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ORIGINAL ARTICLE

Contribution to cylindrical grinding of interrupted surfaces of hardened steel with medium grit wheel

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Abstract

Grinding is generally the first choice to provide combination of both superior surface finish and closer dimensional tolerances in a machined component. This process can be employed in manufacturing of continuous and interrupted surfaces. Crankshafts and engine piston rings are examples of ground precision mechanical components having interrupted surfaces. However, the specific literature about grinding of interrupted surfaces is still scarce. In this context, aiming to further contribute to the understanding of the behavior of surface integrity of interrupted surfaces during grinding, this paper presents an experimental investigation of interrupted surfaces ground with white aluminum oxide grinding wheel. Discs of AISI 4340 hardened steel with different number of grooves (2, 6, and 12) on the external surface were tested. Experiments with discs without interrupted surface were also carried out for comparisons. In addition to the number of grooves, three values of infeed rate (0.25, 0.50, and 0.75 mm/min) were used as input parameters. The output parameters investigated were the geometric errors (surface roughness and roundness) of the workpiece material as well as the diametric wheel wear. Analysis of variance (ANOVA) test was performed to verify any statistical difference among the output variables. Results showed that both surface finish and roundness of workpieces with interrupted surfaces were higher than those obtained for continuous surface. These parameters also increased with infeed rate up to 0.50 mm/min, whereas the grinding wheel wear was more sensitive to number of grooves and infeed rate. No thermal damages were observed on the machined workpieces under the conditions investigated.

Keywords Cylindrical external plunge grinding · Interrupted surface · Number of grooves · AISI 4340 steel · Geometric errors · Wheel wear · Surface integrity

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1 Introduction

Nowadays, in addition to the constant evolution of machining systems and machine tools, it has been noticed an increasing demand for components with high geometric precision, more complex and miniaturized parts. In this context, it is fundamental to understand the behavior of surface integrity of workpieces having interrupted surfaces during grinding.

The cylindrical external plunge grinding is widely employed in metal-working industry especially when superior surface finish and high accuracy, as well as other geometrical features in cylindrical components, are required [1–3]. However, only a limited number of studies on grinding of interrupted surfaces have been found in the specific literature [4]. Generally, most of researches on machining of interrupted surfaces are machined with process using geometrically-defined cutting edge such as milling and turning, for instance [5, 6]. In these processes, when performing interrupted surfaces, because of interrupted cutting, is generally observed fluctuation in both thermal and mechanical load that adversely affect the efficiency of cutting edges and reflect in the quality of the machined component, thereby leading to reduction in the overall performance of the process. Despite the various benefits that can be achieved with grinding process, special attention has to be drawn to it because of the thermal damages on the workpiece material that can be generated during machining. The most common grinding thermal damages reported in the literature are workpiece surface overheating (also known as grinding burning, cracks, metallurgical alterations, and tensile residual stress [7]. However, these problems can be overcome by the selection of appropriated cutting parameters, such as depth of cut, workpiece speed, dressing method, material and structure of grinding wheel, as well as coolant type, flow rate, and coolant delivery technique. This selection is mainly dependent on the properties and geometry of the workpiece material, as well as on the grinding operation.

In this sense, aiming to further contribute to the understanding of the behavior of surface integrity of interrupted surfaces during grinding, this paper presents an experimental study about cylindrical external plunge grinding of interrupted surfaces of the AISI 4340 steel with conventional abrasive grinding wheel. The two-factor analysis of variance (ANOVA) test with one replication was carried out in order to identify the parameters that were statistically affected (surface roughness, roundness, and diametric wheel wear) by the number of grooves and infeed rate.

1.1 Grinding of interrupted surfaces

Grinding can be considered as an interrupted machining process because of the thousands of cutting edges of the abrasive grains distributed throughout the grinding wheel that are not in constant contact with the workpiece material during the various revolutions per second of the abrasive wheel. According to Al-Zaharnah [8], interrupted cutting occurs when the tool is not in constant contact with the workpiece. This is the case of workpiece surfaces with grooves or also the grinding wheels having profiles, such as structurally profile grinding wheels and gear wheels, for instance. Urbikain et al. [9] reported 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. The milling process is an example of originally interrupted or intermittent cutting [4]. In fact, there are many cutting edges on the tool, which alternate between cutting times (material removal phase) and times without contact with the workpiece (no material removal phase). This will lead to fluctuation in both thermal and mechanical load and adversely affect both tool and workpiece integrities, in especially the machined surface [8]. Furthermore, Kountanya [10] concluded that the cutting temperature developed in interrupted cutting is generally lower than in continuous cutting operations, because alternating periods of coupling and uncoupling provide cooling in the cutting zone.

