GRINDING OF AISI 4340 STEEL WHITH INTERRUPTED CUTTING BY ALUMINUM OXIDE GRINDING WHEEL

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ABSTRACT
There has been a great advance in the grinding process by the development of dressing, lubri-refrigeration and other methods. Nevertheless, all of these advances were gained only for continuous cutting; in other words, the ground workpiece profile remains unchanged. Hence, it becomes necessary to study grinding process using intermittent cutting (grooved workpiece – discontinuous cutting), as little or no knowledge and studies have been developed for this purpose, since there is nothing found in formal literature, except for grooved grinding wheels. In this paper, grinding trials were performed using a conventional aluminum oxide grinding wheel, testing samples made of AISI 4340 steel quenched and tempered with 2, 6, and 12 grooves. The cylindrical plunge grinding was performed by rotating the workpiece on the grinding wheel. This plunge movement was made at three different speeds. From the obtained results, it can be observed that roughness tended to increase for testing the sample with the same number of grooves, as rotation speed increased. Roundness error also tended to increase as the speed rotation process got higher for testing sample with the same number of grooves. Grinding wheel wear enhanced as rotation speed and number of grooves increased. Power consumed by the grinding machine was inversely proportional to the number of grooves.
KEY WORDS: External cylindrical plunge grinding, interrupted cut, finishing, microhardness, cutting power.

1.- INTRODUCTION
Since a long time ago, the external cylindrical plunge grinding operation is widely used in a machining cycle, particularly at the end of it, as it is a traditional finishing process [1]. It is able to produce a workpiece with very satisfactory dimensional and geometric features, such as accurate dimensions and reduced values of roughness and roundness. Grinding is normally used for continuous cutting (i.e., grinding of workpiece without discontinuity), while intermittent cutting (workpiece with grooves, slots or other kind of discontinuity) is little known, since formal literature information is scarce. The intermittent cutting operation is usually studied in conventional processes, such as turning [2].
When compared to other machining operations, grinding can present harmful effects such as rapid grinding wheel wear, greater use of coolant agents and even poor dimensional tolerance, as it involves large specific energy [3]. Furthermore, the biggest problem in the cutting operation is to control heat transferred to the workpiece [4]. This is because cutting fluid is not sufficiently supplied at the cutting zone, in which the temperature rapidly increases and causes damage, such as

burning and microstructural modification of the machined surface. All these factors have made several researchers seek for possible solutions to such problems. Finally, they were able to demonstrate that intermittent grinding (for grooves on grinding wheel) is a promising method to reduce both the average force of grinding [3] as well as thermal damage due to its excellent cooling effect [5,6].
According to [7], discontinuous cutting is a cutting process in which the tool is now in contact with the workpiece, but sometimes loses this contact (inactive time). It is a process widely used in material machining. In the turning process, for example, there is intermittent cutting when the raw workpiece geometry is not cylindrical, such as a square section bar, or it is cylindrical, but it contains a keyway or a transverse hole [8]. With respect to the milling process, it is also naturally considered an intermittent cutting process, since the various cutting edges on the tool, present cutting cycles; that is, at a given instant it is removing material and afterwards it is not. Thus, there is an intermittent period that benefits the cooling process.
Discontinuous cutting is important due to changes in force characteristics acting on the tool. Coupling and uncoupling between the workpiece and tool generates impacts between them that might cause changes in both the forces involved in the process and the machined surface roughness [7].
The aim of this study was to verify whether discontinuous cutting, along with conventional method of lubrication and refrigeration (with abundant fluid use), is suitable under various machining conditions (finishing, semi-roughing and roughing) to obtain the best variables (surface roughness, roundness, diametrical grinding wheel wear, power, microhardness and micrograph), and also studying interruption influence (grooves) on the grinding process of AISI 4340 steel, quenched and tempered using a conventional aluminum oxide grinding wheel under various machining conditions.

