.

Subramanian and Lindsay (1992) have given the concept of grinding system approach that addresses four key inputs to the grinding process viz. machine tool, wheel selection, work material properties and operational factors(Table 1, Fig. 4). Inadequate attentions to details in any one of these systems input parameters can result in uncertain grinding results.

2.3.1 Influence of input process parameters

A very large number of widely varying parameters affects the grinding process. Unlike most of te input values like the machine, grinding wheel, machine setting, etc., which can be optimized, the work material which is selected in view of the required properties of the finished product, cannot be changed. Therefore, in order to achieve a well-adjusted grinding process, the variable process input values must be adapted to the material. The grinding process is temperature, wheel wear and wheel loading (Fig. 5).

The grinding power spent in the process, in other words, the entire mechanical energy is transformed into heat in the contact zone (Konig and Menser, 1981). The temperature distribution in the work-piece is largely dependent on the thermal conductivity of the material. The physical characteristics of the work-piece are not constant but are dependent on the temperature. The value and the distribution of the temperature in work-piece material can be taken as a gauge for assessing the extent of thermal damage. It is well known that thermal damage, cracking and grinding burn can occur in work-pieces when they are ground under certain conditions. However, it is not so well known fact that small but finite form errors also result from the high temperatures developed between the grinding wheel and the work-piece (Hahn, 1976).

In the manufacture of components, which are critical in their application and are highly stressed the need for reliability and safety is high. The surface integrity and precision, surface form of the ground surface also become very important. Aircraft jet engine parts, anti-friction bearings in critical locations are the two examples. To ensure that surface damage and surface form errors do not occur, it is important to select the operating conditions properly to avoid these effects.

Since the major cause of the surface damage in grinding is due to excessive heat, it is important to identify the basic factors that influence the temperature, which occur on and just below the ground surface during grinding. Under certain conditions, surface temperatures can reach around 1800°C in much localized areas and for very short times. This can cause sub-surface residual tensile stresses and unwanted metallurgical phase changes. The work-piece, the wheel speed, interface force intensity, wheel sharpness, equivalent diameter and cutting fluid all affect the generated surface temperature.

The equivalent diameter (d_e) is that diameter of the wheel, which on a flat surface produces the same contact length as in the internal or external configuration. The wheel sharpness is defined in terms of the metal removal parameter. If this parameter is divided by the wheel surface speed (Vs) we get the sharpness (S) in cm^2/N. The sharpness represents the cross-sectional area of the work-piece material being removed by the wheel at any instant per unit normal force. This variable plays an important role in controlling surface integrity. High work speeds, low wheel speeds, low interface force intensity, small equivalent diameter and sharp wheels tend to reduce the thermal stresses.

2.3.2 Grinding power and force

In grinding the chip thickness is very significant with regard to grinding energy and temperatures generated at the surface (Malkin, 1984). The specific energy in grinding is very high due to the removal of small amount of material at very high rate. This is due to the presence of large Inhomogenities, Crystal defects, Grain boundaries and Impurities in a very small size of work material (Matsui and Tamaki, 1986). The large specific energies associated with grinding process can be partially attributed to the plowing and sliding energies expended in excess of the chip formation energy. In addition, the shear strain involved in chip formation is very large thereby chip formation energy is also very high. In addition to chip formation process, the frictional force is also increased at the tool chip interface.

The forces in grinding are due to cutting or chip formation, plowing and sliding. The contribution of these mechanisms depends on the condition of the wheel when the grains are sharp without wear flat and the depth of cut is high, the sliding forces are negligible and the grinding force is equal to the cutting force components. When the metal removal rate is very low or cross section of the chips are low or when the wear flat increases, the vertical force increases linearly indicating that the average contact pressure between wear flats and the work is constant. Linear increase in horizontal force indicates the constant coefficient of friction in grinding.

2.3.3 Wheel wear

The geometry of grits on the wheel surface continuously alters due to the influence of cutting mechanisms and forces. The condition of the wheel is also altered due to the wear of the grinding wheel and by the loading of the work material into its pores. Wheel wear and loading brings down the cutting efficiency and the grinding forces increase gradually (Chander et al., 1978).

Wear of grinding wheel may be defined as the loss of abrasives from the surface of the wheel and are due to (i) attritious wear of grains (ii) mechanical grain fracture and (iii) rupture of bond or gross pullout of whole grain (Pande and Lal, 1976). Attritious wear is a gradual dulling or flattering of abrasive grains by rubbing against the work-piece.

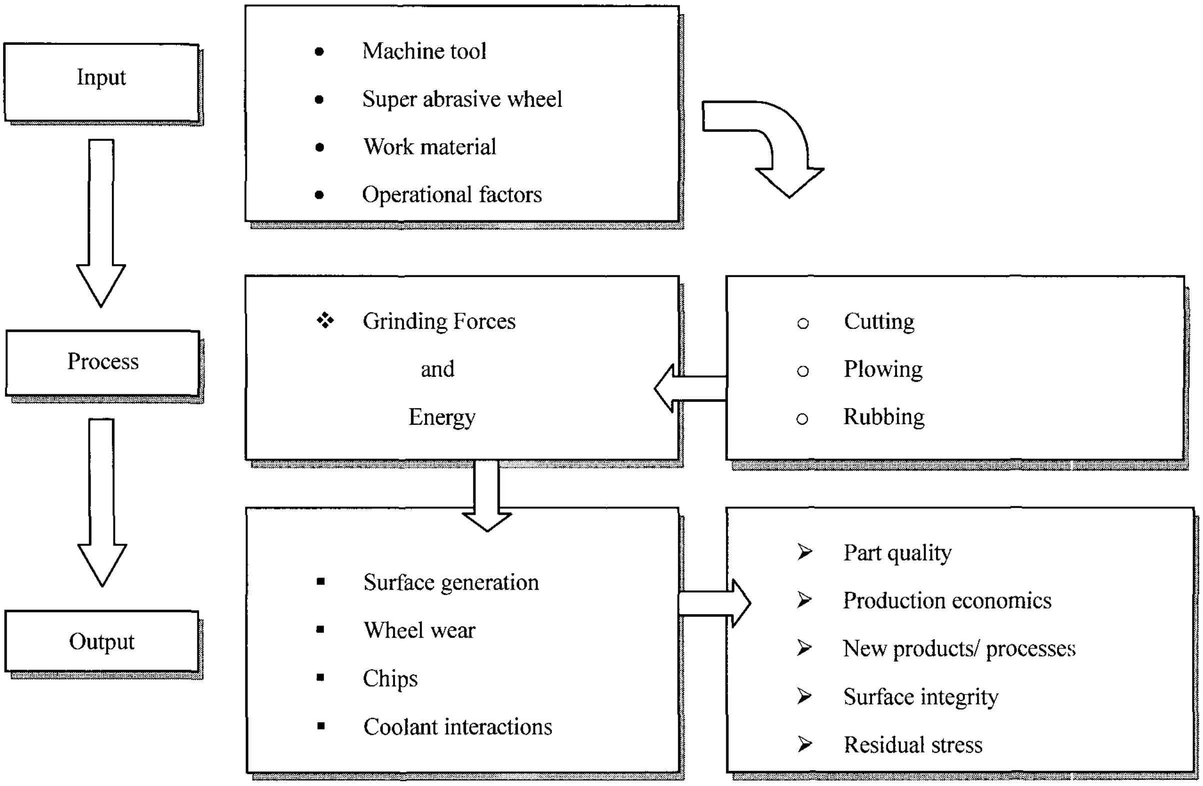
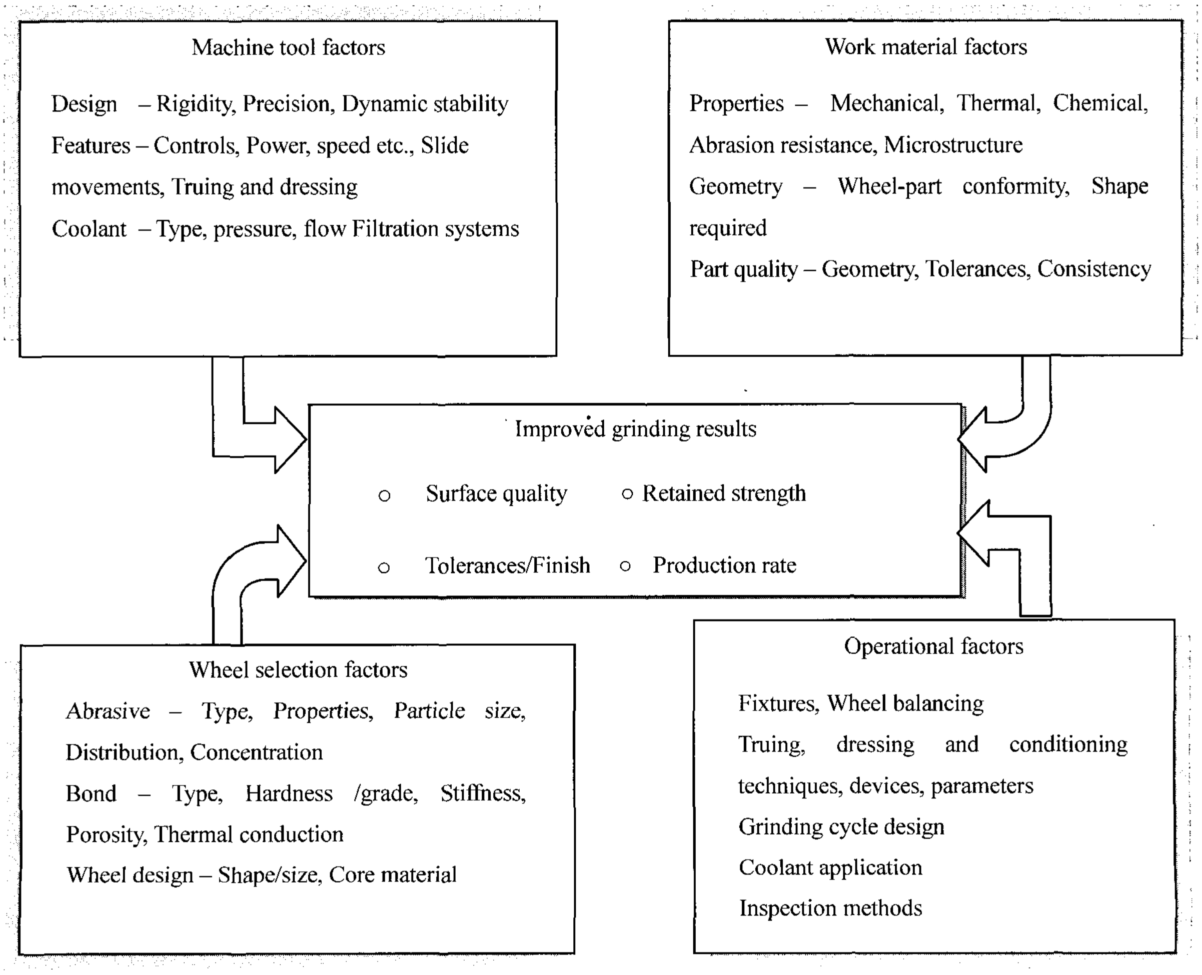


