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CYLINDRICAL EXTERNAL PLUNGE GRINDING OF AISI 4340 STEEL WITH INTERRUPTED GEOMETRY

Diego Rafael de Mello

Hamilton José de Mello

diego.rafa@hotmail.com, hamilton@feb.unesp.br

Rafael Lemes Rodriguez

rodriguez.raaf@gmail.com

José Claudio Lopes

jclaudio.lopes@hotmail.com

Eduardo Carlos Bianchi

bianchi@feb.unesp.br

Universidade Estadual Paulista Júlio de Mesquita Filho, Faculty of Engineering, Department of Mechanical Engineering, Bauru, Brazil

Abstract. Grinding is one of the most used finishing processes in the metal cutting industry. However, the major part of ground workpieces is provided with continuous cutting. The manufacturing of precision workpieces using discontinuous cutting is common in several mechanical components, such as in the automotive industry. Few studies have been done on what happens to the workpiece's quality (roundness errors and roughness), and to the grinding wheel wear, when rotational symmetric parts are manufactured with interrupted cutting. The purpose of this paper is to study the grinding of workpieces (discs) whose geometry provides interrupted cutting (grooves in the discs). For this, a conventional aluminum oxide grinding wheel with resinoid bond was used in cylindrical external plunge grinding to grind grooved discs made of AISI 4340 steel, quenched and tempered, under conventional cooling. The testing samples have two, six and twelve grooves. The samples were ground with three different infeed rates in the plunge grinding: 0.25, 0.50 and 0.75 mm/min. For the same number of grooves, the surface roughness, roundness errors and diametrical grinding wheel wear tended to rise as the infeed rate increased. A slight improvement was observed in the surface roughness from testing samples with six grooves to testing samples with twelve grooves. The roundness errors increase was proportional to the grooves number and the infeed rates. The diametrical grinding wheel wear increase was more sensitive and proportional to the grooves number and to the infeed rates.

Keywords: Cylindrical external plunge grinding; interrupted cutting; conventional cooling.

1. INTRODUCTION

Traditionally well-known as finish process, the cylindrical external plunge grinding is an operation widely used in a machining cycle (Klocke *et al.*, 2005). With this operation, higher accuracy, better surface finish and others geometrical features are provided on the ground parts (Lopez-Arraiza *et al.*, 2013). However, as Karaguzel *et al.* (2016) have exposed, only a limited number of studies on interrupted cutting is found in the grinding literature because, as explained by Diniz *et al.* (2005), the interrupted cutting is usually studied during more conventional processes, such as turning.

Quintana and Ciurana (2011) showed that, in the recent decades, innovative technologies were able to provide significant improvements in the machining processes, such as the introduction of Computer Numeric Control (CNC) in the machines. In addition, according to Quintana and Ciurana (2011), studies and researchers efforts were very important to achieve advanced solutions to solve manufacturing problems and for the development of new concepts, materials and tools, in order to increase the production capability.

In fact, although the cutting processes and the machines have been enhanced a lot, there is even so much to improve. Nevertheless, the grinding machines have been essential in the modern manufacturing processes due to their great accuracy and efficiency (Kim *et al.*, 2013).

This paper aims to verify the behaviors of roughness, roundness error and diametrical grinding wheel wear at the end of the grinding process. For this, a conventional aluminum oxide grinding wheel with resinoid bond was used to grind grooved discs made of AISI 4340 steel, quenched and tempered, under conventional (abundant) cooling. Furthermore, the output variables obtained for interrupted grinding were compared with those obtained for continuous process.

1.1 Interrupted cutting in the grinding process

Interrupted cutting is characterized as a cutting process during which the tool at time is in contact with the workpiece (there is chip launch), at other time it loses this contact (there is not chip launch) (Al-Zaharnah, 2006), whether by grooves in the workpiece, grinding wheel or by some other kind of discontinuity. Urbikain *et al.* (2014) also describes that the interrupted cutting for turning is easily induced when a cylindrical workpiece has a non-constant diameter or when the workpiece has grooves in the periphery. Even the milling process can also be mentioned, which is naturally an interrupted cutting operation, in accordance with Karaguzel *et al.* (2016). In fact, there are many cutting edges on the tool, which alternate between cutting times (material removal) and times without contact with the workpiece (no material removal), assisting in the cooling process.

Al-Zaharnah (2006) even describes that interrupted cutting implies in coupling and uncoupling between the workpiece and the tool. This process generates impacts between workpiece and tool and causes changes on the machined surface roughness.