Crankshaft, engine piston ring, and several cutting tools, such as twist drills, are examples of interrupted surfaces that usually require grinding operation. Sharpening and re-sharpening of twist drills are generally performed in two stages: rough and finishing operations. In terms of the crankshaft production, the complex geometry and the bearing fixation are considered interrupted surfaces. Nevertheless, as previously mentioned, specific literature about grinding of interrupted surfaces is still scarce which is a contrasting situation since, machining of interrupted surfaces is a daily need in the metal-working industry. So, understanding of the behavior of the surface integrity of interrupted surfaces during grinding, especially to determine the proper selection of cutting parameters, is indispensable to ensure the highest efficiency of a grinding process of interrupted surfaces.

1.2 Grinding process cooling in interrupted cutting

The minimization of heat transfer from workpiece to grinding wheel during the cutting is some of the major challenges in grinding process. It is known that most of heat generated during grinding is directed to the workpiece material mainly due to the small section of chip formed and refractory characteristic of the conventional abrasives used in the grinding wheels that impairs heat dissipation. The conventional abrasive materials, such as aluminum oxide, present low thermal conductivity, so that most of the heat generated during the process is transferred to the workpiece material during grinding [7]. It is known that the higher the thermal conductivity of the workpiece material or grinding, the higher the rate of heat removal from the cutting zone, which limits the increase in the temperature of the workpiece [11]. On the other hand, excessive temperatures in the cutting zone adversely affect the surface and subsurface integrity of the workpiece, hence favoring the occurrence of several types of thermal damages, like those previously mentioned and reported by [7, 12, 13]. So, the proper use of coolant and its application are indispensable to cool the workpiece and avoid thermal damages [14]. Nevertheless, Kwak and Ha [15] demonstrated that grinding by interrupted cutting (grinding wheel with grooves) is a promising method to decrease workpiece thermal damages due to the excellent cooling effect of the process. According to Pérez et al. [16], the explanation is based on the grooves, since they provide direct and enough amount of cutting fluid in the cutting zone.

2 Material and method

Grinding tests were carried out in a CNC cylindrical external grinding machine, RUAP 515H model, from Sul Mecânica manufacturer. A resin-bonded white aluminum oxide grinding wheel with designation AA 100 O6 BRC from Sivat Abrasives manufacturer, medium size grits dimensions of 355.0 mm external diameter × 25.4 width × 127.0 mm internal diameter was used in the tests. With regard the grinding wheel designation, the first letter represents the type of abrasive, followed by the grit number (100), wheel grade represented by the letter (O), structure (6), and bond type (B). It is known that the larger the value of abrasive grit, the smaller is the grain [7]. For instance, a very fine abrasive could be 800 grit, while a roughing operation might employ a 46-grit grain size. For the wheel grade, where higher letter is the strongest, it is described as soft, medium, or hard. Regarding the grinding wheel structure, a low numeric value indicates a dense structure, whereas a high value means an open one. So, a grinding wheel more open is recommended for roughing grinding and usually contains a larger grain size. The resin bond provides a denser structure, but also increases the cutting velocity by the fact that it withstands to higher grinding forces and impacts, properties that are desirable to the application in the interrupted cutting process.

The workpiece material is the AISI 4340 steel that was quenched and tempered, which resulted in a hardness of 54 ± 2 HRC. Six specimens with 68 mm outer diameter, 29.20 mm internal diameter, and 4 mm thickness were previously prepared by turning and milling operations, in which two specimens have two (2) grooves, other two specimens have six (6) grooves, and two remaining specimens have twelve (12) grooves, as shown in Fig. 1a, b, and c, respectively. Detailed dimensions of the groove itself are shown in Fig. 1d.

