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Assessment of Plastic Deformation Upon Grinding Using X-Ray Diffraction Profiles

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Abstract*: X-ray diffraction (XRD) scan profiles of medium carbon steel ground samples were analyzed to assess the grinding induced plastic deformation. Broadening of XRD scan profiles with higher downfeed indicated the possible plastic deformation. XRD scan profiles were studied to measure full width at half maximum (FWHM) of profiles for assessment of plastic deformation at various level of downfeed. FWHM analysis revealed that FWHM increases with downfeed owing to plastic deformation. Grain size of deformed layers was also estimated using Scherrer equation to verify the results obtained through FWHM analysis. Grain size was observed to decrease with downfeed due to associated plastic deformation. Assessment of grinding induced plastic deformation using XRD profiles demonstrated the applicability of this new approach for qualitative measurement of surface integrity characteristics like microhardness and surface roughness. Microhardness measurement and surface roughness analysis of ground samples have been undertaken to confirm the results obtained by FWHM study.*

Keyword: Plastic deformation; X-ray diffraction; Grinding; Grain size; FWHM; Scherer's equation; Surface integrity

Nomenclature

V_c	Wheel Velocity
V_w	Work Velocity
a	Downfeed
t	Grain size
β	FWHM in radians
λ	Wavelength(X-Ray)
θ	Bragg diffraction angle
C	Correction factor for Scherer's equation

1.0 Introduction:

Grinding is an abrasive machining process mainly employed for finishing operation of manufactured components. It is often the last process to take place with components which have high added value [1]. Material removal in grinding occurs by the interaction of abrasive grains in the grinding wheel with the workpiece at extremely high speeds and shallow penetration depths [2]. Abrasive grain while engaging with the workpiece slides without cutting on the workpiece surface due to the elastic deformation of the system. As the stress between the grain and workpiece is increased beyond the elastic limit, plastic deformation of workpiece occurs [3]. Induction of plastic deformation in the ground surface layers affects the important surface integrity characteristics like roughness, microhardness and residual stress.

Moore and Evans [4] reported that the FWHM (Full width at half maximum) of an X-ray diffraction peak profile indicates the plastic deformation. Measurement of FWHM of X-ray diffraction (XRD) profiles allowed researchers to obtain important information about the surface state of material as this quantity is related to the grain distortion, dislocation density and residual stresses [5]. Pariente and Guagliano [6] observed that shot peening increases the value of FWHM in the surface layer of 42CrMo4 steel due to plastic deformation of the surface layer of material associated with the multiple shot impacts. They also reported FWHM as a more accurate index of the surface work hardening in comparison to micro-hardness testing, which involves a finite thickness of material, and the results are an average value on the thickness of material where the indentation has been done. FWHM typically increases with increase in residual stress, grain refinement and plastic deformation in the work material [7-9]. Grain size is an important index to indicate plastic deformation. Recently, Elilarassi and Chandrasekaran [10] calculated grain size using scherer's equation and correlated FWHM with the grain size while studying the effect of annealing temperature on structural and optical properties of ZnO films.

Literature survey indicated that various researcher studied the effect of grinding process parameters on surface integrity characterizes using various laboratory tools. But, assessment of plastic deformation upon grinding using grain size estimation was not attempted by previous researcher. Hence, to fill this gap, in the present work an attempt has been made to analyze the effect of downfeed on plastic deformation using FWHM of XRD profile and grain size measurement.

2.0 Experimental details

All the surface grinding tests were carried out on annealed AISI 1060 steel. The reason for selecting AISI 1060 steel is that it consists of large metallurgical grains as well contains medium carbon percentage, which represents distinctive behavior of many carbon and alloy steels. This would enable the observations developed to be reasonably applied to other steels, which undergo grinding under the manufacturing environment. The chemical composition of medium carbon steel investigated is given in Table 1.

Table 1 Chemical composition of material studied

Chemical element	Fe	C	Si	Mn	Cr	P	S
%	Balance	0.57	0.1	0.49	0.04	0.03	0.04

Ground samples, with all of same rectangular shape [75mm x 10mm x 9mm] were prepared under plunge surface grinding mode using four levels of downfeed. Table 2 shows the grinding process details.

Table 2 Grinding process details

Grinding machine	Tool grinder
Grinding speed (V_c)	18 m/s
Grinding wheel	A 60 K 5 V
Wheel dimension	Bore - 30 mm, Diameter - 125 mm
Environment	Dry
Work speed (V_w)	3 m/min
Grinding mode	Up grinding
Downfeed (μm)	5, 20, 40 and 60

X-ray diffraction patterns of ground samples were collected using a Philips PW 1710 diffractometer. Scan parameters were collected using Philips X'pert Data Collector software with 2θ ($110 \leq 2\theta \leq 113$) values chosen to encompass the Fe-Kα doublet for the {211} planes. Philips Expert Stress Software was used for analysis of scan XRD profiles of ground samples. The Full Width at Half Maximum (FWHM) of a X-ray diffraction peak contains useful information related to the dislocation density, as broadening of the peak indicates an accumulation of plastic damage, such caused by dislocation generation during deformation of workpiece surface. FWHM values of the diffraction peaks were measured using Philips X'pert stress software. Experimental parameters for XRD measurement are summarized in Table 3.

