EVALUATION OF SURFACE ROUGHNESS IN TURNING OF HIGH CHROMIUM WHITE CAST IRON USING PCBN TOOLS

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Abstract. *Components manufactured in high chromium white cast iron promote high resistance when submitted to abrasive wear. This high abrasive wear resistance is associated with presence of high volume fraction of carbides in microstructure matrix. In other hand, the microstructural characteristics of high chromium white cast iron limited a wide application due to the challenges mainly for machining processes. Carbides present in the microstructure of high chromium white cast iron are greater than the depth of cut considering, e.g. finishing turning operation. Flank and rake face are strongly deteriorated by workpiece carbides and, consequently, machined surface shows high roughness values. Therefore, the high chromium white cast iron microstructural characteristics require tool materials with high hardness and moderate toughness to avoid deep grooves. Another challenge in turning operations of high chromium white cast iron is the interrupted cutting, because the cyclical shocks promote cutting edges chipping or breakage. The feasibility of the use of high chromium white cast iron depends on proper tools and maintenance of restricted roughness values along the tool life. The objective of this research is evaluate the surface roughness of the high chromium white cast iron using PcBN tools in the continuous and interrupted cutting. It was conducted a factorial design with turning tests and two variables – cutting conditions and PcBN grade – and on two levels - continous and interrupted cutting and low content and high content of CBN, respectively. The statistical analysis shows that, at the beginning of tool life, the mentioned variables did not significantly influence the surface roughness. However, at the end of tool life, using a confidence interval of 90%, changing the cutting condition promoted a reduction in the surface roughness values. Results also showed that the turned surface roughness values are compatible with surfaces typically obtained by the grinding process.*

Keywords*: high chromium white cast iron, roughness, PCBN grades, turning.*

1. INTRODUCTION

The turning of materials with high hardness (45 - 62 HRC), also called hard turning, is mainly used in finishing operations replacing the grinding operations. The utilization of turning for manufacturing materials of high hardness is possible due to ultrahard tool materials (oxide ceramics and PCBN), which have high wear resistance and are proper to withstand the tribological conditions imposed in cutting zone (GRZESIK, 2008a; LAHIFF *et al*., 2007).

Properties and application characteristics of engineering materials have a strong relationship to their microstructure. One example is the material submitted to abrasive wear. This application requires moderate matrix hardness and the presence of high volume fraction of carbides in the microstructure. These requirements become the microstructure of white cast iron an excellent choice for the context. However, the challenges encountered in manufacturing processes, especially machining, limit the wide application of the material. The hard chromium carbides (M_7C_3) present in the material microstructure are greater than the depth of cut (a_p) used in finish turning operations. Carbides deteriorated the flank surface of the tool, promotes high wear rates and poor quality machined surface (LAIRD *et al*., 2000).

In addition to the challenge imposed by white cast iron microstructure, another difficulty is the interrupted cutting, which promote chipping or damage to the cutting edge because the cyclical shocks. Therefore, the feasibility of the use of white cast iron depends on proper tools and the maintenance of restricted roughness values along the tool life.

Whitehouse (2003) states the evaluation of the surface roughness could be performed through several parameters. However, for the evaluation of turned surfaces, Rech and Moisan (2003) and Thiele and Melkote (1999) suggested the use of a roughness parameter which represents the profile of the average roughness (*Ra*) together with a parameter that detects individual features of turned surface, such as *Rz*. Roughness *Ra* is still used to identify grades of surface roughness through the system N, which is shown in Table 1. This classification is present in the NBR 8404 (1984) to assist the comparison of surfaces quality.

Table 1. Roughness grades. According to Whitehouse (2003) and NBR 8404 (1984).

Roughness Grade	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
Ra [μm]	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50
Machining Process			Grinding and/or Hard Turning									

According to the Tab. 1, grinding and hard turning usually promote surface roughness between 0.1 and 1.6 μm *Ra* (or N3 to N7 grades). Despite the hard turning and grinding are typically employed as finishing operations, with similar values of roughness, the surfaces produced by these processes have different the topographies. Turning promotes a surface characterized, mainly at the beginning of tool life, by symmetry and periodic variation of the peaks and valleys, called periodic roughness profile. On the other hand, grinding produces random distributions of peaks and valleys, called aperiodic roughness profile. These topographies have different tribological behaviors, influencing the surfaces performance through of physical phenomenon such as friction, wear, and fatigue (WAIKAR and GUO, 2008; GUNNBERG, ESCURSELL and JACOBSON, 2006).