2.- MATERIAL AND METHOD

2.1.- Material and testing samples

Testing samples were made of AISI 4340 quenched and tempered steel of 54 HR_c hardness. Figures 2.1.a, 2.1.b and 2.1.c show different testing sample (TS) geometries and Figure 2.1.d their dimensional specifications.
The grinding wheel used in trials has the following specification: RT 355 mm x 25.4 mm x 127 mm (diameter x thickness x bore diameter); AA 150 L6 VS (where AA: soft white aluminum oxide; 150: fine-grained; L: medium hardness; 6: basis; V: vitrified bonding; S: manufacturer private brand) and a cutting speed (V_s) of 30 m/s.

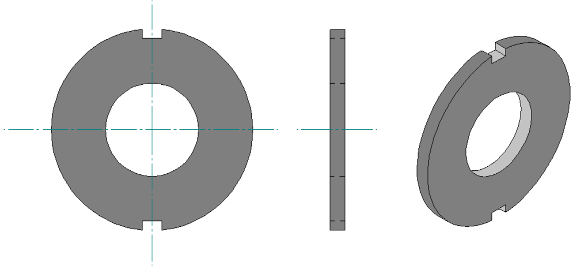

Figure 2.1.a – TS with two-groove.

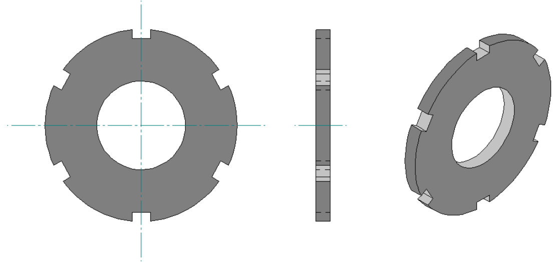

Figure 2.1.b – TS with six-groove.

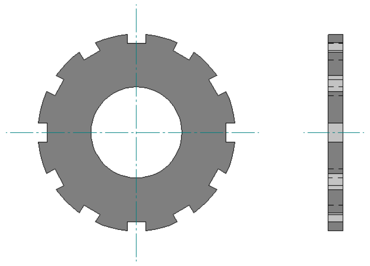

Figure 2.1.c – TS with twelve-groove.

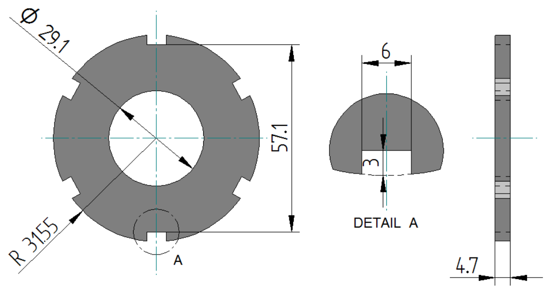

Figure 2.1.d – TS dimensional specification (mm).

2.2.- Experimental method

For the grinding operation, an external cylindrical plunge grinding machine was used. The TS was placed on an axis, which lay between the grinding edges, allowing the TS's surface to be perpendicular to the wheel plunge. Before contact between the workpiece and abrasive tool, both were rotated in the same direction, in order to remove greater amounts of material, besides having the cooling system turned on for abundance. The grinding wheel cutting speed was 30 m/s and workpiece rotation (n_w) 204 rpm. Grinding depth was 5 mm, with 0.1 mm penetration depth between each spark-out time (about 3 s), infeed rates (V_f) of 0.25 - 0.50 - 0.75 mm/min for each one of the three TS types. At each dressing operation, two trials were conducted in different cutting surface areas of the grinding wheel. Dressing was done with a conglomerate type dresser, whose penetration was 40 µm and lateral displacement speed= 100mm/min.

To analyze the diametrical wear of the grinding wheel, abrasive tool imprints were made before its dressing into pre-machined cylinders at a infeed rate of 0.25 mm/min, at which improved accuracy was promoted. Using a proper equipment-aid, wear was measured by means of these imprints.

Then, the TS's were subjected to soaking in chemicals to become the cleanest possible in order to perform roundness and roughness analyses, using tweezers as an aid to avoid contact with the natural fat on hands. Therefore, they were immersed in the following baths: kerosene or turpentine; thinner; ethyl or hydrated alcohol; and methyl alcohol. The purpose of this sequence is to remove coarse impurities, such as coolant, by solvents with greater power of removal, such as kerosene and thinner.

