

## Thermal Effect on Surface Finish in Grinding Process



Engineering

KEYWORDS :

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### ABSTRACT

Within the spectrum of machining process, the uniqueness of grinding is found in its cutting tools. Pre-historic man's abrasive tool was natural sandstone, which contains grains of sand in a silicate bond matrix. Modern grinding wheels are fabricated by cementing together abrasive grains, usually from man-made materials, with a suitable bonding material. Grinding processes are often selected for final finishing of components because of their ability to satisfy stringent requirements of surface roughness. The reliability of mechanical components, especially for high strength applications, is often critically dependent upon the quality of the surface produced by machining. Surface quality may be considered to consist of two aspects: surface integrity and surface topography. Surface integrity is associated with mechanical and metallurgical alterations to the surface layer induced by machining.

Surface roughness produced by grinding depends on various factors such as, type of grinding wheel, spindle speed, collent, alignment of workpiece, feedrate, depth of cut etc. among these factors, we analyze variation of surface roughness with varying three parameters 1. Wheel Head Speed 2. Depth of Cut and 3. Feedrate. It is found that there are certain values of parameter for getting good surface finishing in grinding process for each material and size of the workpiece. If we decrease or increase these values from its optimum value, it results in bad surface finish. Thus we will perform experiment on two workpiece of different material and get optimum value of these parameter, as how variation in these parameters affect the surface finishing.

### 1. THERMAL ASPECTS OF GRINDING :

The grinding process requires extremely high energy expenditure per unit volume of material removed. Virtually all of this energy is converted to heat which is concentrated within the grinding zone. The high temperatures produced can cause various types of thermal damage to the workpiece, such as burning, phase transformation, softening (tempering) of the surface layer with possible rehardening, unfavourable residual tensile stresses, cracks and reduced fatigue strength. Furthermore, thermal expansion of the workpiece during grinding contributes to inaccuracies and distortion in the final product. The production rates which can be achieved by grinding are often limited by grinding temperatures and their deleterious influence on workpiece quality.

From metallurgical examinations of ground hardened steel surfaces reported in 1950, it was conclusively shown that most grinding damage is thermal in origin. In the first attempt to correlate actual grinding temperatures with structural metallurgical changes in the workpiece five years later, the temperature distribution in the subsurface was measured during grinding of hardened bearing steel by means of a thermocouple embedded in the workpiece. Numerous other methods have also been developed to measure grinding temperatures using either thermocouples or radiation sensors. While considerable difficulties may arise in interpreting such measurements due to the extreme temperature gradients in time and space near to the surface, embedded thermocouples and infrared radiation sensors utilizing fiber optics have been shown to provide a reasonably good indication of the workpiece temperature near the ground surface. Both of these temperature-measuring techniques have been found to give results which are consistent with each other, and also been found to give results which are consistent with each other, and also with measurements of the surface temperature using a thin foil thermocouple.

Thermal analysis of grinding processes is usually based upon the application of moving heat source theory to the workpiece being ground. For this purpose, the grinding zone is usually modeled as a band source of heat which moves along the surface of the workpiece. All the grinding energy expended is considered to be converted to heat at the grinding zone where the wheel interacts with the workpiece. A critical parameter needed for calculation the temperature response is the energy partition to the workpiece, which is the fraction of the total grinding energy transported to the workpiece as heat at the grinding zone. The energy partition depends on the type of grinding, the wheel and workpiece materials, and the operating conditions. For conventional shallow cut grinding with conventional aluminum oxide wheels, the energy partition is usually generally bigger than

for creep-feed grinding or for grinding with CBN wheels.

#### 1.1 THERMAL DAMAGE :

Excessive grinding temperatures cause thermal damage to the workpiece. In this section, a few common types of thermal damage will be considered. By establishing a direct relationship between the heat transfer analysis of the previous section and some types of thermal damage, it becomes practically feasible to predict and control thermal damage by in-process monitoring of the grinding power.