Fig. 4 Input/Output model of the precision grinding process

Table 1 Selected variables influencing the grinding process



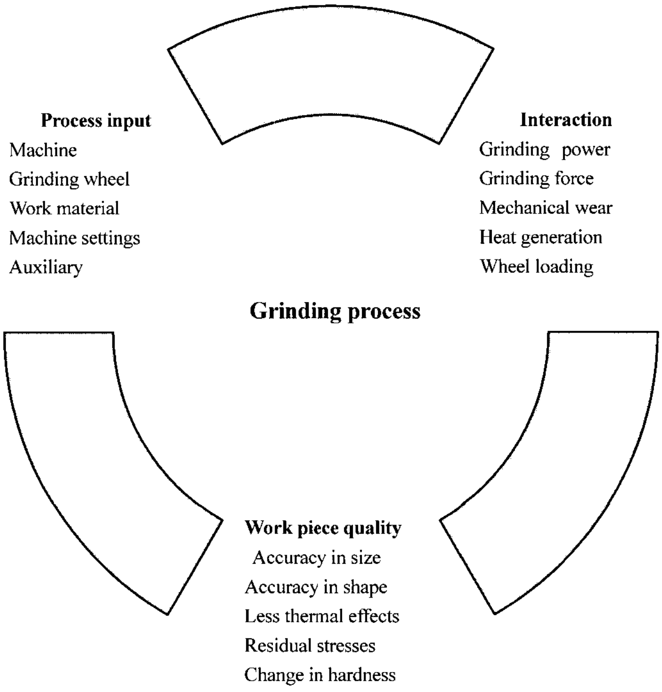


Fig. 5 Influences of process input on grinding process and work quality

This type of wear has much influence on the cutting action of abrasive grain and the cutting forces are dependent on it. Such a wear occurs mostly under mild grinding conditions imprecision grinding. It generates wear flats on the grain thus reducing the cutting efficiency of the grains. Severe grinding conditions subject the wheel material to fracture and the surface is modified constantly due to self-sharpening phenomenon. Grain fracture occurs as a result of mechanical forces associated with chip formation or due to thermal shock induced by instantaneous high temperatures. Gross pullout or bond fracture depends upon the tensile stresses in the bond bridge, which in turn depends on the grade of the wheel (Yoshikawa and Sata, 1963).

Wheel wear rate is found to be an exponential function of grinding force. As the grinding process is continued, the wheel loses its form due to non-uniform removal of material on the wheel surface. Hence, the condition of the wheel is continuously altered and a stage reaches after which the grinding performance and efficiency starts deteriorating and starts adversely affecting the work-piece finish and surface integrity.

The pattern of wheel wear and its associated pattern of forces are shown in Fig. 6. The wheel wear pattern may be classified into three phases.

(i)Phase A – intensive wheel wear and it is related to the wheel dressing techniques,

(ii)Phase B – a constant time – rate of wear under good grinding conditions remains constant over long period. This is the optimum condition for economic grinding practice and

(iii)Phase C – results when either the wheel is overloaded or excessive vibrations occur and wheel wear occurs due to bond post rupture. Whole grits being dislodged from the wheel.

Wheel wear measured from the reduction in wheel diameter does not give accurate estimate of the wheel wear. From the wear particle size distribution analysis of the wheel, wear can be ascertained accurately but the procedure is cumbersome (Grisbrook et al., 1962). The rate of wheel wear depends upon the work speed, wheel speed and grinding depth. Employing reduced wheel speeds can reduce wheel wear. Low work speeds will reduce the wheel wear for the same metal removal rate but it may cause thermal damage to the work-piece (Malkin and Cook, 1971).

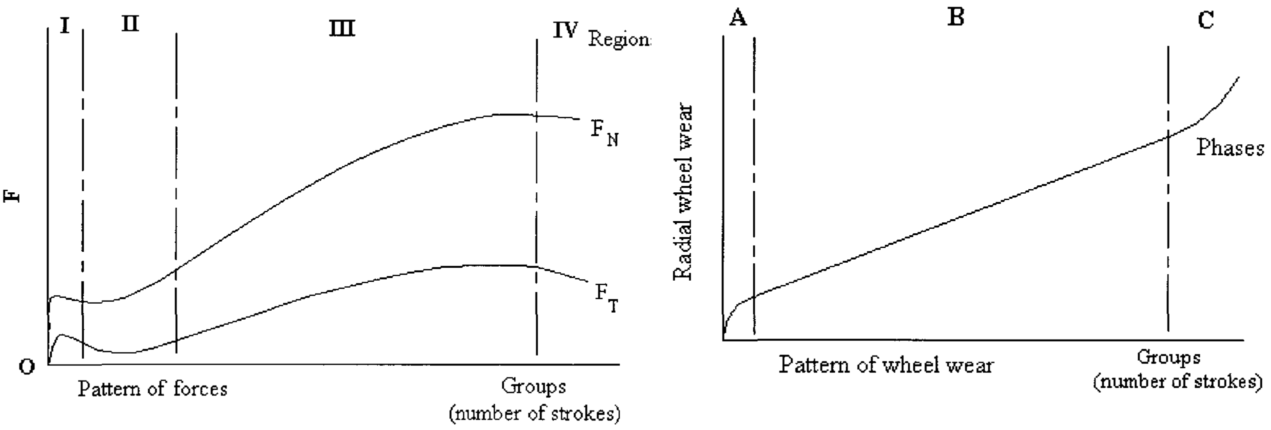


Fig. 6 Relative patterns of wheel wear and force

2.3.4 Loading of grinding wheels

The quality and efficiency of grinding process is largely dependent on the condition of the cutting edges as well as on the condition of the pores on the wheel surface (Konig and Aachen, 1978). Frequently, loading of the grinding wheel with chips occurs when ductile or high adhesion materials like aluminum, titanium and stainless steel are machined. Wheel loading is one of the important parameters, which determines the useful life of a wheel in precision grinding (Srivatsava et al., 1985). Due to loading, the outer surface of the wheel becomes glazed and results in excessive rubbing. Chips in the grinding wheel will alter the grain edge geometry and the friction process occurring during grinding operations. The loaded wheel will result in increased cutting forces and grinding power consumption, which in turn may lead to a breakdown of the grinding wheel structure.

The loaded wheel also generates more heat, which in turn affects the surface integrity of the work-piece such as surface roughness or surface topography and surface metallurgy. Alterations of the surface layers include plastic deformation, micro cracking, phase transformation, micro-hardness changes, tears associated with built up edge and residual stress distribution (Shah and Chawala, 1979). To ensure consistent results in grinding, one has to continuously investigate the condition or the modifications occurring on the wheel and control them suitably.

If the cutting efficiency of the process is to be improved, the wheel has to be provided with new sharp grains with porosity for chip flow. The wheel is dressed to remove the clogged chips on the wheel material so that new grains with sharp edges appear. One has to monitor continuously the wheel condition and control them suitably to achieve consistent performance in grinding.

2.4 Cylindrical grinding

Cylindrical grinding designates a general category of various grinding methods, which have the common characteristic of rotating the work- piece about a fixed axis while grinding outside surface section in controlled relation to that axis of rotation. The plunge type cylindrical grinding is required for profiled surfaces and for the simultaneous grinding of multiple surfaces of different diameters or located in different planes. Table 2 gives general guideline about the depth of cut conditions followed in plunge grindin.