For roundness evaluation, each TS was placed in the equipment, performing three measurements each, where the initial contact position of the workpiece's touch-sensitive edge differs by 120º from the previous contact point. Tayrond 31c equipment (Taylor Hobson brand) has been used for roundness evaluation.

In a similar way, the surface roughness (R_a) was measured; that is, three measurements were made at each TS, each differing 120° from the previous. The equipment used was the Surtronic 3^+ (Taylor Hobson brand).

Grinding wheel wear was measured by using a surface roughness measuring device. In a previously machined cylinder, an imprint was made, and this cylinder got the same grinding wheel profile. This "imprint" is nothing more than grinding wheel penetration into the cylinder (in this case, 0.1-mm penetration at an infeed rate of 0.25 mm/min and full cut depth of 1.0 mm). Thus, the device is set to scan a given length and, in this way, detects depth changes of the imprint, revealing the abrasive tool wear through a software.

The power required by the machine was measured by means of a potentiometer that acquired grinder signals and sent them to the dedicated software (LabView® 7.1, National Instruments®) in the computer. The file generated by the software was processed in MATLAB® 2012.

3.- Results and discussion

This section presents the experimental results of the output variables for each grinding condition.

3.1.- Surface roughness

Surface roughness behavior (R_a) is presented in Figure 3.1.a according to trials, and their respective standard deviations.

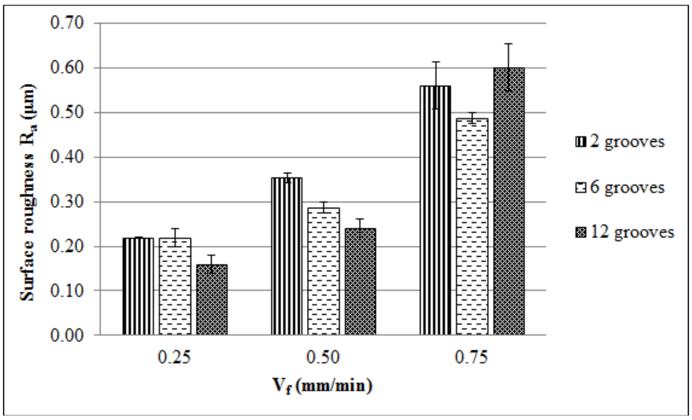

Figure 3.1.a – Surface roughness due to the grinding wheel infeed rate.

It can be observed that there is a trend of increasing roughness as infeed rate increases for the TS type (same number of grooves). According to [6], grinding wheel speed affects workpiece surface finishing by means of changing tangential cutting force, which increases surface roughness as the force soars up. Thereby, surface roughness is increased as the infeed rate increases from 0.25 mm/min to 0.75mm/min. This result can be explained through constant hits between TS and wheel, in such way that at first cut, after going through one of the grooves, the impact causes an increase in cutting force in coupling, resulting in a decrease in surface quality. The higher the infeed rate of the grinding wheel in TS, the more severe the workpiece-tool impact and friction are, leading to higher force peaks and greater roughness. In [7], explains that discontinuous cutting is important due to changes in the acting force characteristics of the tool, i.e., coupling and uncoupling between workpiece and tool would generate impacts between them that might cause changes both in forces and surface roughness. According to [3], forces in an intermittent grinding process (with the grinding wheel grooves) are changed compared to conventional grinding (grinding wheel without grooves). The same author noted there was a decrease of average force and increase in force peaks for the intermittent process when compared to the conventional one, and conclude that the fewer the grooves, the smaller the average forces and the higher the peaks. And also, according to [9], who studied the influence of intermittent grinding (grinding wheel with grooves) in the machining process of ceramic matrix composites (CMC), the surface roughness value for conventional grinding was slightly lower than for the intermittent process, explained by the constant hits between the abrasive tool –

workpiece in the intermittent grinding. This is due to the coupling and uncoupling between the grinding wheel and workpiece. However, when observing trials with the same infeed rate but different TS's, it appears that there is a trend of roughness decrease for removal rates of 0.25 and 0.50mm/min , i.e. roughness decreases with the increase in groove number. At an infeed rate of 0.75mm/min, for trials 03 (2 grooves) and 06 (6 grooves), a decreasing roughness trend was maintained; nevertheless, for trial 09 (12 grooves) it remained high. As the number of grooves grows at a certain infeed rate, there is less friction between the workpiece and wheel, resulting in higher peak forces [3] and lower temperature in cutting area by greater couplings and uncoupling frequency, promoting a cooling process. In [4], who when working with grooved wheels, concluded that the cutting temperature is reduced as the number of grooves on the wheel increase, which may be justified by a more effective coolant supply at the cutting area in intermittent compared to conventional grinding.; thus, reducing the surface roughness.

