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An Investigation into the Influences of Grain Size and Grinding Parameters on Surface Roughness and Grinding Forces when Grinding

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This study was carried out to investigate the effects of grain size on workpiece surface roughness and grinding forces when surface grinding AISI 1050 steel. A previously designed and constructed dynamometer was used to measure and record the forces developed during grinding. Grinding tests were carried out using different grinding wheels of different grains. Ground surface roughness measurements were also carried out. The results showed that grain size significantly affected the grinding forces and surface roughness values. Increasing grain size and depth of cut increased the grinding forces and surface roughness values. For different grain sizes, depth of cuts of 0.01 and 0.02 mm did not result in any significant variations in the grinding forces but further increase in depth of cut led to variations of up to 50% in grinding forces.

Keywords: surface grinding, grinding forces, surface roughness, grinding wheel, grain size

0 INTRODUCTION

Grinding is probably the oldest surface processing method. It has been utilised since the early days of civilisation. In these early days, it was observed that some natural materials scratched the others and resulted in wear in these other materials when they were slid against each other under pressure. These hard materials used by mechanic action were called "abrasives" and parallel to the developments in technology, these abrasives and abrasive processes also developed. Abrasives were called with different names depending on their purpose of use and their properties [1]. Grinding is an important manufacturing process which shapes the workpieces with the required geometry, dimensions and tolerances. This process is especially used when the workpieces cannot be shaped with the required accuracy and surface quality by the other processes such as turning and milling [2]. In grinding terminology, increasing grain number means decreasing grain size.

For manufactured products, surface integrity is important as it affects various properties of the manufactured parts like fracture toughness, corrosion rate, stress corrosion cracking, wear, magnetic properties and dimensional stability. Surface integrity covers surface related aspects influencing surface quality. These are surface finish, metallurgical damage and residual stresses. Surface finish is related to the quality of processed surface [3] to [5]. Many machine parts like measuring devices, shafts, gears and rolls must have good surface properties. Grinding process is required to make the surfaces of these parts resistant to corrosion [6].

Some values obtained through engineering calculations do not coincide with those obtained through experimentally measured ones due to some unknown factors and stresses whose effect cannot be determined exactly. In engineering applications, theoretical calculations usually fail to produce accurate results and therefore, experimental measurements become unavoidable. The accuracy of the empirical equations is also verified by experimental measurements. Wearing of abrasives and its detachment from grinding wheel is a factor which affects the grinding process. The researches on machine tools, cutting tools and workpiece materials necessitated knowledge of cutting forces developed during machining. Therefore, accurate measurement and analyses of the cutting forces are important. Although much work has done for grinding in this area, the problems have not been solved completely [7] to [11]. Fastening of the

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workpieces in grinding is one of the important steps and grinding related many errors are the result of unsuitable fastening and inadequate rigidity. Accurate determination of grinding forces and taking precautions by taking into consideration these forces eliminates the likely problems. Predetermination of the fastening forces is very important for automation of the design of workholding devices. When selecting standard workholding device components, accurate determination of cutting force dependent fastening forces is of crucial importance.

The aim of this investigation was to examine the influences of grinding wheel grain size and grinding parameters on ground surface roughness and grinding forces when grinding hardened AISI 1050 steel workpieces. The grinding wheels used had different grain sizes.

1 MECHANICS OF CHIP FORMATION DURING GRINDING

For grinding of a workpiece surface, ideal cutting can be obtained by many process combinations like ploughing due to lateral displacement, workpiece movement, grinding wheel movement, elasticity of the workpiece and vibration. Many parameters have effects on grinding process. Some of these parameters can be controlled while the others not [12] and [13].

Kinematic relation between grinding wheel and workpiece in grinding process is applied to each grain of the grinding wheel. Previous work in this area was based on mechanics of mean single grain. Some faces of grain during grinding can be illustrated the geometrical relation between a single grain and workpiece. Non-deformed chip shape, tool path length of the abrasive grain (*lk*), maximum non-deformed depth of cut (h_m) and chip geometry are shown schematically in Fig. 1.

Chip formation in grinding process can be divided into three successive stages: friction, ploughing and cutting. In up-cut grinding, grinding wheel grains rub on the workpiece surface rather than cutting due to the elastic deformation of the system. This is called friction stage. And then, plastic deformation takes place as the elastic limit is exceeded between the abrasive grain and workpiece. This is called ploughing stage. Workpiece material flows plastically through forward and sideward ahead of the abrasive grain and forms a groove. When the workpiece material can not resist the flow stress, chip is formed. The chip formation is called cutting stage. In this chip formation stage, energy is used most efficiently [13] to [16].