The workpiece was fixed on a mandrel and placed between head and tail stock of the grinding machine to provide the perpendicular position between the workpiece surface and

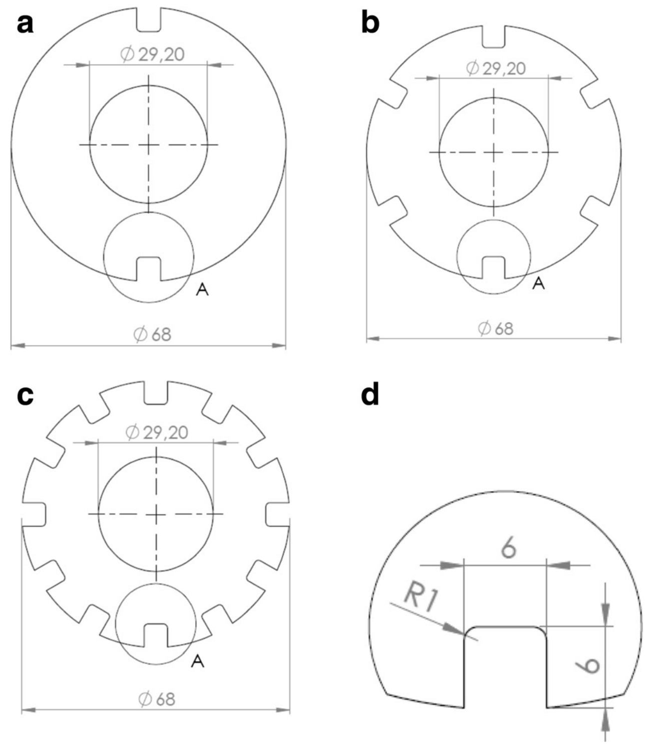

Fig. 1 Geometry of samples of AISI 4340 with interrupted surfaces. **a** Two grooves. **b** Six grooves. **c** Twelve grooves. **d** Dimensions of the groove

the plunge movement of the grinding wheel as shown in Fig. 2. The cutting and workpiece speeds were 30 m/s (v_s) and 40.4 m/min (v_w), respectively. Three values of infeed rates (v_f) (0.25–0.50–0.75 mm/min) were tested. Prior to each grinding test, sparkout of workpiece was performed for 1.5 s using a depth of cut of 0.1 mm, without wheel feed. This grinding condition aims to gradually eliminate the deformations and geometric deviations.

A water miscible—semi-synthetic—vegetable oil, ME-1 (Quimatic/Tapmatic do Brasil Ltda) at dilution ratio of 1:30 (oil/water)—was delivered at a cutting zone at a flow rate of 15 l/min and a pressure of 0.6 MPa by the optimized nozzle which is shown in Fig. 2.

In terms of dressing procedure, it was employed a diamond cluster dresser with a volume of 15 mm × 8 mm × 10 mm and the following parameters were selected: dressing depth (ad) of 4 μm and dressing speed (vd) of 100 mm/min.

The output parameters investigated in this work were surface roughness and roundness deviations of the workpieces as well as diametric wheel wear.

The surface roughness (R_a) was measured using Taylor Hobson Surtronic3+ portable stylus instrument. The measurements were taken using a cut-off of 0.25- and 1.25-mm sampling length. The measurement results correspond to the average of readings in three different positions (120° spacing) for each workpiece under the same cooling-lubrication conditions.