Furthermore, Kountanya (2008) concluded that the cutting temperature is smaller in interrupted cutting operations than in continuous cutting operations, because alternating periods of coupling and uncoupling provide cooling in the cutting zone.

The interrupted cutting process is employed not only in crankshaft production, but also in drill sharpening process. On this way, after the formation of grooves, the grinding process provides the drill sharpening with, respectively, rough and finishing grinding operations. In terms of the crankshaft production, the complex geometry and the bearing fixation are finished by an interrupted grinding process. Nevertheless, there are low amount of research done about the interrupted cutting process, it contrasts with the important application of this production operation which is involved daily in the industrial sector.

2. EXPERIMENTAL PROCEDURE

The testing samples (TSs) used during the experimental campaign were made of AISI 4340 steel, quenched and tempered, with 54 HRC of average hardness. Figures 1, 2 and 3 show the three different types of TSs used in the tests.

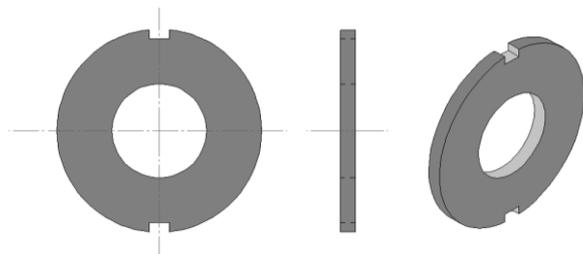


Figure 1. TS with two grooves.

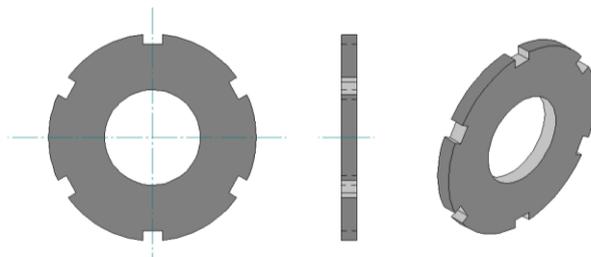


Figure 2. TS with six grooves.

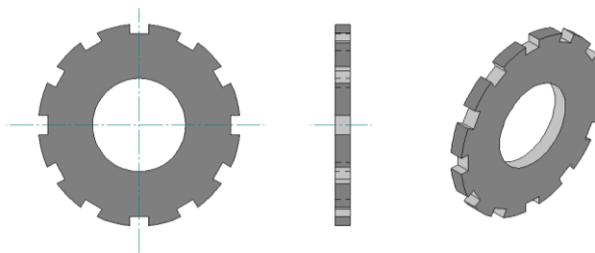


Figure 3. TS with twelve grooves.

The grinding wheel used in the tests had the following specification: RT 355 x 25.4 x 127 mm (diameter x thickness x hole diameter); AA 100 O6 BRC, where AA: white oxide aluminum; 100: fine grain; O: medium hardness; 6: structure; BR: resinoid bond; C: manufacture's private brand.

For roughness measurement (R_a parameter), three measurements differing 120° from each other was carried out on each TS as well. The equipment used was Surtronic 3+ (Taylor Hobson brand). For roundness errors measurement, each TS was placed on the equipment and three measurements were carried out on each TS: the initial contact position of the touch-sensitive edge differs 120° of the previous contact point. The equipment used for roundness errors measurements was Talyrond31c (Taylor Hobson brand).

For the grinding process, a CNC SULMECÂNICA RUAP 515H cylindrical external grinding machine was used. The cutting velocity (v_s) of the grinding wheel was 30 m/s and the workpiece velocity (v_w) was 40.4 m/min. Each TS had a total diametrical removal of 5 mm. Each experiment removed 0.1 mm among each spark-out time (1.5 s) and the three infeed rates (v_f) used were 0.25 - 0.50 - 0.75 mm/min for each TS type. The cooling fluid used during the tests was a semi synthetic oil ME-1 (Tapmatic do Brasil Ltda. brand), with dilution of thirty parts of water. The cooling fluid got out from the nozzle of the cooling system with flow of 15L/min (0.015 MPa).

For diametrical grinding wheel wear analysis, before the dressing process, printings of the grinding wheel were made on pre-turned cylinders using the infeed rate of 0.25 mm/min and cutting depth of 1mm. This infeed rate was used due to the better accuracy and quality of the printings. The grinding wheel wear was measured through these printed grinding wheel profiles using Surtronic 3+ rugosimeter and the Talyprofile software tool (Taylor Hobson brand).