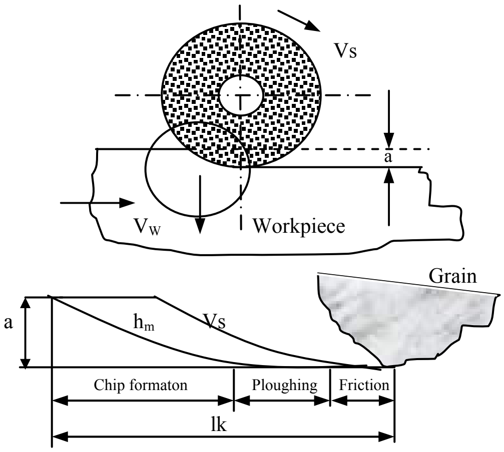


Fig. 1. *Three stages of chip formation in grinding [13] and [17]*

Grinding forces not only affect chip formation mechanics, grain wear and temperature distribution but also efficiency of the grinding operation. Therefore, grinding forces are among the most important factors affecting grinding quality.

2 MATERIALS AND METHOD

In order to measure the grinding forces, a previously designed and constructed dynamometer was used [8]. The workpiece material was AISI 1050 steel in rectangular blocks of 15 x 15 x 100 mm. Chemical composition of AISI 1050 steel is given in Table 1. This material was supplied as rolled condition. Before the tests, AISI 1050 specimens were heat treated and subsequently stress relief annealed. Hardness measurements were also carried out on these specimens using an INSTRON WOLPERT DIA 7571 hardness measuring device. Hardness of this material was found to be as 50 HRc. In order to fix the specimens properly to the dynamometer and to eliminate any distortion due to the heat treatment and to remove defects or other impurities, the wider surfaces of the specimens were ground.

Table 1. *Chemical composition of AISI 1050 steel (weight %)*

Element	[%]	Element	[%]
C	0.510	Mo	0.042
Si	0.113	Sn	0.032
P	0.033	Pb	0.064
Mn	0.757	Cr	0.271
Co	0.020	Cu	0.227
V	0.020	S	0.044

The grinding tests were carried out using a TAKSAN TYT-400 surface grinder. Two components of the grinding forces were measured during a single pass. These grinding forces were recorded on a personal computer (PC) using the necessary hardware and software. Aluminium oxide grinding wheels of different grains were used as grinding wheel. Grain numbers of the grinding wheels were 36 (535), 46 (360), 60 (255) and 80 (180). All the grinding wheels were commercial products and produced by EGESAN, TR. Their grade and structure were M and 5, respectively according to ANSI. The grinding tests were carried out at depth of cuts (down feed) of 0.01, 0.02, 0.03, 0.04, 0.05 and 0.06 mm as grinding process is generally a finishing process. The wheel 350 mm in diameter was run at a constant revolution of 1596 rev/min and this resulted in a wheel surface speed of 1754 m/min. Table feed was 460 mm/s. Prior to each test, the grinding wheel was dressed and trued by diamond. After the grinding tests, surface roughness values (R_a) of all the ground surfaces were measured using a MITUTOYO Surftest 211 surface measuring device. For comparison purposes, pictures of these grinding wheels were also taken using a Vitec camera at x10, x20 and x30 magnifications.

3 RESULTS AND DISCUSSIONS

There are many factors affecting the grinding forces and workpiece surface quality during grinding operations. In this study, the influences of grinding parameters (grinding wheel grain size and depth of cut) on surface roughness and grinding forces were examined. For the grinding tests, grinding wheel grain size and depth of cuts were varied while grinding wheel revolution, wheel dressing rate and flow rate of coolant were kept constant when grinding AISI 1050 steel workpieces. Variations of the workpiece surface roughness values measured after the tests and the grinding forces were evaluated by constructed graphics in Microsoft Excel. Before the graphics were constructed, regression analyses of the data were carried out and the highest regression coefficient were determined and then the curve model was chosen. Tangential force (Ft) and normal force (Fn) components were measured individually during grinding and their vector sum was regarded as the grinding force. This is given below:

$$F = \sqrt{Ft^2 + Fn^2}\ . \qquad (1)$$

3.1 Grinding Wheel Grain Size – Surface Roughness Relation

Variation of mean surface roughness (Ra) values obtained after grinding with grinding wheels of 36, 46, 60 and 80 grain and at depth of cuts of 0.01 to 0.06 mm is given in Fig. 2. Surface roughness values (Ra) depending on the depth of cut after grinding with grinding wheels of 46, 50 and 80 grain are below 1 µm. However, grinding with grinding wheel of 36 grain results in surface roughness values (Ra) between 1.29 and 2.56 µm, increasing with increasing depth of cut. Increasing depth of cut beyond 0.03 mm increases the difference between the surface roughness values obtained after grinding with grinding wheels of 46, 60 and 80 grain. Surface roughness values obtained after the tests carried out by changing grinding wheel grain size are as follows: 0.63 to 1.11 µm for grinding wheel of 46 grain, 0.46 to 0.80 µm for grinding wheel of 60 grain and 0.37 to 0.81 µm for grinding wheel of 80 grain. The lowest surface roughness value is obtained after grinding with grinding wheel of 80 grain. Fig. 2 shows that grinding wheel grain size has great influence on workpiece surface roughness. At 0.04 to 0.05 mm depth of cuts, the surface roughness obtained using grinding wheel of 80 grain was seen to be higher than those obtained by grinding wheels of 60, 46 and 36 grains by up to 30, 80 and 400%, respectively. Increasing grinding wheel abrasive grain size led to increases in surface roughness values. The larger is the grinding wheel abrasive grain size the larger is the distance between the grains and also the larger is the removed chip cross-section [9]. In addition, roughness variation range becomes larger with increasing grinding wheel grain size and this, in turn, makes the control of surface quality difficult (Fig. 2). Decreasing grinding wheel grain size value both results in diminishing roughness variation range and decreasing surface roughness value. The surface quality obtained using grinding wheel of 36 grain is not representative of a finishing surface and can be regarded a cleaning and a large volume of chip removal operation.

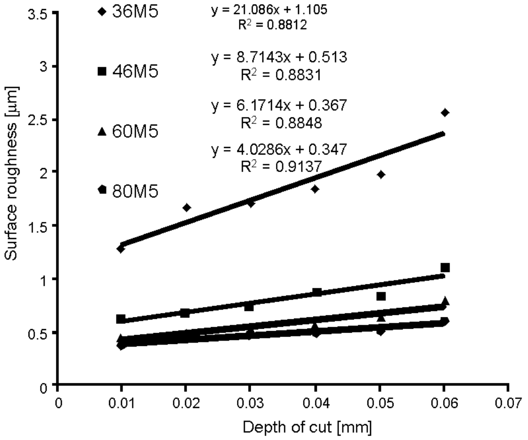


Fig. 2. *Grinding wheel grain size, depth of cut and surface roughness relation*

In this study, in order to show the influence of grinding wheel grain size on surface roughness well, arithmetical average of the surface roughness values obtained using the grinding wheels of same grain were obtained as follows:

$$Ra_{\mathrm{avr}}=[(Ra(td\!=\!0.01\ \mathrm{mm}))+(Ra(td\!=\!0.02\ \mathrm{mm}))+ +\ldots+(Ra(td\!=\!0.06\ \mathrm{mm}))]/6\ . \qquad (2)$$

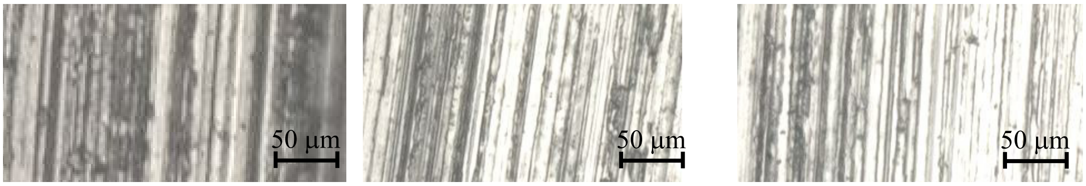
By using these arithmetical average values, the graph was plotted (Fig. 3). Surface roughness values were seen to increase significantly with increasing grinding wheel grain size. For example, with decreasing grinding wheel grain size, surface roughness values increased by 1.7, 2.29 and 5 times for grinding wheels of 60, 46 and 36 grains when compared to grinding wheel of 80 grain. These results show that a small increase in grain size leads to considerable increases in ground surface roughness values.

When the surface pictures of the ground materials are compared, it is seen that increasing depth of cut and grinding wheel grain size increases the depth and width of the grooves (Fig. 4). Grinding with grinding wheel of 46 grain at 0.02 mm depth of cut produced larger grooves (Fig. 4a) while decreasing grain size led to smaller grooves (Fig. 4b and c).