##### 1.1.1 WORKPIECE BURN :

One of the most common types of thermal damage is workpiece burn. This phenomenon has been investigated mainly for grinding of plain carbon and alloy steels, although it is also a problem with some other metallic materials. Visible workpiece burn with steel is characterized by bluish temper colors on the workpiece, which are a consequence of oxide-layer formation. The temper colors are usually removed by spark-out at the end of the grinding cycle, especially with cylindrical grinding, but this effect is cosmetic and the absence of temper colors on the ground surface does not necessarily mean that workpiece burn did not occur.

At the onset of burning, there is a tendency for increased adhesion of metal workpiece particles to the abrasive grains, thereby causing the forces to grow, the workpiece surface to deteriorate, and the rate wheel wear to increase. A discontinuity in the force versus wear-flat-area relationship also occurs, which indicates an abrupt change in the grinding mechanisms possibly related to a metallurgical transformation. From microhardness distribution in the subsurface of the workpiece. For a hardened steel ground without any burning, there is generally some softening due to tempering close to the-

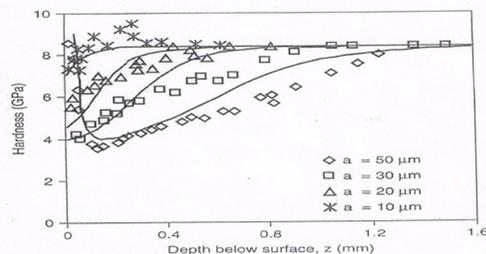


Fig.6 Microhardness versus depth beneath surface after grinding SK7 tool steel at four depths of cut.

surface. Some examples of such tempering behavior are shown for grinding of hardened tool steel at four depths of cut in fig. 6. Starting with an initial hardness of about 8 GPa, a greater de-

gree of tempering can be seen with increasing wheel depth of cut due to higher temperatures to a greater depth below the surface. With the onset of burning, rehardening of the steel workpiece also occurs towards the surface as shown by the hardness curve at the biggest depth of cut in fig. 6. Rehardening is a consequence of re-austenitization followed by the formation of untempered martensite, which can be identified after etching as white phase in the surface layer or in patches. Workpiece burn and austenitization by grinding heat of soft steels, even hardenable types, is not necessarily accompanied by surface hardening. The metallurgical evidence and microhardness measurements suggest that the visible burn threshold is virtually co-incident with the onset of that for austenitization.

### 1.1.2 TEMPERING AND REHARDENING :

Steel are often ground in the hardened state. Transformations which may occur due to excessive grinding temperatures include tempering (softening) of the hard martensite phase, and also the formation of brittle untempered martensite (rehardening) if the temperature is high enough and persists long enough for re-austenitization to occur. The formation of untempered martensite is the consequence of rapid cooling of the re-austenitized material mainly by heat conduction to the workpiece bulk after the grinding zone (heat source) passes.

Tempering is a complex phenomenon which is mainly due to carbon diffusion and is dependent upon both temperature and time. In general, the hardness  $H$  obtained after tempering  $\theta$  for time  $t$  can be expressed a single-valued function of the time-modified temperature parameter,  $\theta (C + \text{Log } t)$ , or

$$H = H [\theta (C + \text{Log } t)]$$

Where  $C$  is an experimentally determined constant for each steel.

In order to predict the effect of the grinding temperatures on the metallurgical state and hardness distribution in the workpiece subsurface after grinding, the reaction rate kinematics were coupled with a thermal analysis, similar to the one presented above, which also took into account the effect of temperature on the thermal properties and of multiple grinding passes over the same area. Some examples of the results obtained are shown by the solid lines for the subsurface hardness distribution in fig. 6. Considering the complexity of the tempering and rehardening analysis are in very good agreement with the experimental measurements.

Tempering commonly occurs near the workpiece surface during grinding of hardened steels, and it may be accompanied in severe cases by rehardening. The depth of the thermally affected layer may be reduced by the use of faster workpiece velocities which results in shallower heat penetration and shorter heating times. Some or even all of a shallow thermally affected layer produced during aggressive rough grinding at high removal rates may be removed by gentler finish grinding and spark-out at the end of the grinding cycle.