Table 2 Plunge grinding- Depth of cut conditions

Work material	Infeed per revolution of the work (mm)	
	Roughing	Finishing
Steel soft	0.0125	0.005
Plain carbon steel hardened	0.005	0.00125
Alloy and tool steel hardened	0.0025	0.00065

2.4.1 Operational data for cylindrical grinding

In cylindrical grinding, similar to other metal cutting processes, the applied speed and feed rates must be adjusted to the operational conditions as well as to the objectives of the process. Grinding differs, however, from other types of metal cutting methods in regard to the cutting speed of the wheel in grinding. It is generally not a variable and should be maintained at, or close to the optimum rate.

In establishing the proper process values for grinding, the prime consideration is the work materials, its condition (hardened or soft), and the type of operation (roughing or finishing). The other influencing parameters are the characteristics of the grinding machine (stability, power), the specifications of the grinding wheel, the material allowance, the rigidity and balancing of the work-piece, as well as several grinding process conditions, such as wet or dry grinding, the manner of wheel truing, etc.

Variables of the cylindrical grinding process, often referred to as grinding data, comprise the speed of work rotation (measured as the surface speed of the work), the infeed (in mm per pass for traverse grinding, or in mm per minute for plunge type grinding). This data is for the purpose of stating the values in setting up a cylindrical grinding process, a brief listing of basic data for common cylindrical grinding conditions and frequently used materials is presented in Table 3 (Erik Oberg et al., 1996).

2.4.2 Operating conditions

The success of any grinding operation depends on the proper selection of various operating conditions like wheel speed, traverse feed, infeed, area of contact, grinding fluids, etc.

Wheel speed

If the wheel speed is increased at a constant longitudinal or rotary feed rate, the size of the chips removed by a single abrasive grain is reduced. This reduces the wear of the wheel. If the wheel speed is reduced, the wear is increased. From this, it is clear that from the point of view of wear, it is better to operate at higher wheel speeds (Opitz and Guhring, 1968). However, this is limited by the allowable speeds at which the wheel can be worked, as well as the power and rigidity of the grinding machine. Normally, the grinding wheel speed ranges from 20 to 40 m/sec. The wheel speed also depends upon the type of grinding operation and the bonding medium of the grinding wheel (Table 4).For example, resinoid bonded wheels can be generally used at higher peripheral speeds than vitrified bond wheels.

Work speed

Work speed is the speed at which the work-piece traverses across the wheel face or rotates between centers. If the work speed is high, the wheel wear is increased but the heat produced is reduced. Hahn et al. (1956) stated that high work speeds are effective in reducing heat checks and cracking of heat sensitive materials and may also influence the life of the tool or part. On the other hand, if the work speed is low, the wheel wear decreases but the heat produced is more. The ratio of wheel speed to work speed is of much importance and it should be maintained at the proper value. Low work speeds result in local overheating and bring about deformation or tempering of the hardened work-piece. The in turn affects the mechanical properties of the work piece and very often micro-cracks will appear on the work-piece. The increase in work speed is limited by premature wheel wear and vibrations induced by wear. Generally, if the wheel wear increases, the work speed should be reduced. If the heat produced is high and clogging occurs, especially with hard wheels, the work speed should be increased.

Down feed or infeed

If the infeed is high, the wheel wear increases and the surface finish deteriorates, thus affecting the dimensional and geometrical accuracy of the ground work-piece. The material removal rate, however, increases if the infeed is high.

Table 3 Basic process data for cylindrical grinding

Work material	Material Condition	Work surface speed (m/min)	Infeed(mm/pass)		Traverse for each work revolution, in fraction of the wheel width	
			Roughing	Finishing	Roughing	Finishing
Plain carbon steel	Annealed	30	0.076	0.0130	½	1/6
	Hardened	22	0.076	0.0076 to 0.0130	¼	1/8
Alloy steel	Annealed	30	0.076	0.0130	½	1/6
	Hardened	22	0.076	0.0076 to 0.0130	¼	1/8
Tool steel	Annealed	19	0.076	0.0130	½	1/6
	Hardened	16	0.076	0.0076 to 0.0130	¼	1/8

Traverse feed

The traverse feed or cross-feed rate is governed by the width of the wheel and the work speed. Normally, the traverse-feed rate is adjusted to two-thirds to three-fourths of the wheel width while grinding steels and three-fourths to five-sixths of the wheel width while grinding cast iron. Heavier cross-feeds increase the wheel wear and produce rougher finish and slower cross-feeds reduce the wheel wear and produce finer finish (Arabatti et al., 1996).

Area of grinding contact

The area of grinding contact between the wheel and the work affects the choice of grit size and grade. The area of contact is relatively large in the case of internal grinding and surface grinding and also when large diameters of work are ground with a small diameter wheel. A larger area of contact produces a lower pressure. On larger areas of contact and lower pressure, a soft grade wheel provides normal breakdown of the grit, ensuring continuous free cutting action. In addition, coarser grit is preferred to provide adequate chip clearance between the abrasive grains. When the area of contact becomes smaller, the pressure, which tends to break down the wheel face, becomes greater, finer grit, and harder grade wheels should be used.

2.5 Metallurgical effects associated with grinding

When a metal is ground, its surface is not only plastically strained by the grits, but is also heated. It is the plastic flow induced by the stress ahead of a grit, which causes chips to be produced when the grit is favourably placed, and which leaves the work-piece surface in a state of plastic strain. Much redundant work is done in removing metal in this way, so that a large power is commonly developed at the contact between the grinding wheel and the work-piece. If this rises too much, it cannot be dissipated without an excessive rise in work-piece temperature, which may cause grinding burn or cracks. Clearly, the metallurgy of the work-piece influences the stresses and power developed at the contact under given grinding conditions. It also influences the temperatures and thermal stresses, which a work-piece can withstand without damage (Torrance, 1978).

Table 4 Recommended bonds and wheel speeds for different grinding operations

Type of grinding	Wheel speed (m/sec)
Rough grinding wheels with vitrified bond	25
Rough grinding wheels with resinoid bond	45
Surface grinding wheels with vitrified bond	20-25
Internal grinding wheels with vitrified bond	20-35
Centreless grinding wheels with vitrified bond	30-45
Cylindrical grinding wheels with vitrified bond	20-35

2.5.1 The nature of grinding damage

Tarasov (1950) investigated the microstructure and hardness changes, residual stresses and occurrence of tiny surface cracks or heat checks in the ground surfaces of hardened steels, which are generally attributed to the unsatisfactory grinding practice, such as the use of too hard a wheel, or a dull wheel, or the rate of stock removal, is excessive. Tarasov's approach addressed not only the surface cracking of hardened steels but also its connection with related problems, such as grinding burn and soft skin. He showed that the grinding process is capable of affecting the metallurgical and physical condition of the surface layers and in turn, the original metallurgical condition of the steel could affect the way it would respond to grinding.

When hard materials such as hardened steels, cast cobalt alloys and cemented carbide are ground under abusive conditions, it is found that the surface got cracked after grinding. These cracks are found to be shallow and bear some relationship to the grinding marks. In fact, they are found to be primarily perpendicular to the grinding marks. If the crack pattern is more pronounced, there might be cracks joining the perpendicular ones and forming a network. In case of hardened steels, Tarasov investigated the carbide network, which initiates the cracks. He also found the proper heat treatment process to eliminate such network, which were cracking. He investigated the metallographic features of burn in several steels using a taper sectioning technique. They confirmed that burn is as described above in a fully hardened 18:4:1 tool steel and showed that the martensite formed during rehardening burn etches white. Beneath this white layer was a thin transition zone in which the prior austenite grain boundaries etched white and the grain centres dark. Beneath the transition zone was a dark etching tempered zone gradually merging with the structure of the substrate. Caste iron, both grey and white and AISI 52100 steel were also studied. Rehardening burn could be induced on the hardened steel and on the grey iron, but did not occur in soft steels or white iron. Burnt specimens were examined visually after macro etching. Abusively ground soft steel work-pieces showed dark etching flecks, which the authors suggested, were zones of high residual stress, preferentially attacked by the etchant. Rehardened zones were usually slightly harder than the substrate, whereas tempered zones were softer. The dark flecks on the soft steel were of similar hardness to the substrate (Malkin and Fedoseev, 1991).

Torrance (1978) gives details of the changes produced in C1023 work-pieces ground in creep feed. This is a nickel-based alloy designed for service at temperatures approaching 1000 ° C, So temperatures of this order must be generated in the contact before burn becomes noticeable. When burn does occur, the γ precipitates responsible for the alloy's high temperature strength are dissolved to a depth of up to 1 mm beneath the surface. If the work-piece is then heated to its service temperature, the deleterious sigma phase is precipitated in the burnt zone. Surface changes of much smaller depth were also observed on correctly ground work-pieces, their nature depends on the grinding conditions

2.5.2 Metallurgical factors

Some investigators have claimed that metallurgical factors influence susceptibility of steel to grinding damage. Tarasov (1950) states that many authors have found steels containing residual austenite to be prone to grinding cracks. He suggests that this may be due to stresses set up by the transformation of residual austenite to martensite under the influence of grinding strains. The increasing chromium content in low alloy steels favours cracking and more alloying elements are added to retain the austenite.

Littman and Wulff (1955) confirmed that the hardness changes induced in AISI 52100 by grinding burn were consistent with the temperature rises linearly with the energy input to the grinding zone and it falls off very steeply with depth beneath the surface.