Table 3 Parameters for XRD measurement

Radiation	Fe-Kα
Current	20 mA
Voltage	40 KV
Step size	0.05
Number of steps	60
Number of scan	5

To increase the accuracy in experimental results five XRD scans were obtained for each ground sample. Figure 1 represents the three-dimensional XRD profiles of all five scan in single frame. Average value of FWHM obtained from five scan profiles was considered for analysis

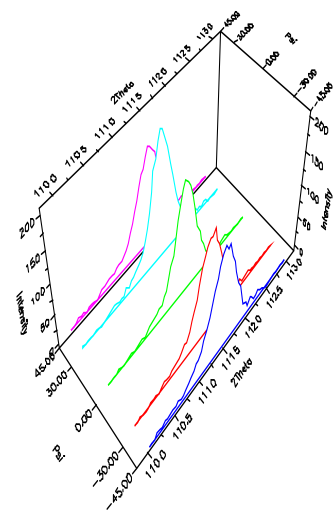

Fig. 1. Three dimensional XRD scan profile a ground sample.

The grain size (t) of the ground layers of sample was calculated using the Scherer's formula from the parameters derived from the X-ray diffraction patterns [10].

$$t = \frac{c\lambda}{\beta \cos\theta}$$

Where, t is the grain size (nm).

β is the full width at half maximum (in radians) of XRD profiles

λ is the X-ray wavelength (1.9374 Å)

θ is the Bragg diffraction angle (56.5^0)

C is a correction factor which is taken as (0.94)(assuming rectangular grain)

Microhardness tester LM 700 (Leco, USA) was employed to measure the microhardness (HV) of ground samples at the surface. Microhardness tests were carried out with 50 gm load

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and 10 second dwell time on the cross sections of ground samples with a Vickers indenter starting from 25 μm depth from the surface.

Surface profile of ground surface was traced by 2-D profilometer (Model: Surtronic 3 + make: Taylor Hobson, with cut off: 0.8 mm) in the transverse direction and the data were treated by Taly profile version 3.1.9 software for surface roughness analysis.

3.0 Result and discussions:

Broadening of X-ray diffraction peak indicates an accumulation of plastic damage, such caused by dislocation generation during the deformation of workpiece surface. Figure 2 to 5 shows the XRD peak profiles of medium carbon steel samples ground at various downfeed.