### 1.1.3 RESIDUAL STRESSES :

The grinding process invariably leads to residual stresses in the

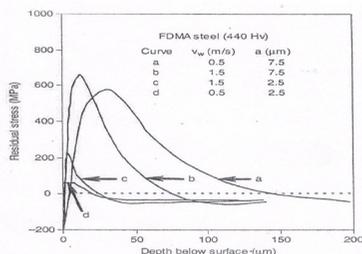


Fig.7 Residual stress distribution induced by grinding of an alloy steel. Residual tensile stresses observed are considered to be thermally induced.

vicinity of the finished surface, which can significantly affect the mechanical behavior of the material. Residual Stresses are in-

duced by non-uniform plastic deformation near the workpiece surface. Mechanical interactions of abrasive grains with the workpiece result in predominately residual compressive stresses by localized plastic flow. The effect may be likened to that of shot peening. Residual tensile stresses are caused mainly by thermally induced stresses and deformation associated with the grinding temperature and its gradient from the surface into workpiece. At the grinding zone, the thermal expansion of hotter material closer to the surface is partially constrained by cooler subsurface material. This generates compressive thermal stresses near the surface which, if sufficiently big, cause plastic flow in compression. During subsequent cooling, after the grinding heat passes, the plastically deformed material wants to be shorter than the subsurface material, so the requirement for material continuity causes tensile stresses to develop near the surface. In order to ensure mechanical equilibrium, residual compressive stresses must also arise deeper in the material, but these are much smaller in magnitude than the residual tensile stresses.

Some examples of the distribution of the residual stress component along the grinding direction are shown in fig. 7. for an alloy steel. Residual Stresses measurements, which are usually based upon X-ray methods, typically reveal a biaxial stress state in the surface layer, with the stress along the grinding direction approximately equal to the stress across the grinding direction. In much production grinding, the residual stresses are predominantly tensile, which would indicate that they are mainly thermal in origin. Residual compressive stresses are considered to have a beneficial effect on mechanical strength properties, whereas residual tensile stresses have an adverse effect.

The influence of residual stresses is relatively more pronounced with higher strength brittle materials for which strength considerations are often critical. More severe grinding conditions on high-strength steels and aircraft alloys generally cause larger residual tensile stresses, thereby leading to reduced fatigue strength and cracking. The situation may be further aggravated in steel by hydrogen embrittlement, owing to significantly higher levels of hydrogen being released as a result of grinding fluid breakdown. Abusively ground hardened steel components exposed to hot acid develop surface cracks, which can be attributed to the presence of residual tensile stresses acting on brittle untempered martensite formed by formed by workpiece burn. Cracks induced by acid etching and abusive grinding are usually oriented normal to the grinding direction is the predominant one. The tendency for microcracking in high strength nickel base alloys due to residual tensile stresses may be further promoted by the onset of non-equilibrium constitutional melting at elevated grinding temperatures.

It is generally desirable to control the grinding condition so as to induce residual compressive stresses or, at least, to limit the magnitude of the peak residual tensile stress. As a practical matter, demands for more efficient production and faster removal rates result in higher residual tensile stresses, such as are seen in fig. 7. In order to obtain residual compressive stresses, it is usually necessary to maintain extremely low removal rates. However, the introduction of CBN abrasive wheels in place of aluminum oxide has been shown to induce compressive instead of tensile residual stresses when grinding with CBN, due to lower specific energies. Another factor is the very high thermal conductivity of CBN, which promotes its condition to the wheel, thereby lowering the energy partition on the workpiece.

## 2. SURFACE ROUGHNESS :

Grinding processes are often selected for final finishing of components because of their ability to satisfy stringent requirements of surface roughness and tolerance. Surface roughness and tolerance are closely inter-related, as it is generally necessary to specify a smoother finish in order to maintain a finer tolerance in production. For many practical design applications, it is tolerance requirement which impose a limit on the maximum allowable roughness, although the proper operation of many devices also necessitates smooth surface.

The reliability of mechanical components, especially for high strength applications, is often critically dependent upon the quality of the surface produced by machining. Surface quality may be considered to consist of two aspects: Surface Integrity and Surface Topography. Surface integrity is associated with mechanical and metallurgical alterations to the surface layer induced by machining. For grinding, the most important aspects of surface integrity are associated with thermal damage caused by excessive grinding temperatures. Surface topography refers to the geometry of machined surfaces, which is usually characterized by surface roughness, although there are other parameters which may also be of interest.