2.5.3 Grinding mechanics and contact temperatures

Hahn (1966) has studied the way tensile residual stress is generated in an abusively ground work-piece, suggesting that it arises in the following way: as the work passes through the arc of cut, its surface is heated locally, causing it to expand against the constraint of the cool surrounding material. If the temperature rises sufficiently, the heated spot will soften and flow plastically under the thermal stress. When it emerges from the arc of cut, it will be rapidly quenched by the bulk of the work-piece and by the coolant. The hot spot contracts during the quench and is left in a state of tension. In steels, martensite may be formed during this cycle. Since a volume increase occurs, the stress is modified to leave the martensite in compression.

The stress developed in this way in a given material depends mainly on the temperature reached in the arc of cut and quenching rate. Both depend on grinding conditions. The problem of grinding damage may therefore be treated as a heat transfer problem, the work of Jaeger (1942) being used to relate contact temperatures to the power developed in the arc of cut. The problem is extremely complex, since the heat generated in the arc of cut is partitioned in an unknown way between wheel, work, chip and coolant. A detailed treatment has been given by Des Ruisseaux et al. (1970) who allowed for cooling of the work-piece by convection and consider the effect of coolant application, wheel speed and work speed on work-piece temperature. They showed that this could be calculated by ignoring the effects of individual grits and treating the arc of cut as a band heat source.

Another difficulty with this approach is that the lower tendency to grinding burn at higher infeed is not predicted. Presumably, the partition of energy changes as the infeed is increased, a higher proportion going to material, which is eventually removed. This kind of consideration has led other authors to place more emphasis on the mechanics of grinding in predicting burn. Hahn (1955) introduced an empirical wheel sharpness factor to allow for this but did not consider the effect of coolant. He, however, predicted the same behaviour as Des Ruisseaux et al. (1970) at constant wheel sharpness in the absence of coolant. Malkin (1978) found that for a given material grinding burns occur when the total wear flat area on a grinding wheel exceeds a fixed level (approximately 4% of the total), independent of wheel grade. The grinding forces are proportional to the wear flat area and the constant of proportionality rise sharply at burn. However, it appears that the burn referred to here is rehardening burn. Tempered burn, which can be extremely damaging in hard components, is not considered in this study. Malkin's work stresses the importance of the detailed interaction of grit and work piece in determining the partition of energy. He divides forces into cutting, ploughing and rubbing components. Cutting energy may be partly carried off with the chip but rubbing energy goes to the work piece, so a high rubbing energy favours burn. Anything, which reduces the rubbing energy, such as lubrication or wheel sharpness, reduces the tendency to burn.

The literature cited above shows that it is primarily the generation of high temperatures, which causes grinding damage. Where the work-piece is kept cool, damage is minimized. Unfortunately, the thermal analysis of grinding is hampered by an inadequate knowledge of grinding mechanics, so that no one theory of grinding damage can be considered complete. It was hoped that metallurgical changes on the surface layers of both burnt and normally ground work-piece would indicate more clearly the mechanics of the grinding process.

3. Quality and productivity in grinding

3.1 Surface integrity

3.1.1 Introduction

The term surface integrity in machining and grinding was coined by researchers at Metcut Research Associates. Surface integrity is defined as the unimpaired surface conditions, which are developed in hardware by using controlled manufacturing processes. Two elements comprise the surface integrity. The first is the topography that is produced on the surface and the second is the metallurgical alterations produced at or near the surface. It thus includes surface finish, accuracy, residual stresses and metallurgical damage to the ground or machined surface. Several causes can be attributed to poor surface integrity, including, sub-surface plastic deformation, phase transformations, intergranular attack , thermal softening or hardening , redeposited layers, micro as well as macro cracks, recrystallization and residual stress distribution. Typical surface integrity problem includes grinding burns, untempered martensite, grinding cracks, lower fatigue strength of parts, distortion and residual stresses and their effect on distortion, fatigue strength and stress corrosion (Taylor, 1907).

Surface texture is defined as the inherent or enhanced condition of a surface produced in a machining or other surface generating operation. It was found in many cases, the nature of the surface layer has strong influence on the mechanical properties of the material. This association is more pronounced in some materials and under certain machining operations.

Nam et al. (1987) stated that the surface finish is a major concern in manufacturing. Yet very little attention has been given to elucidate the relationship between the characteristics and the functional requirements of surfaces. A recurring problem in the specification of surface characteristics and the design and manufacture of tribological surfaces has been the lack of a clear understanding of the friction and wear phenomena. Consequently, despite the engineering importance of low-friction and low-wear surfaces and the resulting economic benefits, so far it is very difficult to choose manufacturing process and its parameters for sliding surfaces to optimize the functional requirements.During grinding, the topography of the wheel surface changes by wear, which usually results in a poor surface finish of the work-piece. Metal removal rate and grinding time or ground volume have a considerable effect on the work surface roughness (Verkerk, 1978).

The quality of a machined surface is becoming more and more important to satisfy the increasing demands of sophisticated component performance, longevity and reliability. Structures for military and commercial aerospace, automotive and other capital goods industries are being subjected to more severe conditions of stress, temperature and hostile environments (Field and Kahles, 1971).In response to the above needs, there has been a continued increase in the development and use of heat resistance, high corrosion resistant and high strength alloys in the wide variety of structural applications.

One of the many problems facing the metal working industry is the production of accurate surfaces of good surface finish in a minimum of time. Grinding has been an accepted means for producing precision surface, with low values of surface finish for many years. However, as surface finish requirements become more stringent and the demand for shorter cycle times and reduced costs more prevent the problem of generating an accurate surface of low surface roughness in a short time becomes important (Hahn and Lindsay, 1966). This physical surface state of machined work-piece is a function of its material processing and the machining conditions. This surface state is summed up by the “SURFACE INTEGRITY”.

This surface integrity has two important parts, viz.,
(i) surface texture and (ii) surface metallurgy.

(i) **Surface Texture:** This governs principally the surface roughness, which essentially is a measure of surface topography or its interface with its environment.

(ii) **Surface Metallurgy:** This is the study of nature of the surface layers produced in machining. It describes the nature of the altered layers below the surface respect to the base of the material.

3.1.2 Factors related to surface integrity

When dealing with manufacturing issues, it is important to keep in mind that all the parameters involved in the finishing process have a direct influence on the surface integrity of the part. The six groups of key factors presented in Fig. 7 are not random, but are rather the deterministic outcome of the process chosen (Subramanian and Lindsay, 1992). Basic understanding of the casual relationships between the mechanical, thermal and chemical aspects of a finishing process and the six groups of key factors related to surface integrity is the key to successful improvement of a finishing process.

3.1.3 Surface integrity problems

Typical surface integrity problems include:

(i) Grinding burns on high strength steel landing gear components,
(ii) Untempered martensite in drilled holes.
(iii) Effect of cutting fluid on the stress corrosion properties of titanium
(iv) Grinding cracks in root section of cast nickel base gas turbine buckets
(v) Lowering of fatigue strength of parts processed by EDM or ECM
(vi) Distortion of thin components and
(vii) Residual stress induced in machining and its effect on distortion, fatigue and stress corrosion.

3.1.4 Factors affecting surface integrity

There are seven major factors influencing surface quality in machining operations

(1) Finishability of cutting tool
(2) Type and condition of cutting tool
(3) Machine tool rigidity and bearing
(4) Application of cutting fluid
(5) Method of chip removal
(6) Geometry of cutting tool and

Cutting variables like feed, speed, depth of cut etc.

3.1.5 Control of surface texture

Surface characteristics should not be controlled on a drawing or specification unless such control is essential to functional performance or appearance of the product. Imposition of such restrictions may unnecessarily increase the production cost and lessen the emphasis on the control specified for important surfaces.

Smoothness and roughness are relative, i.e., surface may be either smooth or rough for the purpose intended, what so smooth for one purpose may be rough for another purpose. In the mechanical field, comparatively few surfaces require control of surface texture beyond that afforded by the processes required to obtain the necessary dimensional characteristics.

Working surfaces such as those on bearings, pistons and gears are typical of surfaces for which optimum performance may require control of the surface characteristics. Non-working surfaces such as on the walls of transmission cases, crankcases to bearings seldom require surface control.

Determination of required characteristics for working surfaces may involve consideration of such conditions as the area of contact, the load speed, direction of motion, type and amount of lubricant, temperature, material and physical characteristics of component parts. Variations in any one of the conditions also may require a change in the specified surface characteristics.

3.1.6 Effect of surface roughness on the performance of machined parts

The surface roughness of machined surfaces has an important effect on the functional properties and performance of machine parts. It greatly affects the wear resistance, fatigue strength and corrosion resistance of the part.