3.2.- Roundness

Roundness values of the testing samples for each trial and their standard deviation are presented in Figure 3.2.a.

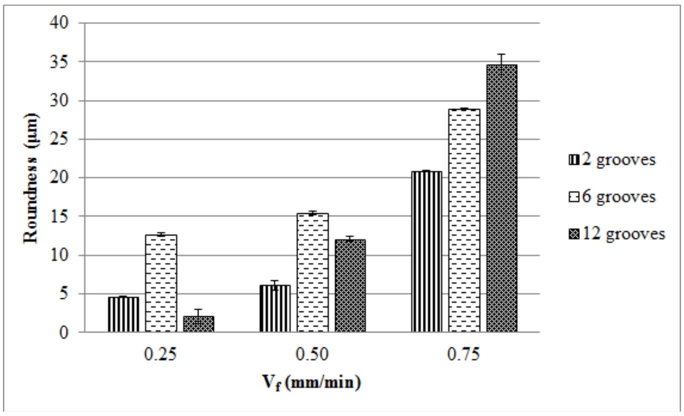

Figure 3.2.a – Roundness due to the grinding wheel infeed rate.

The above results allow to conclude that, as roughness results, there was a trend in roundness increase; i.e., for same TS; as infeed rate increased, roundness increased [roundness can be understood as "oval shape" growth or macro-geometric deviation as described by [10]]. This fact occurs because the higher the speed plunge, the more severe is the cut, which makes the workpiece undergo increasingly intense compressive strain, facilitating its circular profile (ideal) deviations.

Comparing trials at the same infeed rate, it can be observed that an increase in groove density from two to six at 0.25 and 0.5 mm/min speeds enhances roundness, which conversely decreases with twelve grooves. This fact is given due to a "low infeed rate", since the more grooves, the lower the external TS profile is. That way, 12-groove TS's have a lower profile than the others, helping to reduce macro-geometric deviation.

In contrast, for 0.75mm/min, increasing the groove number from two to six, promotes roundness values to increase, which also increases when using twelve grooves. This is the case of a higher infeed rate where a high level of mechanical stresses takes place, and the profile variation is observed for all grooved workpieces. According to [11], spark-out time implies in roundness deviation reduction. Higher spark-out

periods (12 to 15 seconds) would result in minor deviations and would increase machining time, which can represent a capital loss to industry. The same author also found that in regards to conventional refrigeration, spark-out time alteration does not result in significant changes in roughness and wheel wear.
It can be observed from the roughness results that there is no defined trend among the infeed rates, that is, the roughness and roundness values tended to increase as the infeed rate increases, but when one assesses the results for a given infeed rate there is no consistent trend. However, smaller differences and a decreased measurement scale, hundredth of μm, in roughness values can be noted. In regard to the roundness values, the workpiece fixture plays an important role in the measurments performed, in other words, the ground workpiece is fixed to the chuck and when it is released, the stresses generated by the fixture setup are reflected in the roundness error. Nevertheless, the tendency of increase in roundness values as the infeed rate increases was possible to observe.

3.3.- Diametral grinding wheel wear

Figure 3.3.a presents the grinding wheel wear at each trial.