**2.1 GROUND SURFACE MORPHOLOGY :**

The fine-scale morphology of the surface generated by grinding consists mostly of overlapping scratches produced by the interaction of abrasive cutting points with the workpiece. An example of a typical ground surface is shown in the scanning electron microscope (SEM) photograph in fig. 10. For this example of straight plunge grinding, as with other types of grinding, the grit motion relative to the workpiece is readily identified from the directionality of the scratches and grooves. Sideways displacement of material from some scratches by plowing is also evident.

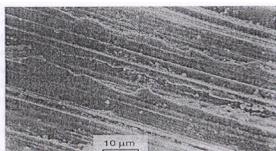


Fig.10 SEM micrograph of a medium carbon steel workpiece surface after straight surface grinding with a vitrified aluminum oxide wheel (32A6018VB6) and soluble oil.

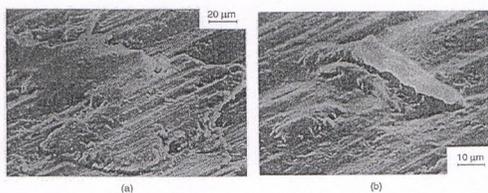


Fig.11 SEM micrograph of a titanium alloy (Ti-6Al-4V) surface after straight surface grinding with a vitrified aluminum oxide wheel (32A6018VB6) and soluble oil.

Scratches on the finished surface correspond to only the bottom portions of the cutting paths of the outermost cutting points on the wheel surface. Here the underformed chip thickness is considerably smaller than the maximum grit penetration at the chip formation, so plowing is more likely to be less than the critical minimum depth for upon the particular workpiece material being ground. Metals which are more adhesive, such as titanium, nickel-base alloys, and austenitic stainless steels, tend to exhibit more sideways flow. Conversely, grinding fluids which are more effective in lessening grit-workpiece adhesion by lubrication reduce plowing.

The ground surface morphology is further complicated by numerous other phenomena. Back transfers of workpiece metal often occur, especially with adhesive metals, whereby metal particles adhering to the abrasive grits are redeposited on the workpiece. An example of this behavior is seen in fig. 11(a), for grinding of a titanium alloy. Interruption of the cutting action by fracture of the abrasive grit may leave a crater on the workpiece, as in fig. 11(b), possibly with an abrasive fragment embedded in the surface. When grinding steels, craters are more frequently observed at the start of grinding after wheel dressing when the rate of wheel wear by grit fracture is more rapid, and also with coarser dressing conditions. Some difficult-to-grind metals, including titanium and austenitic stainless steels, seem to exhibit more extensive cratering and grit embedding. This type of surface damage provides a source of localized stress concentrations, which can be expected to have an adverse effect on in-service strength and fatigue properties.

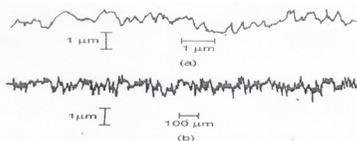


Fig.12 Profile of a medium carbon steel surface after grinding with a 60-grit vitrified aluminum oxide wheel: (a) along the lay, and (b) across the lay.

The topography of surfaces produced by grinding can be recorded by surface profiles taken along and across the grinding direction, as shown in fig. 12 for straight surface grinding of mild steel. Adjacent peaks and valleys within the profile along the grinding direction are much more widely spaced apart than across the grinding direction. Spectral analysis of these profiles revealed a predominant wavelength of 0.25mm along the lay as compared with only 0.034 mm across the lay.

**2.2 SURFACE TEXTURES AND TOLERANCE :**

The characteristic patterns of peaks and valleys on the finished workpiece are known as surface texture. As a basic for quantitative describing terization of surface texture will be briefly reviewed. For this purpose, we will refer to the American Standard for characterization of surface texture, which is also in substantial agreement with British (BS), German (DIN), and International (ISO) standards.

The concept of surface texture is illustrated in fig. 13. Most machined surfaces exhibit a predominant lay coinciding with the direction of cutting-tool motion relative to the considered to have components of roughness and waviness. Roughness is associated with closely spaced perturbations which are superposed on waviness components more widely spaced apart. Surface flaws, such as cracks, adhered metal, and craters, also contribute to the surface texture.