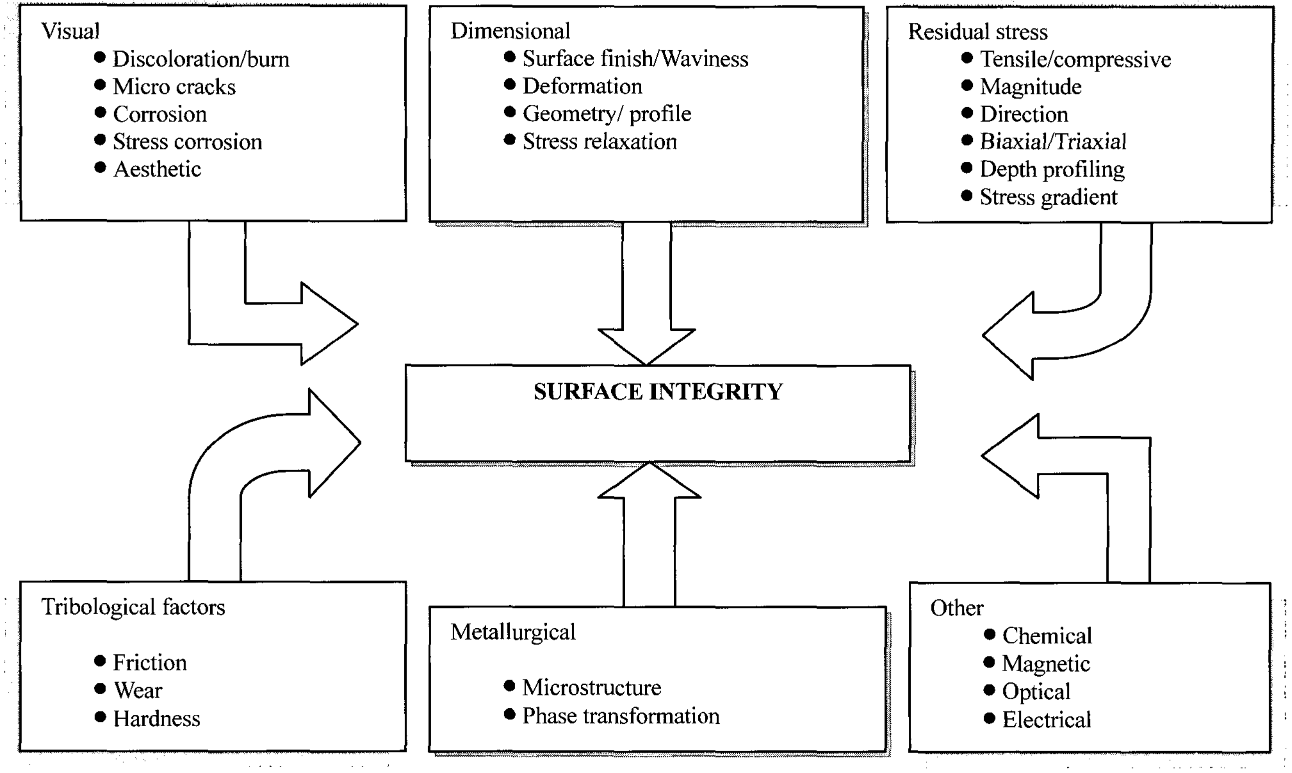


Fig. 7 Six different groups of key factors that define the surface integrity of a finished material

Wear resistance

The wear resistance of two rubbing surfaces depends upon the stability of the surface layers against failure, which in turn, depends to a great extent on the specific pressure between the two rubbing surfaces. Micro irregularities and waviness on the surfaces reduce the area of contact between them, since the surface make contact only at the crests. This increases the specific pressure and temperature at the places of contact. This leads to more intensive deformation, crushing, shearing and chipping of the ridges on both surfaces, results in increased wear on surfaces. The peaks on the two surfaces also break the lubricating oil film, resulting in dry friction conditions, which lead to increased wear. However, some sort of surface roughness is desirable to retain the lubricating oil, which is not possible with perfectly smooth surfaces. The retaining of the lubrication oil on the surfaces, under various conditions of friction (in accordance with the load, velocity and material of the main parts etc.) depends largely on the size of the micro-irregularities (Chisholm, 1949)

HIf the height of the micro-irregularities is extremely small, there may also be intensive wear between two rubbing surfaces since the co-efficient of friction is first reduced with a decrease in the height of the micro-irregularities, reaches a minimum value and increases. Thus, an optimum value of surface roughness can be established to suit definite friction conditions. Macro-geometric deviations may also lead to uneven wear of certain section of the surface.

Fatigue strength

Almen and Black (1966) investigated that the lines, deep and sharp scratches across a surface become points of internal stress concentration. The bottom of the valleys between the ridges of surface micro-irregularities may be such point at stress concentration. Thus, in turn, may lead to formation of cracks, which substantially reduce the strength of the part and ultimately may result in failure of the part.

Corrosion resistance

The valleys are the places where the corrosive agents may accumulate. Therefore, the rougher the surface, that is, the deeper and the more sharply deepened the valleys between the ridges of micro-irregularities, the more favourable the conditions for corrosive action and its penetration into the depth of the material. The smoother the surfaces, lesser will be the area of contact of the surface with the corrosive medium. Consequently, lesser will be the attack of corrosive medium on the surface.

3.1.7 Measurement techniques and instruments used in surface metrology

During the last several years, there has been a dramatic evolution of instruments for measuring roughness. Surprisingly, the evolution has not been concentrated in the filed of area techniques where the global economic pressure towards automated factories is a driving force; rather, its main thrust has been in the profiling of very smooth surfaces (Hocken 1987).

Roughness specifications are important to the function of many kinds of industrial surfaces. The traditional areas of application have been in the automotive, aircraft and other metal working industries where the surface roughness of many kinds of machinery components is well controlled.

Machining operations and wear processes affect the surface topography of engineering components in a way, which may have a significant influence on their function (Sherrington and Smith, 1986). Interest in this phenomenon has lead to the development of a plethora of instruments for measuring surface topography.

In recent years, this development has centered largely on instruments, which measure surface topography to optical means (Sherrington and Smith, 1988). However, these devices are, as yet, not particularly well established in terms of the number of people who use them routinely. This situation may well change in the future but, for the moment, more traditional techniques share the bulk of the workload. It is therefore, appropriate to review this field.

Surface structure or topography is commonly characterized along the

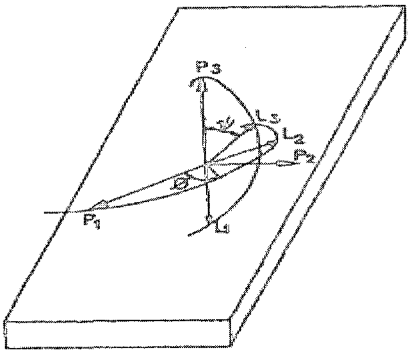


Fig. 8 Axial system for residual stress measurements

vertical direction by height (amplitude) parameters and along the horizontal directions by spatial (wavelength) parameters. Any measurement method should ideally be able to record both forms of roughness variation to allow a complete description of a specimen surface to be obtained.

In the vertical plane, roughness amplitudes vary widely. Coarse machining operations can produce features several hundred micrometers high. However, in contrast, some surfaces manufactured for special applications may contain perturbations of only molecular dimensions.

In the horizontal plane, roughness variations arise on a scale, which varies from the dimensions of the specimen down to atomic diameters. It is clear, therefore, that wide extremes of range need to be encompassed by any technique used to measure surface topography.

3.2 Residual stresses in materials

3.2.1 Introduction

All the manufacturing processes introduce residual stresses due to non-uniform changes induced by the process within the body. These stresses influence the mechanical properties like fatigue strength, depending on their nature, magnitude and distribution across the body. There is basically no material or situation free of these stresses. Hence, the general interest today is the recognition and measurement of these residual stresses. The X-ray diffraction method is used to determine the residual strains present in the surface of the material. This method is non-destructive in nature. This is based on the measurement of changes in lattice spacing. Such relative changes of the distance between lattice planes are called lattice strains. In the X-ray method, an X-ray beam, which leaves the material unscathed, is irradiated on the specimen's surface and the lattice strain is calculated from the diffraction peak shift.

3.2.2 Principle of X-ray diffraction method

X-ray diffraction method employs Bragg's law to estimate residual strains present in the atomic planes. In this method, a monochromatic X-ray beam of sufficient intensity is made incident on the atomic planes. The reflected beam from successive planes of atoms is observed Bragg's law defines the condition for diffraction through the following equation.

$$\lambda = 2d \sin \theta \tag{8}$$

Where,

λ - Wavelength of incident X – Rays,

θ - Angle between incident or reflected beam and reflecting planes,

d - Interplanar spacing, and n - Order of reflection (n = 1, 2, 3...)

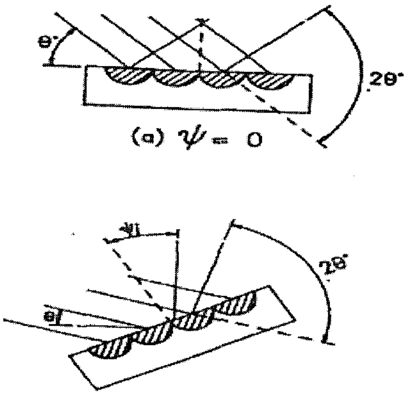


Fig. 9 Sampling of different grains in the specimen by incident X-ray beam at (a) ψ =0° and (b) ψ = ψ_i

The Equation (8) shows that, if the wavelength of X-rays is known, the interplanar spacing'd' can be determined by measuring the angle θ . In presence of residual stresses, the d-spacing changes and this in turn results in shift in X-ray diffraction peaks. Therefore, this shift in diffraction peaks is a measure of residual stresses. Fig. 8 Shows the configuration generally followed for residual stresses measurements P_1, P_2 and P_3 refer to three orthogonal directions relative to the sample under investigation and L_1, L_2 and L_3 describe the laboratory or measurement frame of reference.The angles ψ and θ define the relationship between P_i and L_i axes describes the angle between the specimen surface normal (P_3) and the direction of strain being measured (L_3); θ denotes the angle between one of the principal stress axes (P_1) and the projection of the measured strain direction (L_3) on to the specimen surface. In the widely used "$\sin^2 \psi$ Method, diffraction measurements are made at several tilt angles ψ . For the general case of two measurements at ψ =0° and $\psi = \psi_i$ (Fig. 9), Noyan and Cohen (1986) have given the following equation for the surface residual stress σ_ϕ

$$\sigma_\phi = \frac{E}{1+\nu}\;\frac{1}{\sin^2\psi}\;\frac{d_{\phi\psi} - d_{\phi\psi=0}}{d_{\phi\psi=0}} \tag{9}$$

Where,

$d_{\phi\psi}$ – Interplanar spacing in the described by the angles ϕ and ψ

$d_{\phi\psi=0}$ – Stress free interplanar spacing value

E – Young's modulus of the material and

ν – Poisson's ratio.