Fig. 3. *Grinding wheel grain size and surface roughness relation*

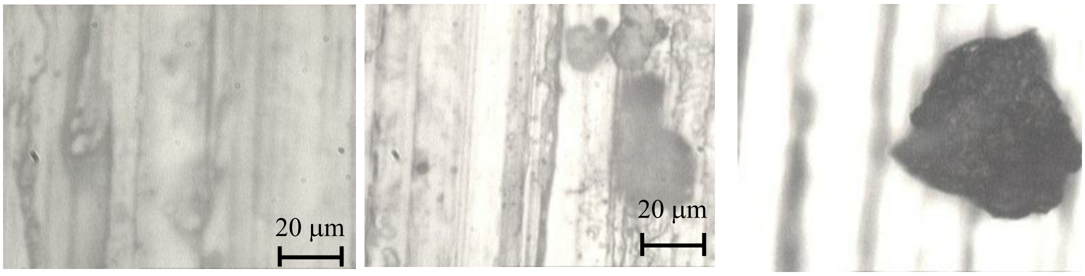
Small dirt and crater wear due to detached grains were observed after grinding with grinding wheel of small grain size (80 grain) at 0.03 mm depth of cut (Fig. 5a). Grinding wheel grains were found to penetrate the ground surface at higher depth of cuts of 0.04, 0.05 and 0.06 mm, Figs. 5b and c. Therefore, from Figs. 5b and c, the harmful effects of higher depth of cuts, which depend on the grain size, are seen. On the other hand, Figs. 6a and 6 show small parts of workpieces filling the porosities on the grinding wheel. In Figs. 6a and b, the white areas belong to a needle indicating the filled porosities on the grinding wheel for comparison purpose. Filling of the grinding wheel porosities results in deterioration in surface roughness. Detachment of the grinding wheel grains during grinding reduces the diameter of the wheel and this, in turn, leads to deviation from the required part dimensions [18]. Therefore, the grains embedded into the workpiece give rise to various problems like scratches on the workpiece and grain detachment. These sorts of problems, in turn, cause undesirable results during service life of the parts.

It was observed at all stages of this study that surface roughness values significantly increased with increasing depth of cut. Fig. 7 shows that increasing depth of cut deepened and widened the grinding marks as grooves on the ground surfaces.



a) 46M5 *b) 60M5* *c) 80M5*

Fig. 4. Workpiece surface appearance depending on grinding wheel grain size



a) Grinding wheel: 80M5 Depth of cut: 0.02 mm *b) Grinding wheel: 80M5 Depth of cut: 0.04 mm* *c) Grinding wheel: 80M5 Depth of cut: 0.04 mm*

Fig. 5. Workpiece surface appearance depending on grinding wheel grain size

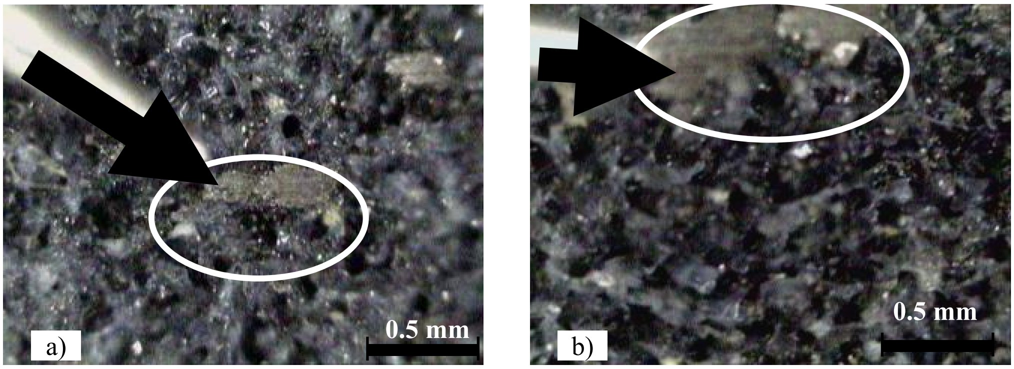
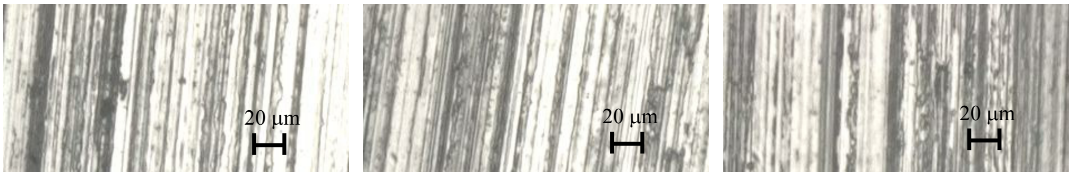