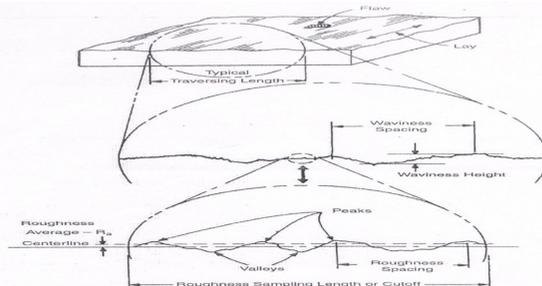


Fig.13 Illustration of surface texture according to ANSI Standard.

Surface texture is commonly measured by a stylus instrument which traces the profile of the surface. For equivalent assessment of surface roughness, a sampling length along the profile is selected, long enough to include a representative number of roughness per turbations but shorter than the waviness spacing. Therefore, the sampling length is also referred to as the cut-off length, as some stylus instruments electronically filter longer wavelengths for analyzing surface roughness. A typical sampling length for roughness measurements on ground surface is 0.8 mm. Each roughness measurement with a typical stylus instrument is taken over a number of successive sampling lengths representing the total traversing length.

A number of roughness parameters are defined from the surface profile, but for our purpose we will start with only two: arithmetic average roughness and peak-to-valley roughness. The arithmetic average roughness  $R_a$  is the mean value of the average deviation of the surface profile from the centerline in each sampling length. The peak-to-valley roughness  $R_v$  also referred to as the total roughness, is defined as the difference in elevation between the highest peak and lowest valley in the traversing length.

It is apparent that  $R_v$  should be substantially bigger than  $R_a$ . For a perfect sinusoidal profile, it can be readily shown that  $R_v = \mu R_a$ . For grinding, differences between  $R_v$  and  $R_a$  are considerably bigger, which is a consequence of the broad distribution of peak heights

and valley depths within the surface profile. The profile height distribution of ground surfaces appears to be nearly Gaussian and the peak and valley height distributions might also be approximately Gaussian. For ground surfaces, the  $R_t$  roughness is typically 7-14 times  $R_a$ . However somewhat smaller ratios of 4-7 are obtained if the extreme values for the highest peak and lowest valley deriving the peak-to-valley roughness are smoothed out either by ignoring unusually high peaks and low valleys in the profile or by taking the elevation differential between the average of the five highest peaks and five lowest valleys in the traversing length.

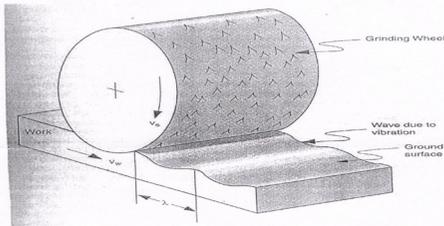


Fig.14 Illustration of waviness generation in straight surface grinding due to forced vibration.

The heights associated with the waviness component of the profile can be obtained for perturbations identified as having characteristic spacings longer than the cut-off length. Waviness is caused mainly by grinding vibrations. There are generally two types of vibration: forced and self excited. Forced vibrations arise from external vibration sources, such as an unbalanced wheel or other rotating elements, and the frequency coincides with that of the vibration sources of some harmonic thereof. The generation of waviness by forced vibration of an unbalanced wheel is illustrated in fig. 14. for straight surface grinding. This is likely to cause a visible pattern of successive straight lines or bands across the workpiece width spaced apart along the grinding direction by the wavelength.

Where  $V_w$  is the workpiece velocity and  $f$  is vibration frequency which in this case corresponds to the wheel rotational frequency. Such waviness may be difficult to measure by profilometry.

Self excited vibration is caused by a regenerative effect whereby a fundamental insatiability of the machine is dynamically excited during successive workpiece revolution. Regenerative chatter builds up progressively by growth of waves around the wheel and workpiece peripheries. The vibration frequency is usually much higher than with forced vibration, so the characteristic wavelength on the workpiece is proportionally shorter. In many practical cases, lobbing of the workpiece is significantly attenuated by a mechanical filtering effect because the wavelength is less than the arc length of contact at the grinding zone. In homogeneities in the wheel structure increase the tendency for self-excited vibration and a mottled workpiece appearance.