The term E / ($\sin^2\psi$) (1+ν) is constant and is defined as K. Using the linear relationship given in Equation (9) for surface residual stress, the lattice strain Δ d/d plotted against $\sin^2 \psi$ would produce a straight line whose gradient is a function of σ_ϕ, ν and E.

Then, $$m^* = \delta\varepsilon_{\phi\psi} / \delta \sin^2\psi \tag{10}$$

$$\sigma_\phi = m^* / \{(1+\nu)/E\} \tag{11}$$

Where,

m* - Gradient of a least squares straight line fit through the data points and $\varepsilon_{\phi\psi} = \Delta d / d$

Depending on the incident beam energy and the material under study, the information on surface residual stresses with in a depth of 10 – 30 μm is possible. For example, in the case of Cr, Kα , and X-rays the depth of penetration in steel is of the order of 15 to 20 μm.

3.2.3 Mechanism of residual stress formation

First, while considering the thermal influence, the temperature developed at the contact zone of the work-piece and grinding wheel is of very high order. The heat developed at the interface flows into the work-piece and it also increases the local temperature. The cooling is associated with the reduction of elastic deformation thus producing "Tensile Residual Stresses" (Fig. 10).

Secondly, while considering the mechanical influence, the normal force produced by the grinding wheel on the work-piece plays a major role. This normal force produces an elastic or plastic tensile deformation on the surface layer of the work-piece. (Fig. 11). "Compressive residual stresses" are produced due to the decrease of normal force with the reduction of elastic deformation (Brinksmeier et al., 1982).

Finally, while considering the material influence, the temperature developed at the contact zone plays a major role. The heat developed during machining flows into the work-piece and increases the local temperature thus causes some phase transformations on the surface layer of the work-piece. If the phase transformation is martensite to ferrite/pearlite then the volume decreases hindered by the bulk material produces "Tensile Residual Stresses". If the phase transformation is ferrite /pearlite to martensite then the volume increases hindered by the bulk material produces Compressive Residual Stresses.

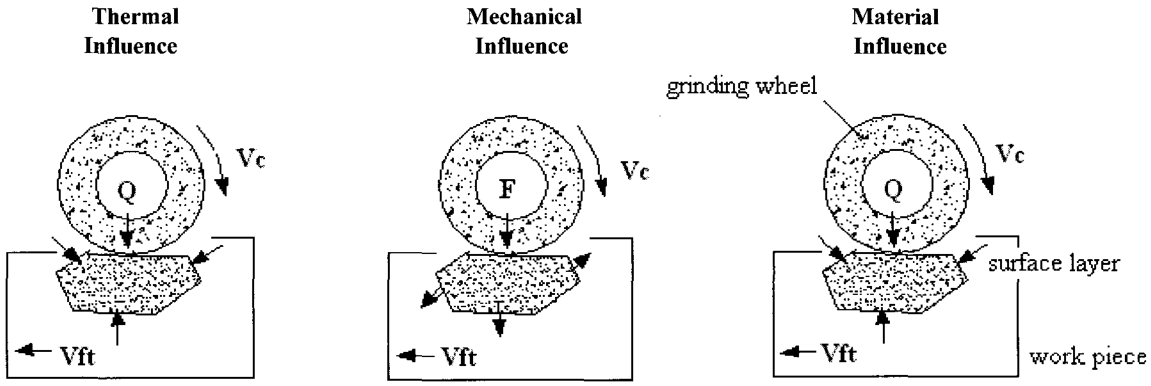
3.3 Time Temperature Transformation (TTT) diagram

It is observed from TTT diagram (Fig. 12), the ferrite-cementite mixture formed at different temperatures due to the transformation of austenite, differs primarily in the degree of dispersion (or refinement) of both phases.

At lower transformation temperatures, both the phases are most dispersed. But, at high transformation temperatures (at about 700 ° C) the ferrite-cementite mixture becomes sufficiently distinct and is known as pearlite

It has also been observed that at somewhat lower transformation temperatures (at about 650°C) the ferrite-cementite mixture is more dispersed and is shown as sorbite. At still lower transformation temperatures (at about 600°C) the ferrite-cementite mixture becomes so dispersed and its structure is similar to pearlite and sorbite and is known as troosite.

At still lower transformation temperature (from about 550°C to 200°C) the ferrite-cementite mixture is more dispersed and is known as acicular troosite. It has a needle like structure. At still lower transformation temperatures (below 200°C) the austenite does not change into ferrite-cementite mixture, but is changes into martensite. The formation of martensite does not take place instantaneously. It depends upon the temperature and occurs over a wide range. The upper and lower limits of the transformation range are known as martensite start (Ms) and martensite finish (Mf) respectively. When the specimen of eutectoid steel is rapidly cooled from austenite region, a new phase martensite is formed at temperature below 220°C. 100% martensitic transformation cannot be possible even if the high carbon steels are quenched in ice-cold water. Some austenite is always left untransformed. This austenite is known as retained austenite or residual austenit



# Heat flow to the workpiece # Local temperature increase elastic/plastic compressive deformation of the surface layer hindered by the bulk material # Cooling with reduction of elastic deformations	* Affecting normal force * Elastic/plastic tensile deformation of the surface layer * Decrease of normal force with reduction of elastic deformations	□ Heat flow to the workpiece □ Local temperature increase □ Phase transformations	
		Martensite to ferrite / pearlite Volume decrease Hindered by the bulk material	Ferrite / pearlite to Martensite Volume increase hindered by the bulk material
⇩	⇩	⇩	⇩
Tensile residual stresses	Compressive residual stresses	Tensile residual stresses	Compressive residual stresses

Fig. 10 Mechanism of residual stress formation

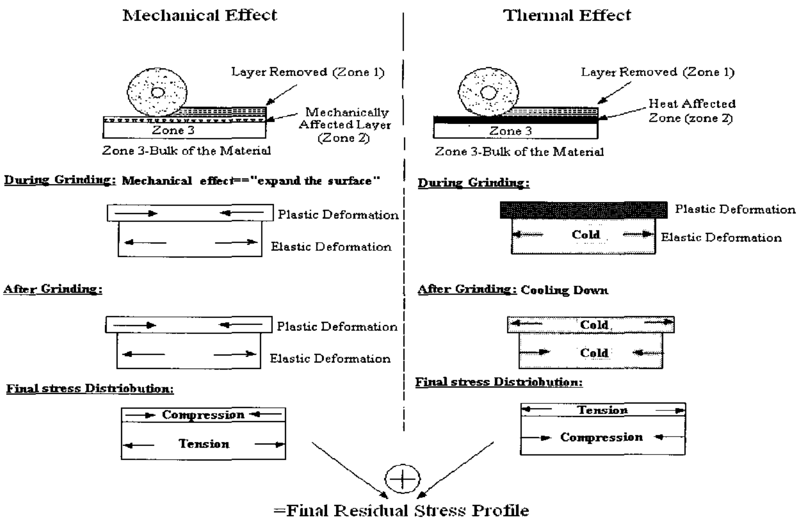


Fig. 11 Residual stress profile left in ground components by the superimposition of mechanical and thermal effect

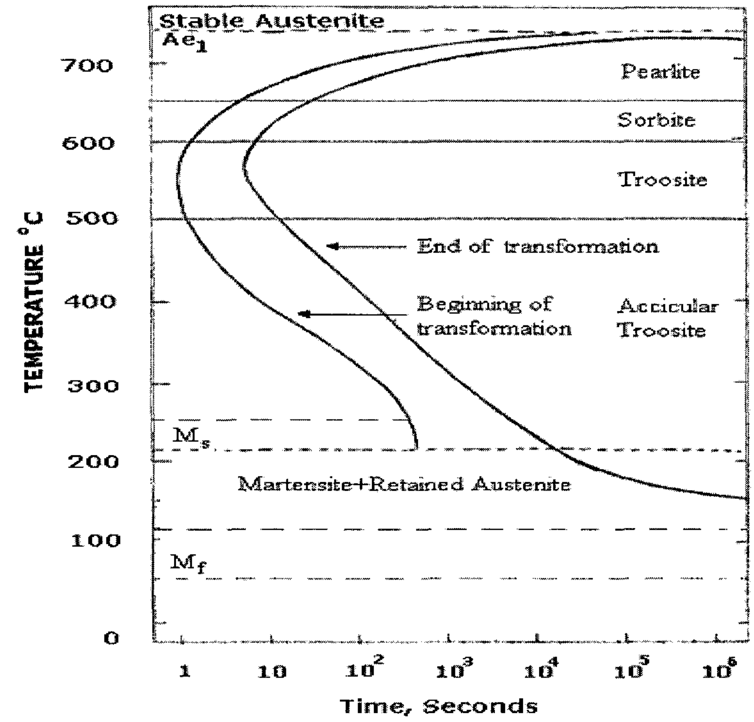


Fig. 12 Time – Temperature – Transformation diagram

3.4 Design of Experiment

3.4.1 Introduction

In the industrial scenario, TQM has become the most important concept because the quality of the product makes the difference between success and failure of any organization. TQM is the integration of all functions and processes within an organization in order to achieve continuous improvement of the quality of goods and services.