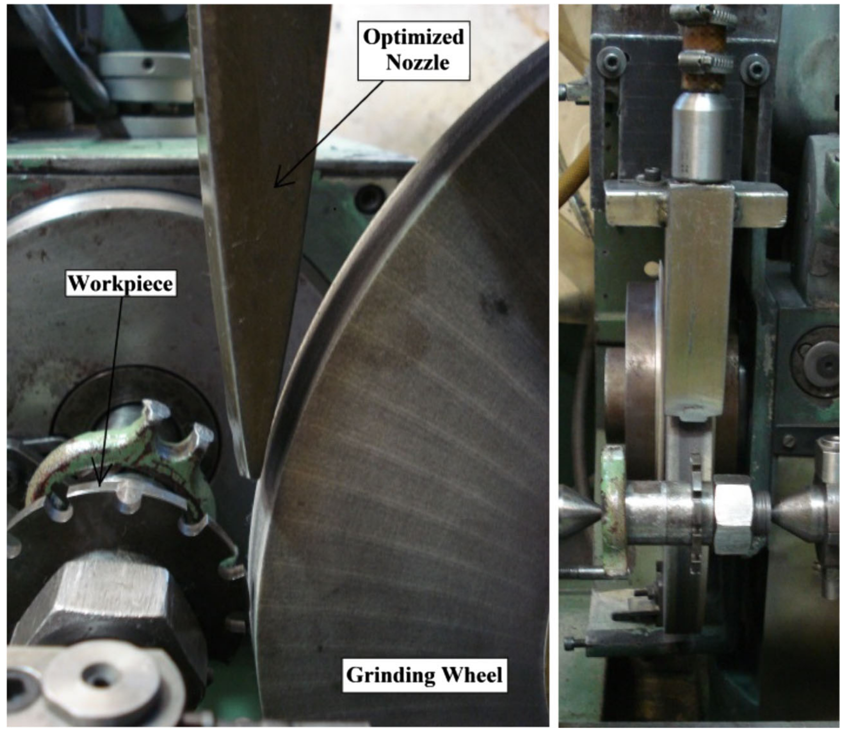

Fig. 2 Experimental setup for the grinding tests

Roundness deviation measurements were taken in all workpiece materials using a Taylor Hobson Talyrond 31C device.

The diametric grinding wheel wear measurements were performed, prior to the dressing operation, through the imprint method, which replicates wheel surface (after machining) on a second body, in general a soft steel cylinder. This procedure is an indirect measurement reported by Malkin and Guo [7] and well described in the work carried out by Oliveira et al. [17]. Initially, printings of the grinding wheel were made on a cylindrical AISI 1020 steel workpiece material with dimensions of 38 mm diameter × 90 mm length (that were previously prepared by turning operation), under the following grinding conditions: infeed rate of 0.25 mm/min and depth of cut of 1 mm. This infeed rate was used due to the better accuracy and quality of the printings obtained under such condition. So, the diametric wheel wear was measured via profile projection and measurement with the aid of surface roughness meter software (Taylor Hobson TalyMap).

Once the grinding test was completed, all specimens were properly cleaned with hydrated alcohol and dried for measurements of surface roughness and roundness deviations. After the geometric measurements, all the specimens were also mounted in bakelite, grounded, and polished ready for micrograph analyses.

Aiming to detect possible alteration on microstructure of ground workpieces, all the specimens were examined and photographed with an optical microscope with an attached camera with optical microscopy (Olympus BX-51) with ×500 magnification.

Finally, since the ANOVA test is considered to be simple, powerful, and popular mean to perform statistical testing on experiments that involve two or more groups, this test was performed for the output variables investigated in this work. The interpretation of the ANOVA table was based on the *P* value (probability). Regarding a confidence interval of 95%, there was a probability of 5% ($\alpha = 0.05$) of significance in the differences of the parameters; therefore, *P* values lower than the previously established (0.05) indicated the rejection of the initial hypothesis of equal variances, i.e., a change in the factor (input parameter) caused a significant variation in the output parameter [18].

3 Results and discussion

In this section, the experimental results of the output variables for each grinding condition are presented. The results represent the average of measurements with respective standard deviation values (represented by error bar) that were calculated.

3.1 Surface roughness

Figure 3 shows the surface roughness values of the samples with different grooves after machining with various values of infeed rate. From this figure, it can be seen that R_a values increased with infeed rate values up to 0.50 mm/min, irrespective of number of grooves. It is known that severity of

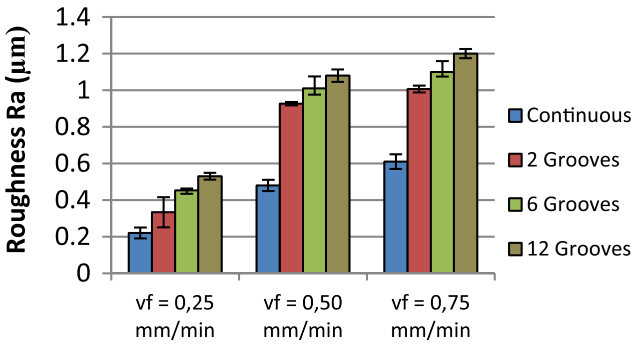

Fig. 3 Surface roughness for different number of grooves and cutting conditions

grinding process increases with infeed rate, the higher is infeed rate, deeper is the penetration of the grinding wheel into the workpiece considering the same time period and, consequently, which means higher material removal rate [7]. The R_a parameter is strongly dependent on the equivalent chip thickness (heq), i.e., when the equivalent chip thickness which is directly proportional to infeed rate increases, it yields the increase of the roughness values [18].