Abrão and Aspinwall (1996) compared the resistance to mechanical fatigue of turned and ground surfaces using workpieces of AISI 52100 bearing steel with 62 HRC. The authors associated the lowest values of roughness *Rt*, obtained by turned surface, to the higher fatigue resistance in the components. In this case, the lower value of the roughness *Rt* turned surfaces topography become less inclined to cracks nucleation and propagation.

At the beginning of tool life, when the cutting edges still keep the initial geometry, the cutting parameters and insert geometry are the main factors to influence the roughness. However, with the growth of flank wear, turned surface topography becomes influenced by tool wear. Flank face topography is partially transferred to the machined surface, mainly at secondary cutting edge region (OLIVEIRA *et al.*, 2009; PENALVA *et al.*, 2002). According to Yallese *et al.* (2009), the most important phenomenon to the profile changing of the turned surface is abrasive wear on the cutting edge.

Pavel *et al*. (2005) observed different topographies in turned surface in continuous and interrupted cutting (using the AISI 1117 steel with 62 HRC). In continuous cutting and at beginning of tool life, the surface roughness remained in class N6 and at end of tool life, surface roughness moved to class N7. The opposite occurred in the interrupted cutting, in which, at the beginning of tool life, surface roughness was in class N6, and at end of tool life roughness decreased to class N5. According to authors, the type of cut promotes different wear mechanisms and damage on the cutting edges, thereby influencing the surface roughness. An explanation to the these results is that, in continuous cutting, the cutting edges shows only abrasive wear, and consequently, the roughness values increase along tool life. On other hand, in interrupted cutting, the cyclical shocks between cutting edge and turned surface promote chippings on the tool and this phenomenon has strong influence on roughness behaviour. If the chipping is small, changes in tool geometry could promote a smoothing effect on the turned surface, which reduced the roughness values along tool life. The reduction in the roughness values along the tool life was also observed by Ko and Kim (2001) in interrupted cutting of AISI E52100 steel with 62 HRC using PCBN tools.

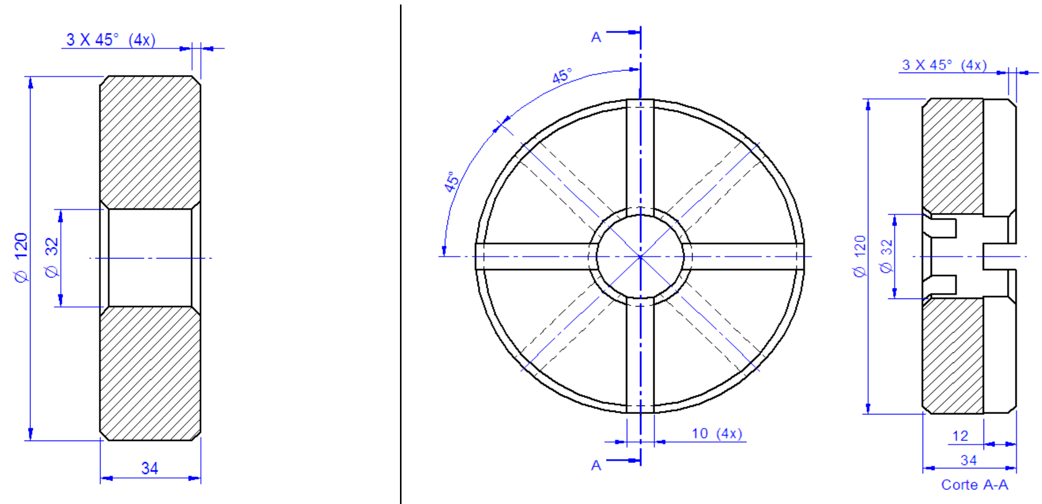
Researches about the performance of the tool life and surface roughness in turning of hardened materials include mainly steels (low alloy and bearing steels), which contain a restricted amount of carbides. Thus, limited research showing the roughness behaviour along the tool life with another materials – especially those containing high volume fraction of carbides in the microstructure – are found in the literature. The comprehension of characteristics concerned in the machining of materials with high volume fraction of carbides assist in the utilization of a wide range of materials limited to applications due to the difficulty of manufacture. Therefore, the aim of this research is to determine the influence of cut type (continuous and interrupted) and PCBN grades in roughness behaviour in turning of material with high volume fraction of carbides in the microstructure. This research use as reference material the high chromium white cast iron (28% of carbides - in mass).