Fig. 6. *Wheel pictures showing the filled porosities with workpiece material at 0.04 mm depth of cut for the grinding wheel of 80 grain*



a) Depth of cut: 0.01 mm *b) Depth of cut: 0.02 mm* *c) Depth of cut: 0.03 mm*

Fig. 7. *The influence of depth of cut on surface structure for the grinding wheel of 60 grain*

3.2 Grinding Wheel Grain Size – Grinding Force Relation

The influence of grinding wheel grain size on grinding forces at 0.01 to 0.06 mm depth of cuts is given in Fig. 8. Grinding forces were recorded as 1.93 to 16.8 N for 46M5, 1.9 to 13.82 N for 60M5 and 1.7 to 9.18 N for 80M5 grinding wheels. These lower forces can be explained by the very small depth of cuts, very high cutting speed and small workpiece width. It was determined that grinding forces increased with increasing grinding wheel grain size at 0.03 mm depth of cut for the three grinding wheels of different grain sizes.

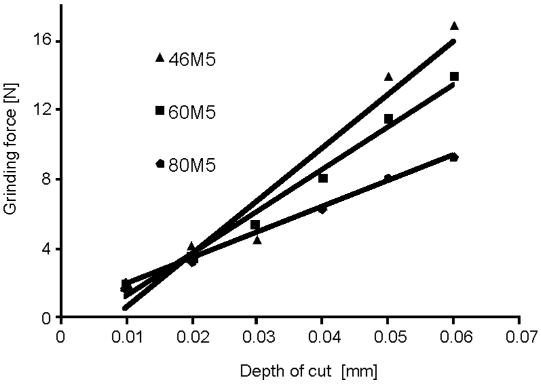
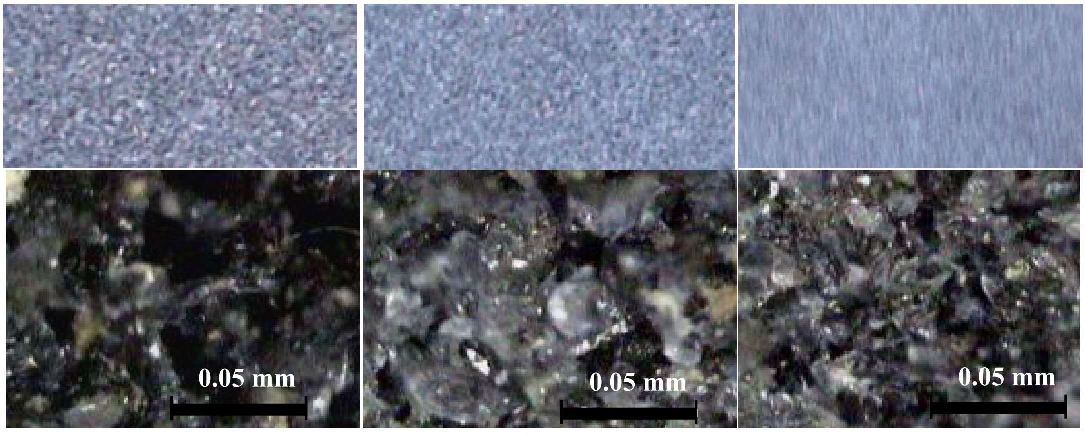


Fig. 8. *Depth of cut – grinding force relation depending on grain size*

Grinding with grinding wheel of 80 grain showed that the wheel was subjected to excessive forces at higher depth of cut (0.06 mm). Some burns and cracks were observed on the ground surface by the naked eye as the results these high forces.