3. RESULTS AND DISCUSSION

In this section, the experimental results of the output variables for each grinding condition are presented. The results are illustrated in bar graphs containing their average measurements (bars) and their respective standard deviations.

3.1 Surface Roughness

Figure 4 presents the TSs' roughness behavior (R_a parameter) and their respective standard deviation, according to the tests.

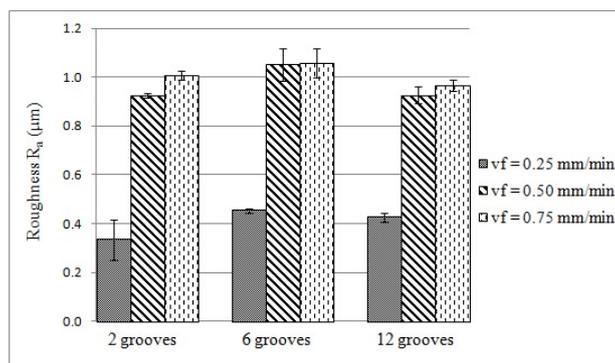


Figure 4. Surface roughness due to the grooves number and the infeed rates.

From Fig. 4, the roughness values tended to increase as v_f rose, for the same TS type (same grooves number). As higher was v_f , more severe was the cutting process, since the grinding wheel has greater penetration in the workpiece, considering the same period of time; i.e., there was a growth in the material removal rate and, therefore, in the chip thickness, increasing the roughness values. The explanation is based on the grinding wheel movement, as the grinding wheel continues its penetration while passing through the groove. Then, at the imminence of contact between the

workpiece and the grinding wheel (at the groove's end), the grinding wheel already has a "cutting depth" with regard to the cutting surface (workpiece external diameter), this "depth" being as greater as higher is v_f . On this way, the mechanical shocks become increasingly intensified due to impacts of the process which are originated by the couplings and uncouplings between the workpiece and grinding wheel. Consequently, bond and grains are fractured, cutting edges are lost and surface roughness becomes inadequate. Al-Zaharnah (2006) explains that interrupted cutting is important due to the coupling and uncoupling process between workpiece and grinding wheel, causing impacts which change both grinding forces and ground surface roughness..

When each v_f is analyzed, the roughness values increased from TS with two grooves to TS with six grooves and decreased to TS with twelve grooves. Moreover, the continuous grinding presented lower roughness R_a values, as can be seen in Fig.4. According to Tawakoli and Azarhoushang (2011), the surface roughness value for continuous grinding was slightly smaller in comparison with interrupted grinding (grooves in the grinding wheel), when ceramic matrix composites (CMC) were ground. In the case of this work, the roughness values between continuous and discontinuous processes can be appreciably noticed. This result was explained by Tawakoli and Azarhoushang (2011) based on the regular shocks between the grinding wheel and workpiece as a consequence of the coupling and uncoupling process. Therefore, the higher the grooves number, the higher the shocks number, negatively influencing in the ground surface roughness, which was observed from TSs among continuous, two grooves and six grooves. Regarding to the slight roughness decrease of twelve-grooved TSs, this fact occurred once the increase in the grooves number (from six to twelve) led to a better cooling and lubrication in the cutting zone because of the greater grooves number, obtaining better surface roughness. As explained by Kwak and Ha (2001), the grinding process by interrupted cutting (grooves in the grinding wheel) is a promising method to decrease workpiece thermal damages due to its excellent cooling effect, since the cutting fluid is provided more directly and in enough amount in the cutting zone (workpiece – grinding wheel contact).

According to the standard deviations, significant differences were found among the roughness results.

3.2 Roundness

Figure 5 presents TSs' roundness errors results and their respective standard deviation, according to the tests.

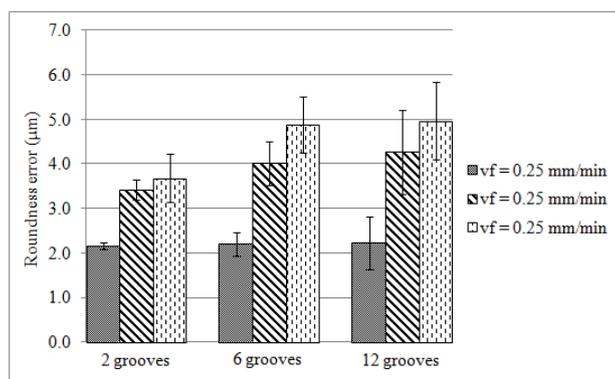


Figure 5. Roundness errors due to the grooves number and the infeed rates.