2. EXPERIMENTAL PROCEDURES

Experiments were carried out in a turning center with 15 kW of power in the spindle motor and speed rotation range between 4 and 4500 rpm.

Two PCBN grades were used: a class with high content of CBN (Sandvik grade 7050, code SNGA 120412) and other low content CBN and a ceramic phase added (Sandvik grade 7025, code SNGA 120412). These tools were assembled on a toolholder (code PSKNL-2020K-12) and clamped with a combination of top clamp and hole center pin aiming to promote high rigidity of the insert and, consequently, avoid chippings.

Two types of workpieces were used to promote continuous and interrupted cutting. Workpieces geometry adopted in this research was based on work carried out by Diniz and Oliveira (2008). Figures 1a and 1b show the continuous and interrupted cutting workpiece, respectively.



a) continuous cutting　　b) interrupted cutting – with 4 interruptions

Figure 1. Workpieces used for turning experiments

According to Figure 1a and 1b, with the aim of minimizing the shocks at the entrance and exit of the tool, were shaped chamfers in the outer and inner diameter of workpiece (3 mm x 45º). Chamfers were turned again when reduced to 0.5 mm x 45º over the experiments.

Aiming to characterize the workpiece material, analysis of microstructure, hardness and chemical composition were carried out. Fig. 2 shows the high chromium white cast iron microstructure - under attack of Nital 3% for 7 seconds.

Figure 2. High chromium white cast iron microstructure: a) carbides (light part) and b) matrix (dark part)

According to Fig. 2, high chromium white cast iron microstructure is composed of chromium carbides (light part) in a perlitic matrix (dark part). It is possible verify that the carbides are dispersed in the matrix and they are heterogeneous, with length greater than 150 µm. These carbides have lengths greater than the depth of cut used in the experiments. This fact emphasizes the difficulty of turning high chromium white cast iron. Hardness analysis was carried out according to ABNT NBR 6507-1. Thus, 20 indentations were carried out on the carbides and other 20 on the matrix. Average hardness of carbides was 1329 HV with a standard deviation of 113 HV. The matrix showed a hardness of 492 HV with a standard deviation of 17 HV. Table 2 shows the chemical composition of the workpiece material - carried out with an Optical Microscopy.

Table 2. Chemical composition of the workpiece material (high chromium white cast iron).

Sample	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%Cu	%Fe
A	2,84	0,61	0,58	0,032	0,025	18,21	0,217	0,080	0,096	77,3
B	2,83	0,60	0,58	0,033	0,018	18,73	0,215	0,079	0,096	76,8

The chemical composition showed in Fig. 2, indicate that the material is classified as grade II and type E, according to ASTM A 532 (1993).

From the point of view of workpiece clamp, increasing system stiffness and dynamic stability is preponderant to turning of hardened materials. Thus, jaws with a large contact area had been designed. In order to minimize the distortion along the experiments, the AISI 1045 steel jaws were also subjected to the quenching and tempering heat treatments increasing hardness to 28 ± 2 HRC. These jaws provide double the contact area when compared to conventional, and consequently, increased the stiffness of the fixation system.

During the turning experiments, surface roughness was monitored along the tool life. For this analysis, the experiments were interrupted every 2.5 minutes (effective cut time), or four passes in the workpiece radial direction. It was used a portable roughness meter Mahr, model Perthometer M4Pi, adjusted for measuring 5 sampling lengths (λc) of 0.8 mm, generating an evaluation length of 4 mm. Measurements were carried out in the feed direction. However, this equipment did not enabled to generate the roughness profile, so in the first and in last pass of the experiments, the roughness profile was evaluated with roughness meter Taylor Hobson, model Talysurf Plus. Analyses were carried out threefold. The roughness parameters evaluated were *Ra, Rz* together with the roughness profile.

As a criterion for tool life, it was adopted the average flank wear VB_B = 0.20 mm. According to Diniz and Oliveira (2008) and Oliveira *et al.* (2009), the level of tool wear (VB_B = 0.2 mm) is able to promote a roughness similar to N6 grade (similar finish grinding). It is pertinent to point out that was not objective of this article to deal the tool life or wear rate behavior along tool life. The objective is evaluate the surface roughness of the high chromium white cast iron using PcBN tools in the continuous and interrupted cutting. It was conducted a factorial design with turning tests and two variables – cutting conditions and PcBN grade – and on two levels. The table 3 shows the variables used in the experiments.