Moreover, according to researches carried out by Malkin and Guo [7], Marinescu et al. [13] and Ruzzi et al. [19] in grinding of hardened steels with conventional abrasive grinding wheels, higher the feed rate, the higher and faster is the advancement of grinding tool against the workpiece. On this way, the surface roughness increases because of the higher cutting forces that are generated by the faster advancement of the grinding wheel moving at higher infeed rate, thereby promoting vibrations and leading to deterioration of the surface finish [20].

Also, as the grinding wheel rotates and continues its penetration while passing through the groove on the workpiece material, and with increase in infeed rate, the apparent contact area between grinding wheel and workpiece increases. This involves higher grinding forces and increase in thermal stress. In this sense, 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. This will lead to fracture of bond and grits and, consequently, loss of grits cutting edges, thereby reducing cutting performance and adversely affecting surface finish [8, 21]. In this current work, it was expected that the increase in number of grooves lead to more bond-grits fracture, but by the surface roughness and standard deviation values obtained, no influence of number of grooves was observed in the surface roughness. From this finding, it can be inferred that the selected grinding wheel performed well in interrupted cutting under the conditions investigated, especially because of all the surface roughness values that are lower than 1.2 μm, below the stipulated rejection limit of 1.6 μm for grinding process generally reported in the literature [7]. However, when comparing results of surface roughness obtained after machining continuous surfaces with the results for interrupted surfaces (Fig. 3), it can be seen that R_a values for the latter increased about 100% under the conditions investigated. From these results, it can be inferred that, in addition to thermal deterioration and mechanical loads, wheel abrasive grits are influenced by the workpiece material geometry, i.e., presence of interrupted surfaces can generate higher impacts because of the alternating periods of coupling and uncoupling of abrasive grits in the cutting zone, which reduces wheel bond resistance and consequently makes grits more susceptible to fracture or to pull out. As a consequence, the grain spacing is increased, which leads to increase in theoretical peak-to-valley surface roughness [13].

Table 1 shows the ANOVA of the surface roughness values.

According to Table 1, analyzing the different numbers of grooves (0 (continuous), 2, 6, 12), *P* value was lower than 0.05; thus, there is significant variation among the R_a values obtained. In fact, the variation of the numbers of grooves affects substantially the value of R_a surface roughness. The same analysis can be employed to the v_f variation, *P* value was lower than 0.05 yielding the fact that v_f value affects the R_a parameter. With regard to the analysis of interaction between the number of grooves and v_f, it can be inferred that the R_a value obtained is significantly affected by the interaction between number of grooves and v_f once *P* value was lower than 0.05. There is not only a combination of number of grooves and v_f value which maximized the R_a roughness value but also another combination which minimized the R_a roughness values.

3.2 Roundness

With regard the roundness deviations, from Fig. 4, it can be seen that, similarly to the surface roughness values, they increased with infeed rate up to 0.5 mm/min. Xu et al. [22] explained that when the infeed rate is increased, deformation of the samples, machine, and tool also increased, therefore raising the roundness error. According to Shaw [23], the increase of the radial feed rate promotes the deterioration of the surface finish because of the increase of the equivalent chip thickness and, simultaneously, specific material removal rate.

Table 1 The ANOVA of the roughness (R_a) values

Source	*SQ*	*DOF*	*MQ*	*F*	*P* value
Number of grooves	0.8851	3	0.2950	124.9580	8.81753E-15
v_f	2.1854	2	1.0927	462.7847	6.79539E-20
Interaction	0.1230	6	0.0205	8.6827	4.43377E-05
Error	0.0567	24	0.0024		
Total	3.2502	35			