As presented in Fig. 5, for the same TS, roundness errors tended to rise with the v_f growth [roundness error means that there is a variation between the workpiece real circle profile and the ideal circle, as explained by Lei *et al.* (2011). When v_f increases, the compression rate on the workpiece surface also increases, because grinding is a cutting process which has the chips removed by compression of the surface in machining. Therefore, the workpiece is submitted to increasing compressive stress and suffers circular profile deviations.

When different TSs were analyzed for the same v_f value, the roundness error values had growth trend as greater were the grooves number. The greater the TS grooves number, the smaller the TS external profile. In fact, the samples which were continuously machined showed the smallest values of roundness errors. Thus, when the previous information is combined with the inherent compression of the grinding process and the mechanical shocks due to the interrupted cutting, the workpiece optimal profile (circular) suffers a deviation, since the TS surface is intermittently smashed by the grinding wheel. This fact can explain the better efficiency in relation to roundness and roughness presented by continuous grinding process in comparison with the interrupt grinding process. As a rough approach, the previous outlined facts are similar to a hammer shocking with some surface at changeable frequency (proportional to TS grooves number, i.e., this frequency is smaller for TSs with fewer grooves and greater for TSs with more grooves).

Statistically, the presented roughness error results had insignificant differences in view of the obtained standard deviations.

3.3 Diametric Wheel Wear

Figure 6 presents the diametrical grinding wheel wear results and their standard deviations, according to the tests.

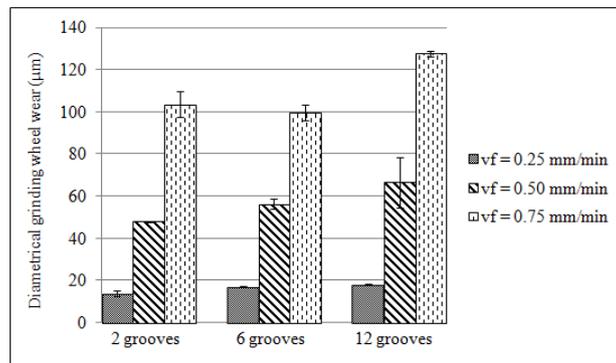


Figure 6. Diametrical grinding wheel wear due to the grooves number and the infeed rates.

About Fig. 6, for the same TS, as the greater was vf , the greater was diametrical grinding wheel wear. Liao *et. al* (2000) explains that the wear in the grinding wheel is related to the break of abrasive grains and bond fracture, both due to thermal damage or due to severe mechanical stress which the grinding wheel is subjected. Thus, the grinding wheel wear occurs due to the greater cutting severity (mechanical shocks caused by the grooves) under vf growth.

Analyzing different TSs for the same vf value, in general, according to standard deviations, the increase in the grooves number provided the increase in the grinding wheel wear. Even in accordance with Liao *et. al* (2000), as the increase in the grooves number implies in increase on shocks between grinding wheel and workpiece, thus the increase in the grooves number leads to a greater cutting severity and, therefore, a greater grinding wheel wear.

According to the standard deviations, the grinding wheel wear results presented significant differences.

4. CONCLUSIONS

From the previous presented results, it was concluded that:

- For the same TS, the roughness values tended to increase with the vf growth. When the same vf was taken, the roughness values rose from TSs with two grooves to TSs with six grooves and, afterwards, the roughness values had a slight decrease to TSs with twelve grooves. With regard to the continuous process, TS's roughness values were notably lower than those obtain in terms of interrupted process;
- For the same TS, roundness errors values had increasing trend with vf growth. When different TSs were analyzed for the same vf , the increasing trend of roundness error values was observed as the grooves number increased. In accordance with the roughness results which were obtained, the continuous grinding were more efficient in reducing roundness error on the workpiece surface;
- For the same TS, the diametrical grinding wheel wear increase was greater as vf rose. When different TSs were analyzed for the same vf , in general, the increase in grooves number provided the growth of the grinding wheel wear. The continuous process diminished the diametrical wheel wear, promoted by the reduction of the cutting severity by the reduction of the shocks between grinding wheel and workpiece;

5. ACKNOWLEDGEMENTS

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