Table 3. Factorial design for the experiments

Factor	Low level	High level
Turning conditions	Continuous cutting	Interrupted Cutting
PcBN content (grade)	Low content (CBN7025)	High content o(CBN7050)

The cutting parameters were kept constant along the experiment. The parameters were: cutting speed (v_c) = 200 m/min, depth of cut (a_p) = 0.15 mm and feed per revolution (f) = 0.08 mm. Therefore, an experiment consisted of several passes of face turning in the radial direction of the workpiece (from largest to smallest diameter), using interruptions at regular intervals in order to analyze the values of roughness on the surface until to the criterion of tool life (VB_B = 0.20 mm) was reached. The set up is shown in Fig. 3.

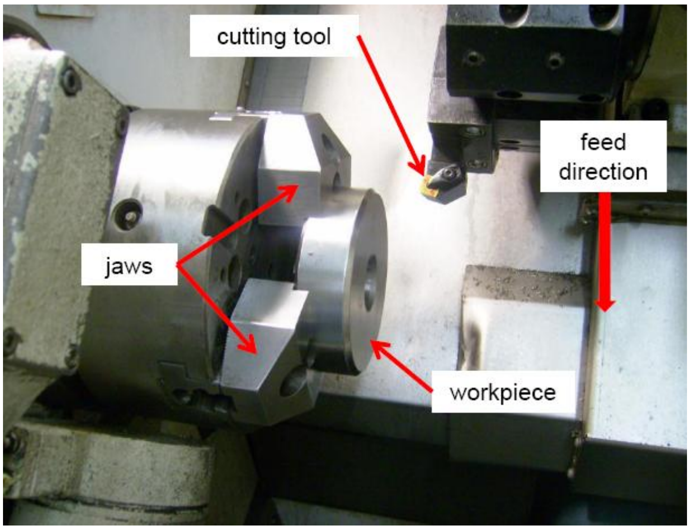


Figure 3. Set up for turning of high chromium white cast iron

3. RESULTS AND DISCUSSION

In all the cutting conditions investigated, turned surface roughness values increased along the tool life. Thus, statistical analysis of the roughness surface profile generated by the tools at the beginning (after the first measurement interval = 2.52 min) and at the end of life tools were carried out. The end of tool life for each tool represents different turning times, since the criteria for the end of tool life is the flank wear (VB_B). Therefore, for the tool grade 7025, the last pass is equivalent to average cutting time of 25.2 and 10.5 minutes for continuous cutting and interrupted, respectively. On the other hand, for the tool grade 7050, the last pass is equivalent to average cutting time of 7.6 and 10.5 minutes for continuous cutting and interrupted, respectively.

Figure 4 presents the results of surface roughness at the beginning of tool life for all conditions.

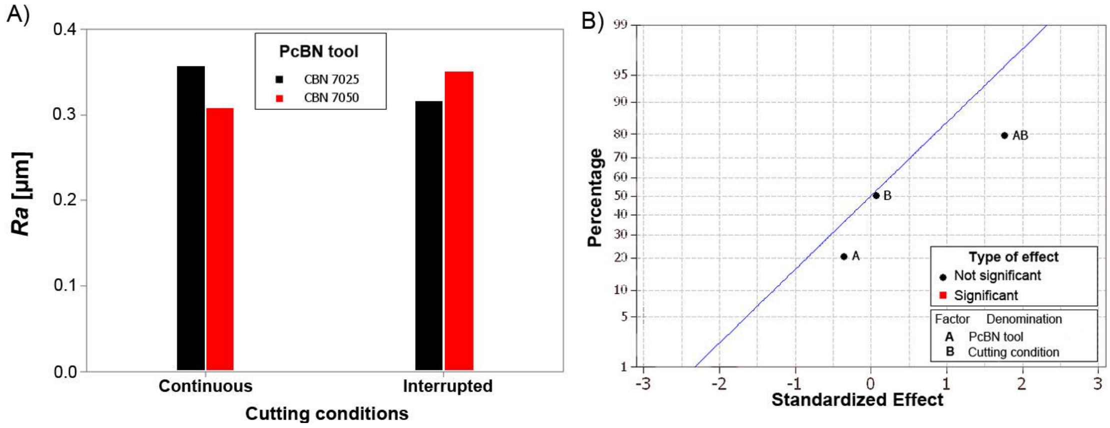


Figure 4. Analysis of the roughness surface parameter *Ra* [µm] at the beginning of tool life: a) interaction in the factorial design, b) normal probability of effects