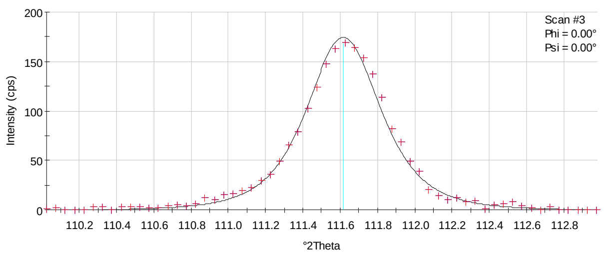


Fig. 2. XRD peak profile of ground sample at 5 μm downfeed

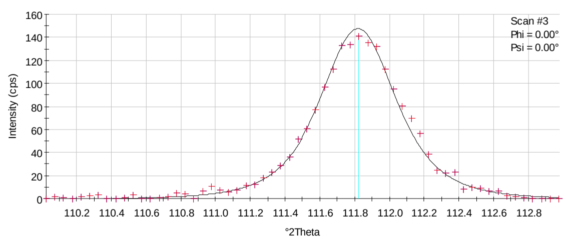


Fig. 3. XRD peak profile of ground sample at 20 μm downfeed

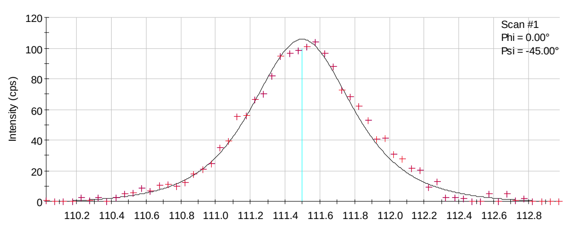


Fig. 4. XRD peak profile of ground sample at 40 μm downfeed

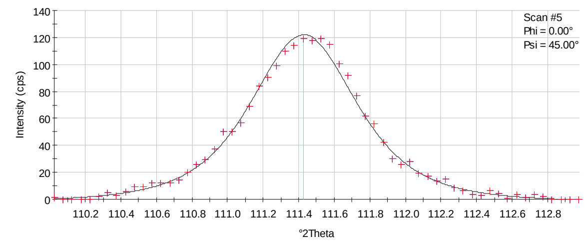


Fig. 5. XRD peak profile of ground sample at 60 μm downfeed

Figure 2 to 5 clearly shows the broadening of XRD peak profiles with downfeed, which in turn reveals the rise in plastic deformation with downfeed. Figure 5 representing the peak profile at highest downfeed while Fig. 2 shows peak profile at lowest downfeed. The large variation in width of peak profile at highest downfeed in comparison to width at lowest downfeed indicates the induction of large plastic deformation with downfeed.

The full width at half maximum of an X-ray diffraction peak profile indicates the plastic deformation and can be used qualitatively to assess plastic deformation during grinding [4]. Increase in FWHM of X-ray diffraction peak profile represents augment in degree of plastic deformation. Figure 6 represents variation of FWHM of XRD peak profile with downfeed in graphical form.

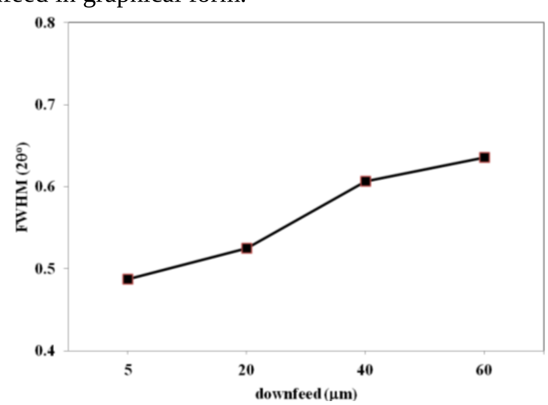


Fig. 6. Variation of FWHM of XRD profiles with downfeed upon grinding of AISI1060 steel

Figure 6 clearly shows continuous increase in FWHM of XRD peak with downfeed, which indicates induction of plastic deformation due to grinding process. FWHM of XRD profiles is not only gets affected by plastic deformation but it is also sensitive to residual stress [11]. Typically in grinding surface integrity characteristics i.e. residual stress, micro-hardness, microstructure, surface roughness changes simultaneously. Hence, in the present study, it becomes essential to analyze whether FWHM increases due to plastic deformation.

Grain size refers to diameter of individual grain of the material. Grain size is an important parameter to assess the plastic deformation of the material as it directly gets affected by plastic deformation. Variation in grain size upon grinding was evaluated using the XRD profiles of ground samples and Scherrer equation. This new approach provides assessment of plastic deformation more quantitatively in comparison with FWHM measurement. Figure 7 depicts variation of grain size with downfeed.

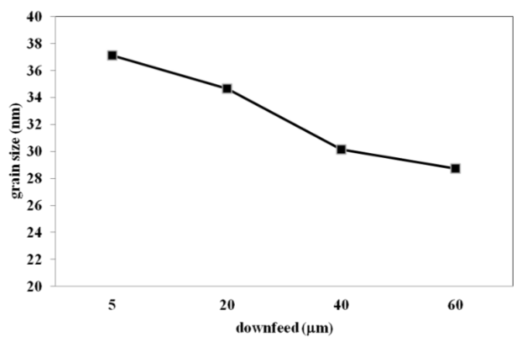


Fig. 7. Variation of grain size with downfeed upon grinding of AISI1060 steel

Grain size continuously decreasing with downfeed as shown in Fig. 7, indicates the plastic deformation of the top layers of ground surface. Grain size sharply reduced from 37 nm to 30 nm with downfeed clearly represents the induction of plastic deformation owing to grinding and confirms the previous FWHM analysis.

It is well known that Vickers hardness increases with plastic deformation [12]. Thompson and Thanner [13] studied the effect of plastic deformation on Vickers hardness value. During their experiment they found that Vickers hardness increases with plastic deformation when pearlitic steel bars were deformed to different degrees of tensile strain. Grinding condition with higher chip thickness and chip load is known to generate higher plastic deformation on surface and sub-surface layer, thus leading to work hardening [14]. The plastic deformation generated in the grinding process also led to slight increase of the micro-hardness in the area near to the ground surface, due to process hardening effect [15]. Fig. 8 shows variation in microhardness of the ground sample at the ground surface for different downfeeds undertaken.