Since the late, 1940's Genichi Taguchi has introduced several new SQC Concepts, which have proven to be valuable tools in the subject of quality improvement. Taguchi has differentiated the quality into three stages; System Design, Parameter Design and Tolerance Design. The Parameter Design stage is also called Robust Design. Its main aim is to reduce costs and improve quality. The quality of a product normally depends on the parameters that govern the behavior of the process for manufacture it. This is achieved through deriving optimum parameters setting using statistical techniques and experiments. Taguchi has suggested a new approach for the design of experiments, which identifies the nature of parameters, by conducting minimum number of experiments, which is extensively applicable in Research and Development sectors and manufacturing industries (Genichi Taguchi, 1987).

Part of a review, information's is provided regarding Design of experiment, Taguchi's method, Artificial Neural Network and applications of ANN.

3.4.2 Definition

The study of most important variables affecting quality characteristics and a plan for conducting such experiments is called the Design of Experiments.

3.4.3 Need for planned experimentation

In a highly competitive market, most enlightened companies recognized the need for continuous improvement to their products and services as a key success factor to maintain market leadership. The challenge therefore for any organizations is to find out the methodology to achieve design optimization for quality, cost and delivery.

The basis for the engineering design activity is the Knowledge of scientific phenomena and past engineering experiences with similar product design and manufacturing processes. However, when a new product has to be developed a lot new decisions have to be made with regard to product profile, critical parameters of the product design, various manufacturing processes to be adopted etc. So many interactive forces may affect the decision. However, it seems to be an overwhelming task to figure out a simple, economic safe course of action.These situations are common in industry; they affect all departments across the organization and at all levels. In these cases, it is necessary to experiment to make a planned change, determine the effect of the change, and use this information to make a decision about accepting or rejecting the new alternative considered. It is the Quality of this decision, which can be improved up on when proper test strategies are utilized.

In general, planned experiment is necessary to distinguish between critical factors and non-critical factors as well as to identify the optimum level of the critical factors so as to pave the way for significantly improved performance. It also enables to predict the extent of improvements possible over the existing performance.

3.4.4 Experimental design

The analysis of any data is dictated by the manner in which data are collected. Design of experiment is then a plan for collection of data on response(s) when the chosen factors are varied in a prescribed. The three types of experiments are:

a. **One factorial at a time**
These are experiments when in each experiment only one factor is changed from one level to another level, keeping all the other factors unchanged.

b. **Full factorial experiments**
This is an experiment method where all factors are tried f or all combinations of their levels.

c. **Fractional factorial experiments**
As the name indicates, instead of doing full factorial, partial factorial is done. This essentially means a reduction in the number of experiments.

3.4.5 Experimental design procedure

Researchers or engineers in all fields of study to compare the effects of several conditions or to discover something new carry out experiments. If an experiment is to be performed most efficiently, then a scientific approach to planning it must be considered. The statistical design of experiments is the process of planning experiments so that appropriate data will be collected, the minimum number of experiments will be performed to acquire the necessary technical information, and suitable statistical methods will be used to analyze the collected data (Fig. 13).

3.4.6 Taguchi's method and steps in designing experimental layout

Genichi taguchi (1959) of Japan, by developing the associated concept of linear graph, was able to device numerous variants based on the OA design, which can easily be applied by an engineer or a scientist without acquiring advanced statistical knowledge for working out the design and analysis of even complicated experiments (Ross J. Philip, 1989).These methods have the advantage of being highly flexible and readily enable allocation of different levels of factors, even when these levels are not the same in number for all the factors studied. The beauty of these methods lies in cutting to the bare minimum the size of experimentation. At the same time yielding results with high precision, thus, by a mere 27experiments, we may be able to evaluate all the main effects along with one technologically relevant first order interaction through the OA design, as against 59,049 experiments needed by a full factorial design for 10 factors each at three levels.

3.4.7 Design layout in Taguchi's Method:

1. List down the Response, Factors and levels along with the desired interactions.
2. Find the Degrees of Freedom for each factor and for each interaction.
3. Compute the Total Degrees of Freedom (TDF).
4. The minimum number of Trials (MNE) is equal to the Total Degrees of Freedom Plus one (TDF +1).
5. Choose the nearest orthogonal array series like : L4, L8, L16 or L9, L27, etc.
6. Draw the required Linear Graph (LG).
7. Number the linear Graph by starting with the Number 1 for Factor A and Number 2 for Factor B. Then check whether any interaction exists. If not, proceed with the Number 3 for Factor C. If there is an interaction, check with the Interaction Table, which Column is to be allotted to the interaction? Then proceed with the next number for the next factor.
8. Complete the numbering as described until the following is achieved.
    All the factors and interactions are numbered.
    There is no repetition of numbers.
    The interaction numbers are as per the Interaction table.
    The numbers used do not exceed the number of columns permitted for the Orthogonal Array Table.
    For Example, only four (4) numbers (Numbers through 4) are permitted for the L9 OA (Table 5).
9. Write the column numbers against each factor. That is the Design Assignment. Rewrite the OA Table with only those columns represented by factors and all the rows as per the OA Table. Replace the 1, 2 and 3 in the Table with the Physical value of the level from the Factors and Levels identified.

This completes the Design Layout.

One need not conduct the Experiment in the same order as in the OA Table. We can randomize the order by any method of Random Number generation.

3.4.8 Analysis of Variance - ANOVA

ANOVA is a technique for determining equality of two or more Averages based on data from samples. It is mainly used to isolate the dominate factors or interactions from a list of suspects and to estimate the proper level for each important factors in order to yield optimum end results.

3.4.9 Signal to Noise ratio

It was developed as a proactive equivalent to the reactive loss function. Signal factors (Y) are set by the designer or operator to obtain the intended value of the response variable. Noise factors s^2 are not controlled or very expensive or difficult to control. In elementary form S/N is Y / s^2

Table 5 Orthogonal array of L9 showing 4 factors with 3 levels

Expt. no.	Factor 1	Factor 2	Factor 3	Factor 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

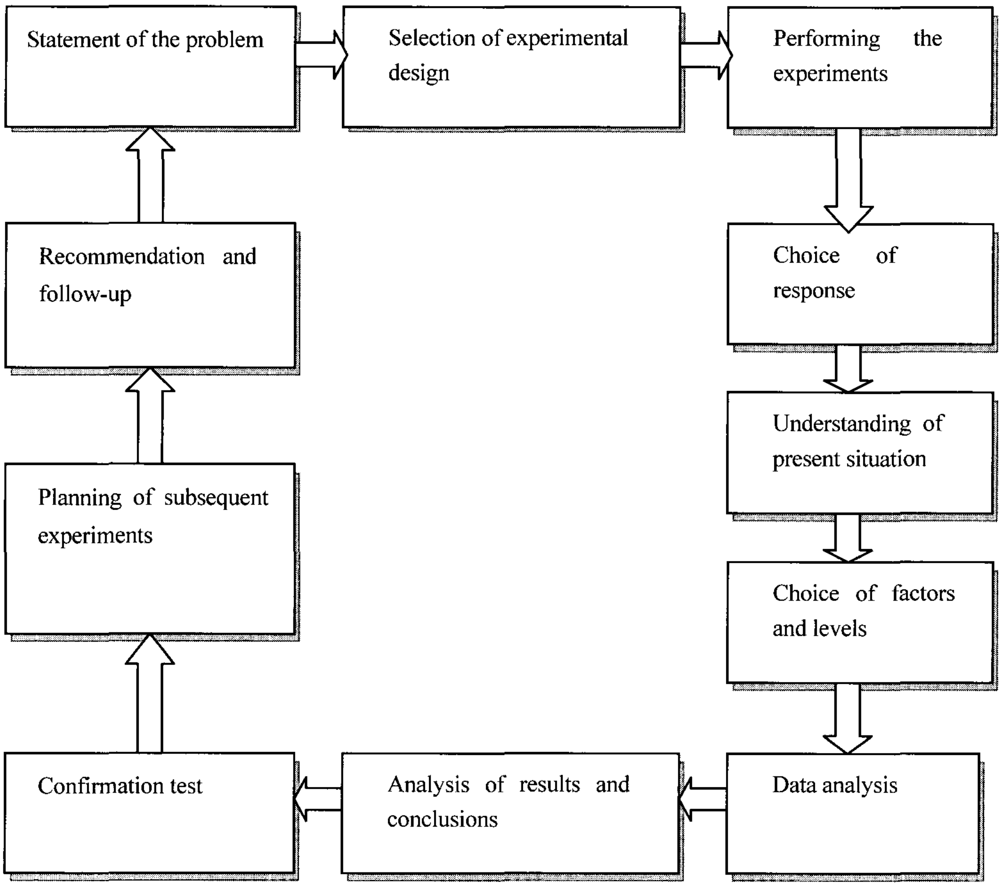


Fig. 13 Outline of experimental design procedure

3.5 Artificial Neural Network

3.5.1 Introduction

With the increasing availability of computers it is possible to built the data bases on several areas of management viz., administration, accounting, personal, purchase, production, marketing and services for the data in the databases to become useful they have to analyze using appropriate expert tools so that relevant results are obtained and valid inferences drawn for decision making. It is most desirable to use MATLAB in integrating the data's of Taguchi's orthogonal array of experimentation with ANN techniques to facilitate the optimization of process variables in grinding.