SQ sum of square, *DOF* degree-of-freedom, *MS* mean square, *F* frequency

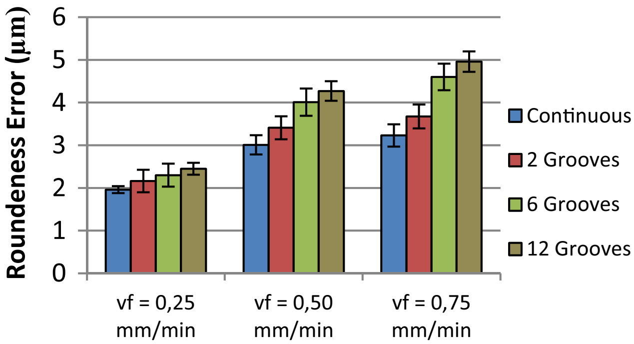

Fig. 4 Roundness deviation for different number of grooves and cutting conditions

Kurt and Köklü [24] carried out an experimental and mathematical investigation to determine the effects of wheel and cutting parameters on shape error in interrupted grinding to select optimum cutting parameters with aid of the Taguchi method. The workpiece material was a rectangular bar of GS-C25 cast steel having a hole with 50 mm of diameter. They varied different cutting parameters, such as wheel grit size (36 to 80), workpiece speed (18 to 30 m/min), and cross feed (1 to 4 mm). As a result, the authors reported that both surface finish and shape error decreased with increase of wheel grit size. They concluded that the best combination among the parameters that lead to minimization of the shape error was grain size of wheel of 80 mesh, grinding depth of 10 μm, workpiece speed of 22 m/min, and cross feed of 1 mm.

In general, when comparing workpiece surfaces with and without grooves, it can be noticed that roundness deviations were higher for the interrupted surfaces. Roundness deviations of a component mean that there is a variation between the workpiece material real circle profile and the ideal theoretical circle [25]. As the infeed rate increases, higher will be the compression rate on the workpiece surface, since grinding is a cutting process in which generated chips are removed by compression of workpiece surface in machining. In general, form error such as roundness is very strongly dependent on vibration and chatter [7]. Although resin bond wheels are recommended for precision applications where resilience provides benefits of withstanding interrupted cuts [13], what is the case of the conditions employed in the current work, higher roundness deviation values were recorded after machining the interrupted surfaces in comparison to the continuous surface (without groove) probably due to increase in the level of excitation of machine tool [26] as a consequence of cyclical loads originated by the couplings and uncouplings between the grinding wheel and the workpiece material. Malkin and Guo [7] reported that the most of geometric deviations generated in grinding process are mainly caused by wheel wear, especially for profile grinding of cross-sectional shapes with sharp radii or deep grooves.

Table 2 shows the two-factor ANOVA employed to analyze the roundness values

Table 2 Two-factor ANOVA test for the roundness values

Source	*SQ*	*DOF*	*MQ*	*F*	*P* value
Number of grooves	6.6838	3	2.2279	5.7619	0.00408
v_f	27.4239	2	13.7120	35.4617	6.8E-08
Interaction	2.6040	6	0.4340	1.1224	0.37909
Error	9.2801	24	0.3867		
Total	45.9919	35			

The analysis of variance in terms of roundness errors showed significant variation with the increase of the numbers of grooves (0 (continuous), 2, 6, 12), since *P* value was lower than 0.05. When the variation v_f values were considered, *P* value was higher than 0.05 which implies the fact that there is significant variation among roundness values to different v_f values. On the other hand, the analysis of correlation among the number of grooves and v_f showed that there is no significant interaction between the two sources of variation.

3.3 Grinding wheel wear

Figure 5 presents the wheel wear values obtained after grinding the AISI 4340 steel with different number of grooves and infeed rates. It can be seen that wheel wear increased with both infeed rate and number of grooves. Besides, this parameter was more sensitive than surface roughness and roundness when number of grooves increased, especially from 6 to 12 grooves at more severe cutting condition ($v_f = 0.75$ mm/min), condition that wear increased over to 20%. The infeed rate increase caused the enhancement of the grinding forces, promoting higher values of diametric wheel wear, accelerating the wear of abrasive grains during the process [18]. In accordance with the findings from Choi et al. [27], with an increase in the infeed rate (and the consequent increase in equivalent chip thickness), the diametric wheel wear was also high.