Force and self-excited vibration may also occur during dressing, producing irregularities in the wheel shape and workpiece waviness. With single-point dressing, forced vibration due to wheel unbalance are especially problematic when the wheel unbalance during dressing is different from that during grinding. Self-excited vibration may occur during rotary diamond dressing resulting in wheel lobbing, and this an alternative to fixed-point dressing. During subsequent grinding, vibration at the wheel lobbing frequency causes workpiece waviness.

Surface topography is often the main factor limiting the tolerance which can be obtained in production. In general, the tolerances represent the acceptable deviation from the nominal intended dimension or geometrical form. Dimension on machined components are measured from one surface to another or, in the case of diametrical measurement, between two opposite locations on the same cylindrical surface. The roughness of the finished surface can be thought of as a measure of the uncertainty in exactly specifying the location of the surface, as illustrated in fig. 15 for a cylindrical component, which means that the dimensional uncertainty depends upon the combined surface roughness at the measuring points. Therefore, it is generally

necessary to have smoother surfaces in

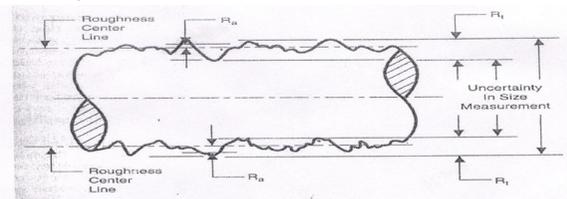


Fig.15 Illustration of the interrelationship between roughness and tolerance.

order to maintain tighter tolerance control. The surface roughness requirement is often a consequence of the dimensional tolerance requirement, and both factors are similarly affected by grinding conditions. There are also a host of other factors which contribute to poor tolerance, including machine deflection, thermal expansion and distortion of the machine and workpiece, and wheel wear. In center less grinding unstable geometric and kinematic condition cause workpiece lobbing, and the situation is further aggravated by machine-tool vibrations.

Typical arithmetic average surface roughness for production grinding operations range from about  $0.15 \mu\text{m}$  to  $1.5 \mu\text{m}$ , although specified outside this range are not uncommon. Corresponding dimensional tolerances specified in production are normally 10 to 50 times the arithmetic average roughness. This ratio will depend upon such factors as the machine-tool condition, allowable rejection rate, assembly requirements, and component size. One way to effectively maintain tolerances at the lower end is by selective grouping of nominally identical machined parts according to size, so that the tolerance within each group is much smaller than that of the entire lot. Selective grouping is commonly applied to rolling element bearing components.

Many of the same factors which affect dimensional tolerances similarly affect form tolerances, since form is also specified in terms of linear as well as angular dimensions. However, the most significant form errors in grinding are usually caused by wheel wear, especially for profile grinding of cross-sectional shapes having sharp radii or deep grooves. Better form control usually requires a slower wearing wheel. But this can be expected to cause bigger forces. Form errors are also associated with elastic deflection during grinding.

#### CONCLUSION:

The value of grinding parameter to get optimum surface roughness for given Mild Steel workpiece are:

Work - heated speed (RPM)	: 70
Depth of Cut (mm)	: 0.005
Feed Rate (MM/min)	: 0.5-1

#### 3. RESULTS AND DISCUSSION:

Grinding of two rods of Mild Steel and Cast Iron was carried out with grinding wheel of aluminum oxide. It is found that there are certain values of parameter for getting good surface finishing in grinding process for each material and size of the workpiece. If we decrease or increase these values from its optimum value, it results in bad surface finish.

For Mild Steel bar we got best surface roughness at work-head speed of 130 (RPM), Depth of Cut 0.05 mm and Feed Rate 0.5-1 mm/min. We can see from table that further increase/decrease of these value had rough surface as compared to these situation.

The Same results were seen in case of Cast Iron bar we got best surface roughness at work-head speed of 70 RPM, Depth of Cut 0.005 mm and Feed Rate 0.5-1 mm/min.

It is also remarkable that the optimum value of these parameters depends on material to be grind, as optimum value for given two materials are different.

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