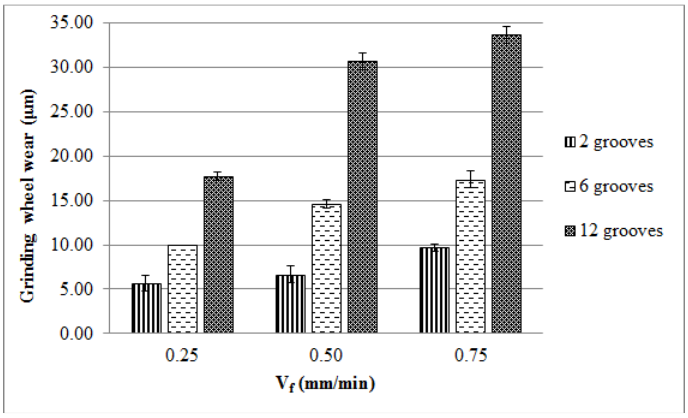

Figure 3.3.a – Diametral grinding wheel wear Vs.

It can be seen that there is a trend of higher wear as infeed rate and groove number increase. This is because higher infeed rates and a greater number of grooves imply in further impacts on the wheel, increasing peak forces as described by [3]. Additional impacts cause grain and bonder (vitrified) fractures resulting in wear. Moreover, by increasing the number of groves, the number of impacts against the wheel also grows due to coupling and uncoupling between tool and workpiece [9], making the grinding operation most severe. As a basis, [12] explains that wear occuring on the grinding wheel is related to abrasive grain breakdown and vitrified bonder fracture, both arising from thermal deterioration or severe mechanical stresses to which the wheel is subjected.

3.4.- Power

Figure 3.4.a shows results for the power applied in the process.

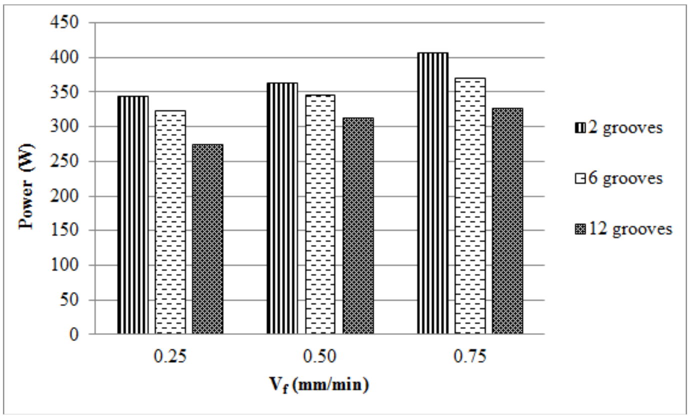

Figure 3.4.a – Power consumed due to the grinding wheel infeed rate.

It can be seen that for the same groove number, there has been a trend of power consumption increase as tool infeed rate increased. On account of higher removal rates leading to greater efforts in the cutting area, as previously mentioned, and, in addition to greater friction, greater machine power is required to perform the machining process, which becomes more severe with the increasing removal rate.

Indeed, when analyzing Figure 3.4.a for the same infeed rate, it can be seen that there was a decreasing power requirement trend, for the three speeds (0.25, 0.50, 0.75mm/min), with an increasing number of grooves. This is explained by the lower contact area between workpiece and grinding wheel, as the number of grooves is higher, resulting in lower cut and friction effort and, therefore, less required power to perform the cutting operation.

These results are similar to the [3] study, who observed that a benefit commonly found in intermittent grinding (grooved wheel) is power reduction, which means that this wheel can work at high rates of material removal without exceeding the grinder limit power. In [13], attributed this power reduction to the thickest splinter and looseness to splinter flow, and concluded that the reduction of required power and better access of cutting fluid lead to a reduction of thermal damage to the machined area.

4.- Conclusion

From obtained results, it can be concluded:

When testing, sample roughness tends to improve as groove number and grinding wheel infeed rate increases, being the lowest roughness value obtained for 12-groove TS's at 0.25mm/min;

Just as roughness, roundness also tends to enhance as the infeed rate increases for the same groove number of TS's. The lowest roundness deviation (2 µm) was also observed for 12-groove TS at 0.25mm/min;

Grinding wheel wear enhances as the infeed rate and groove number increase, and minor wear was noted in trial at 0.25 mm/min for 2-groove TS;

Required power was greater as infeed rate reached higher levels for the same groove number of TS's. The lowest required power was observed for 12-groove TS at 0.25 mm/min rate;

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