Liao et al. [28] explain that structure of grinding wheel, which it is related with breakage capacity of abrasive grits

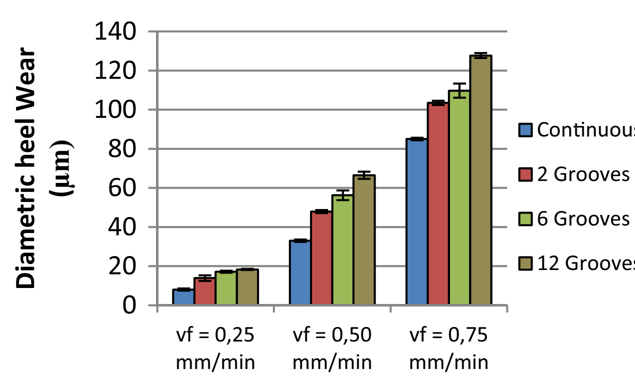

Fig. 5 Diametric grinding wheel wear due to the number of grooves and the infeed rates

Table 3 The ANOVA of the diametric wheel wear values

Source	*SQ*	*DOF*	*MQ*	*F*	*P* value
Number of grooves	3524.8364	3	1174.9455	46.7076	3.6E-10
v_f	48,752.7850	2	24,376.3925	969.0342	1.1E-23
Interaction	1003.5249	6	167.2541	6.6489	0.00031
Error	603.7283	24	25.1553		
Total	53,884.8747	35			

and bond fracture, highly affects the wheel wear behavior, especially because of the thermal damage and severe mechanical stress that the grinding wheel is subjected during grinding. In the current study, the increase in grinding wheel wear can be attributed to the more intense mechanical shocks between abrasive grits and workpiece material as a consequence of grooves in the interrupted surfaces of the workpiece material that means a more severity condition than the workpiece material without groove [13]. Presence of grooves means more impacts because alternating periods of coupling and uncoupling of abrasive grits, which tends to favor more fracture of grits and their pull out, thereby increasing the grinding wheel wear.

Table 3 presents the ANOVA test for the diametric wheel wear results obtained in this work. The results presented by Table 3 showed the significant variation with the increase of the numbers of grooves (0 (continuous), 2, 6, 12). Moreover, the diametric wheel wear values were affected substantially by different v_f values. The interaction of number of grooves and v_f promotes significant variation.