Neural Network process information in a similar way the human brain does. The network is composed of a large number of highly interconnected processing elements working in parallel to solve a specific problem. Neural networks learn by example. They cannot be programmed to perform a specific task. The examples must be selected carefully otherwise useful time is wasted or even worse, the network might be functioning incorrectly. The disadvantage is that because the network finds out how to solve the problem by itself, its operations can be unpredictable. On the other hand, conventional computers use a cognitive approach to problem solving and these machines are very predictable.

Neural networks and conventional algorithmic computers are not in competition but complement each other. There are tasks that are more suited to an algorithmic approach like arithmetic operation and tasks that are more suited to neural networks. Even more a large number of tasks, require systems that use a combination of Neural network with High-level language program to perform at maximum efficiency (Rowe et al., 1996).

3.5.2 An engineering approach

An artificial neuron is a device with many inputs and one output. The neurons are of two modes of operation; the training mode and the using mode. In the training mode, the neuron can be trained to fire or not to fire for particular input pattern. In the using mode, when a taught input pattern is detected at the input its associated output becomes the current output. The statistical models available to study the grinding process are proved to be tedious and time consuming. Due to non-linear nature of grinding process, a large number of experiments are required. In order to obtain functional relationship between process parameters and surface roughness, neural networks are used. Dixit and Chandra (2003) suggested a procedure of developing neural network models with limited number of data sets. Moreover, neural networks are able to learn by examples.

3.5.3 Architecture of ANN

Feed forward networks - allows signals to travel one way only from input to output. Feed back networks - have signals traveling in both directions by introduction loops in the net works. The commonest type of artificial neural network consists of three layers; layer of input units is connected to a layer of hidden units, which is connected to layer of output units (Fig. 14).

Learning process – Learning methods are classified into two major categories.

a. Supervised learning – which incorporates an external teacher so that each output unit is told what desired response to input signals is ought to be.
b. Unsupervised Learning – Uses no external teacher and is based upon only local information.

Transfer function - The behaviour of an ANN depends on both the weights and the input – output function (Transfer function) that is specified for the units. This function falls into three categories namely linear, threshold and sigmoid function.

Back Propagation Algorithm – In order to train a neural network to perform some task, the weights of each unit are to be adjusted in such a way that the error between the decided output and the actual output is reduced. This process requires that the neural network compute the error derivative of the weights (EW). The back propagation algorithm is most widely used methods for determining the EW and is mostly used if all the units in the network or linear. For non-linear network before back propagation, the EA must be converted into the EI, the rate at which the error changes as the total input received by a unit is changed (Fig. 15).

3.5.4 Applications of Neural network

Neural networks have broad applicability to real world business problems like sales forecasting, customer research, Data validation, Risk management, Target marketing and industrial process controls. Nowadays ANN is used in medicine, modeling and simulation of process and product, texture analysis, "three-dimensional object recognition" etc.

4. Concluding Remarks

From the various issues discussed above it may be summed up that,

- Implementation of optimal machining condition in grinding process can improve the surface integrity and reduce the grinding cycle time of the components.
- Adoption of in process energy utilization in the process cycle is a possible alternative to conventional surface hardening processes.
- The knowledge gained from this review is represented in the form of a stepladder pattern (Fig. 16). This pattern of study will pave way for the future researchers to solve any unresolved issue in this field.

Some of the burning issues and future directions put forth here are the views of the authors based on the knowledge acquired and experience gained from the review of the literatures presented here. However, the perspectives and directions in the near future will depend on the needs of the industry and the developments in related areas.

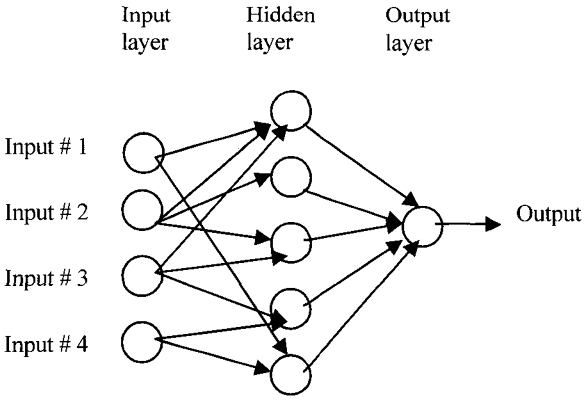


Fig. 14 A Simple Neural Network

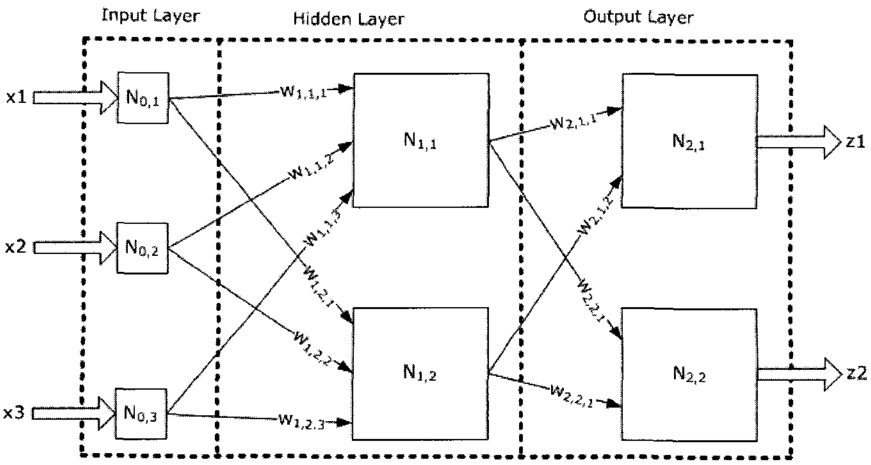
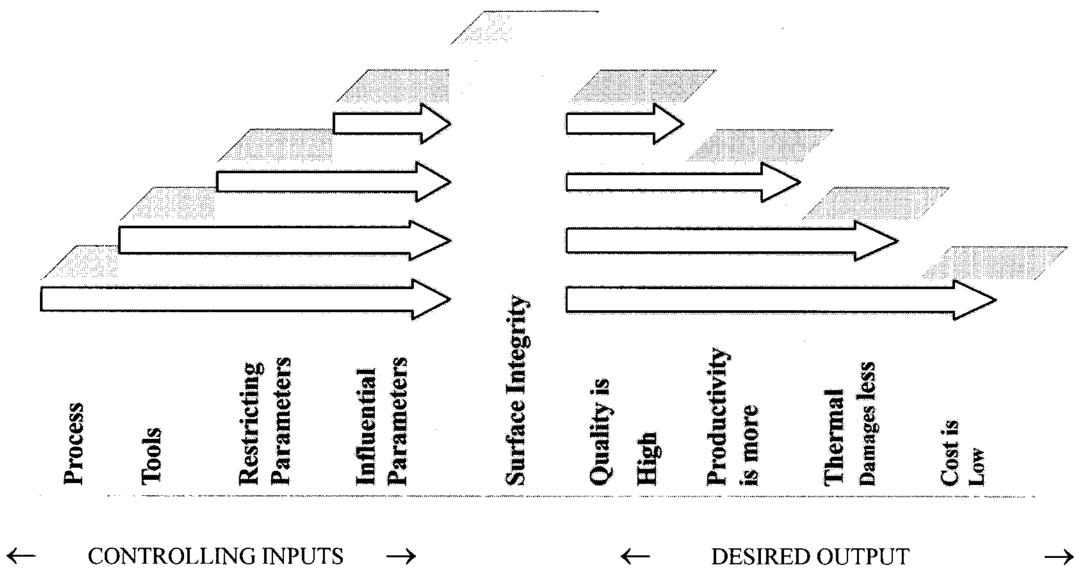


Fig. 15 Back Propagation Algorithm



Controlling inputs are optimized results in better surface integrity thereby desired output can be achieved
Study of process parameters -Study of thermal aspects-study of surface modification aspects -Study of residual stress

Fig. 16 Shows the Grinding Process-Surface integrity – Grinding cost – step ladder pattern

1 Process-Grinding:
2 Tools-
  2.1 Grinding machine
  2.2 Abrasive wheels
3 Restricting parameters
  3.1 Wheel work contact zone temperature
  3.2 Amount heat generation and
  3.3 Amount of heat entering into the work piece
4 Influential parameters –
  4.1 Depth of cut
  4.2 Number of passes,
  4.3 Work speed, and
  4.4 Wheel speed,
5 Surface integrity factors-
  5.1 Visual,
  5.2 Dimensional,
  5.3 Residual stress
  5.4 Tribological
  5.5 Metallurgical and other factor

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