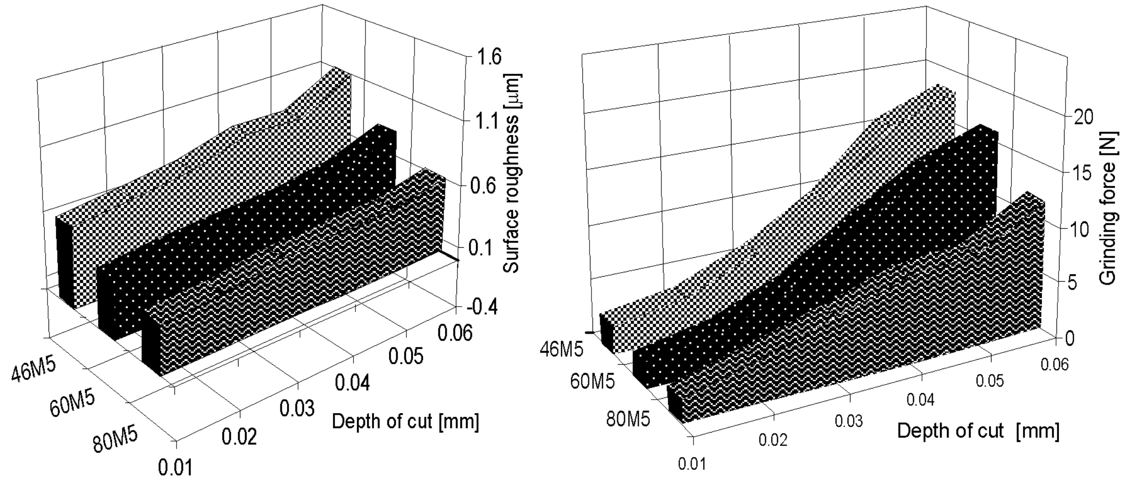
As the grain size of the grinding wheel of 80 (180 µm) grain has smaller grains than those of the grinding wheels of 60 (255 µm) and 46 (360 µm) grains, this wheel results in larger contact area between the wheel and ground workpiece during grinding. This larger contact area increases the friction and workpiece temperature during grinding. As the result of increased temperature, residual stresses occur on the workpice [9] and [19]. This was observed as the residual stress related small cracks on the ground surface. The small cracks on the workpiece were inferred from the chips accumulated along the cracks due to magnetic field of the workpiece table. As grinder spindle rotates at a constant wheel speed, the number of the grains on the wheel which removes chip from the workpiece varies depending on the grain size. Increasing grain number increases the grains which removes chip (Fig. 9). If grinding process is likened to milling operation with a multi-tooth cutter, the cross-section of chip per cutter tooth increases with decreasing number of cutter tooth when milling at a constant cutting speed and feed rate. This also increases the forces developed during milling [20]. Fig. 9 shows porosity and grain size.

Fig. 10a gives the variation of surface roughness values depending on grinding wheel grain size and depth of cut while Fig. 10b gives the variation of grinding force depending on the same parameters. It is seen from Fig. 10a that surface roughness is significantly affected by the grinding wheel grain size while the depth of cut has little influence on it. This can be explained by the different nature of the grinding operations when compared to other machining operations. In turning, milling and other machining operations, the chip is usually removed at one pass. The workpiece surface is formed dependent on feed rate, cutting tool geometry and other parameters. Unlike turning and milling operations, the chip in grinding is removed at several passes. Therefore, the grinding operation is carried out at much lower depth of cuts.



a) 46M5 *b) 60M5* *c) 80M5*

Fig. 9. *Workpiece surface appearance depending on grinding wheel grain size*



a) *b)*

Fig. 10. *Variation of a) surface roughness and b) grinding force depending on depth of cut and grain size*

This situation significantly alleviates the influence of depth of cut on surface roughness. The grinding forces developed at 0.01 to 0.02 mm depth of cuts did not vary much. However, a 50% increase was seen when the depth of cut was increased further (Fig. 10b). The highest cutting force with increasing depth of cut was obtained when grinding with grinding wheel of 46 grain.

4 CONCLUSIONS

The following conclusions can be drawn from the present study investigating the effects of grain size on workpiece surface roughness and grinding forces when surface grinding AISI 1050 steel:

- Grinding wheel grain size was found to have great influence on surface roughness and grinding force values. Increasing grinding wheel grain size increased the surface roughness values and the grinding forces.
- At 0.04 to 0.05 mm depth of cuts, the surface quality (in terms of *Ra*) obtained by 80 grain wheel was better by 30, 80 and 400% than those for 60, 46 and 36 grain wheels, respectively.
- Grinding wheel grains were found to penetrate the ground surface at higher depth of cuts of 0.04, 0.05 and 0.06 mm when the grinding wheel of 80 grain was used.
- At higher depth of cuts, some burns and cracks were observed on the ground surface by the naked eye for the grinding wheel of 80 grain.
- Grooves, burns and waviness can be decreased if depth of cut is reduced when using grinding wheels with small grains.

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