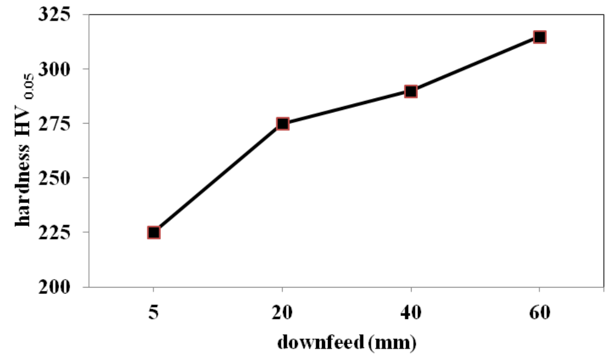
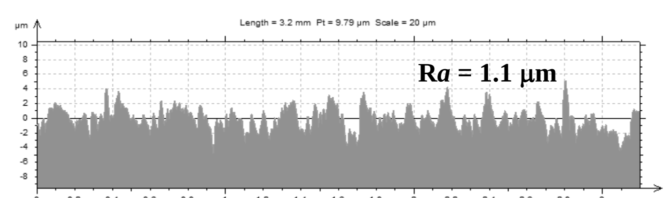


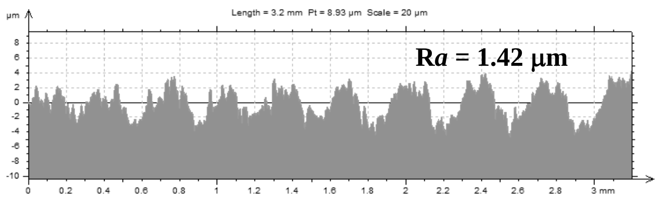
Fig. 8. Variation of ground surface hardness with downfeed upon grinding

The microhardness study shows that microhardness of the ground surface increased appreciably with downfeed. Such increase in microhardness at the surface typically occurs due to grain refinement, phase transformation and plastic deformation as reported earlier [16-20].

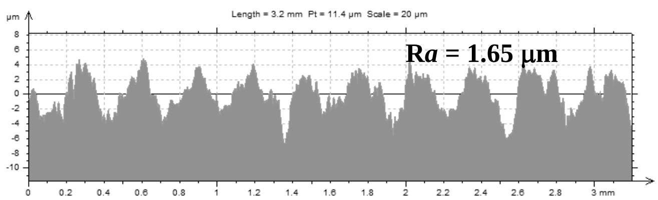
Grinding is supposed to provide a surface that satisfies the functional requirement from the surface topography and finish point of view. In the industry, surface finish better than 0.3 µm R_a, is routinely obtained by employing transverse grinding and longer sparking out. In the present work plunge surface grinding has been used with no spark out. Surface roughness is an important feature of practical engineering surfaces because of its influence on the tribological performance of the surface. Surface roughness parameter, R*a* is ideal parameters to characterize surface condition and to quantify the magnitudes of those surface conditions because of its high level of sensitivity for change in surface topography. Surface roughness profiles along with magnitude of roughness parameter, R*a* of ground samples at various downfeed is represented in Fig. 9.



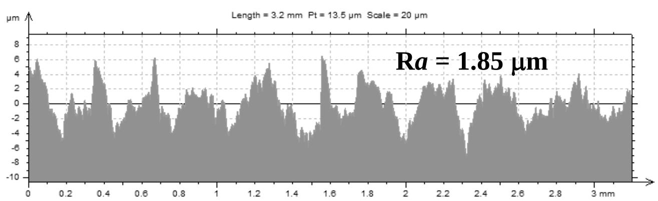
(a) Downfeed – 5 µm



(b) Downfeed – 20 µm



(c) Downfeed – 40 µm



(d) Downfeed – 60 µm

Fig. 9 Surface roughness profiles along with R*a* value at various downfeed

Figure 9 clearly depicts increase in degree of plastic deformation of the ground surface with downfeed as surface roughness magnitude increases from 1.1 to 1.85 µm with downfeed. Field [21] also observed increase in downfeed results in abrasive grains shearing longer and thicker chips and leading to greater plastic deformation of material and to deeper grinding marks. In a similar study, Liu and Malkote [22] observedsurface roughening due to plastic deformation while turning operation and reported plastic deformation roughens a free surface by producing slip bands within grains.

Increase in FWHM and reduction in grain size as represented in Fig. 6 and Fig. 7 can now be attributed to increase in microhardness and surface roughness due to associated plastic deformation along upon grinding.

4.0 Conclusions:

Following conclusions can be drawn by analysing the experimental results.

1. Full Width at Half Maximum (FWHM) of X-ray diffraction peaks, that characterises plastic deformation, has increased with increase in downfeed indicating higher plastic deformation at higher downfeed.
2. Grain size decreases with downfeed owing to grinding induced plastic deformation.
3. Increase in downfeed led to increase in microhardness and surface roughness of the ground surface owing to more plastic deformation.
4. X-ray diffraction profiles of ground surface can be effectively used for assessment of plastic deformation in grinding.

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