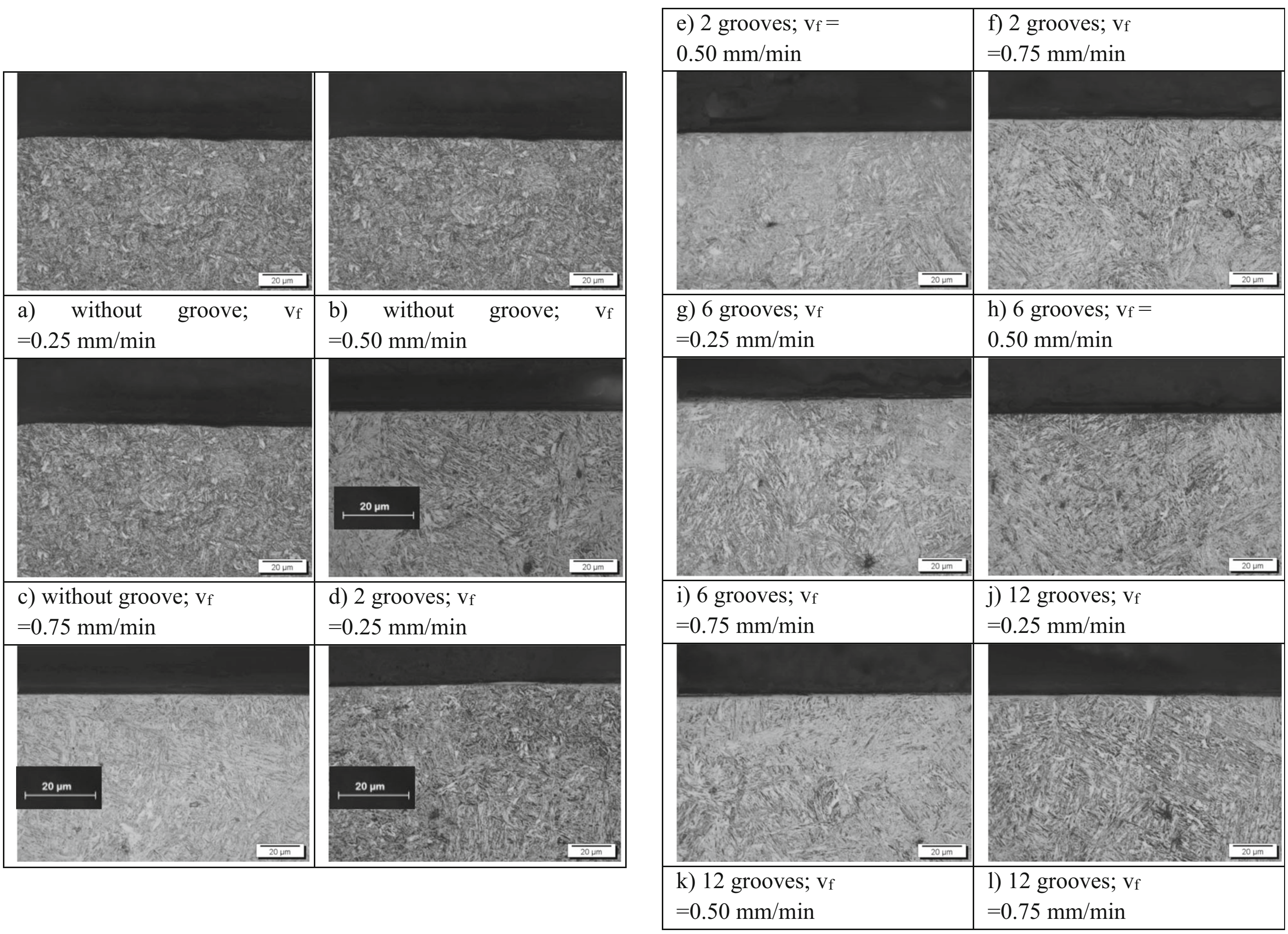

Fig. 6 Micrographs of workpieces after grinding process for different number of grooves and infeed rate: **a** without groove and vf = 0.25 mm/min, **b** without groove and vf = 0.50 mm/min, **c** without groove and vf = 0.75 mm/min, **d** 2 grooves and vf = 0.25 mm/min, **e** 2 grooves and vf = 0.50 mm/min, **f** 2 grooves and vf = 0.75 mm/min, **g** 6 grooves and vf = 0.25 mm/min, **h** 6 grooves and vf = 0.50 mm/min, **i** 6 grooves and vf = 0.75 mm/min, **j** 12 grooves and vf = 0.25 mm/min, **k** 12 grooves and vf = 0.50 mm/min, and **l** 12 grooves and vf = 0.75 mm/min

3.4 Micrographs analysis

Figure 6a–l shows the micrographs of the workpiece material after grinding with different infeed rate values and for the different number of grooves. As reported by Wang et al. [29], burn consists in changes in the metallurgical properties of the workpiece material, which are caused by the high-temperature levels in the cutting zone. In addition, Kwak and Ha [30] reported that these changes are detectable in micrographs because of the discolored layer which is formed on the ground surface and subsurface. From these statements and from analyses of the micrographs in Fig. 6, it can be inferred that the temperature in the cutting zone was not excessive, so it did not adversely affect efficiency of the grinding process, since no evidence of any thermal damages (burns) in both surface and subsurface of the workpiece samples was observed after machining under the conditions investigated.

4 Conclusions

The following conclusions can be drawn from this study:

- Grindability of cylindrical specimens of AISI 4340 steel, in terms of geometric deviations and grinding wheel wear, was influenced by the workpiece material geometry.
- Surface roughness (R_a) values and roundness deviations increased with infeed rate (v_f) values up to 0.50 mm/min, irrespective of number of grooves machined. Despite the fact of all the R_a values were lower than 1.2 μm, the R_a values of interrupted surfaces were about 100% higher when compared to those obtained for continuous surfaces (without groove).
- Roundness deviations were slightly higher for the interrupted surfaces compared to the continuous surface.
- Grinding wheel wear was more sensitive to infeed rate than geometric deviations of workpiece material, and it increased with infeed rate. Also, higher grinding wheel wear was recorded after machining interrupted surface compared to continuous surface, and over 20% increase in wheel wear was recorded when number of grooves increased 6 to 12 grooves at more severe cutting condition.
- No evidence of any thermal damages (burns) in both surface and subsurface of the workpiece sample was observed.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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