For a confidence interval of 90%, the results presented in Fig. 4b showed that, at the beginning of tool life, the cut condition (continuous and interrupted cutting) and the PCBN grade (7025 and 7050) had no significant influence on the roughness *Ra* of the turned surface. Results show in Fig. 4a were expected because, as described by Javidi, Rieger and Eichlseder (2008) and Machado *et al.* (2009), at the beginning of the life, the cutting edges are fresh and show no significant geometric alteration. Thus, roughness surface is connected mainly on the cutting parameters and tool geometry, i.e., the feed for revolution (f) and the tool nose radius (r_ε).

Although the columns shown in Fig. 4a have opposite behavior with the switch from continuous to interrupted cutting, input variables did not significantly influence the values of roughness surface *Ra* at the beginning of tool life. This analysis is confirmed by normal probability of the effects show in Fig. 4b. Still in Fig. 4a also can be observed that all the cutting conditions have similar roughness surface values, between 0.30 and 0.36 µm in the *Ra* scale. These values indicate that the turned surfaces belong to roughness surface class N5, according to NBR 8404 (1984). Thus, all the conditions performed promote, at the beginning of tool life, similar application values to the roughness considering the parameter *Ra*.

A similar analysis for the roughness surface using parameter *Rz* is shown in Fig. 5.

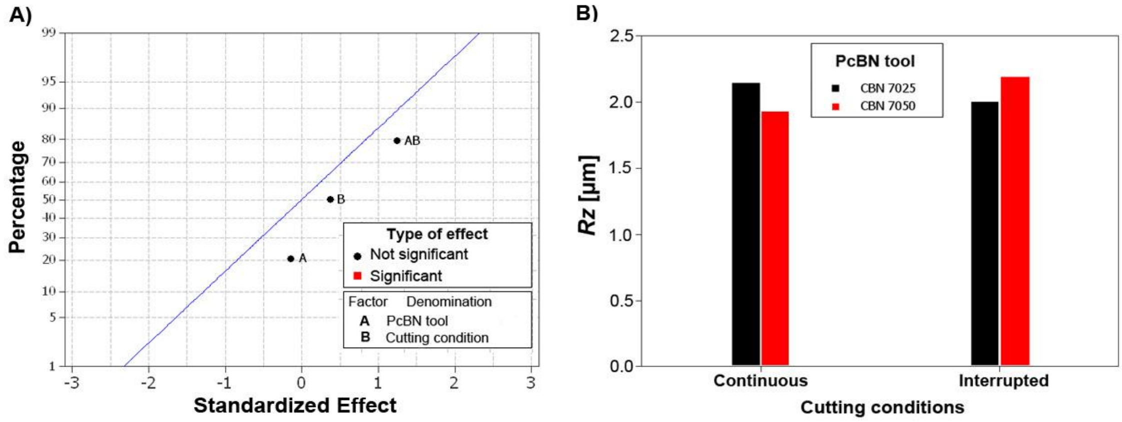


Figure 5. Analysis of the roughness surface parameter *Rz* [µm] at the beginning of tool life: a) normal probability of effects, b) interaction in the factorial design

Based on the normal probability of effects, shown in Fig. 5, and using a confidence interval of 90%, can be observed that, at the beginning of the tool life, roughness surface *Rz* has the same behavior than parameter *Ra*. In other words, values of roughness surface parameter *Rz* were similar, between 1.9 and 2.1 µm. Thus, input variables of the experiments, i.e. tool grade and cutting condition, have no influence at the beginning of the tool life considering the roughness surface *Rz*.

It is suggested that after the tool action, a fraction of carbides were fragmented during de chip formation and remain in the turned surface. These fragments can influence the roughness surface profile at the beginning of the tool life, however, they did not influence the roughness surface *Rz*. Thus, and as described by Rech and Moisan (2003) and Thiele and Melkote (1999), the analysis of roughness surface *Rz* indicates that apparently the turned surface has no defects promotes by carbides after the action of the cutting. Aiming to evidence this fact, Fig. 6 shows the topographies of the turned surface in the conditions performed at the beginning of the tool life.

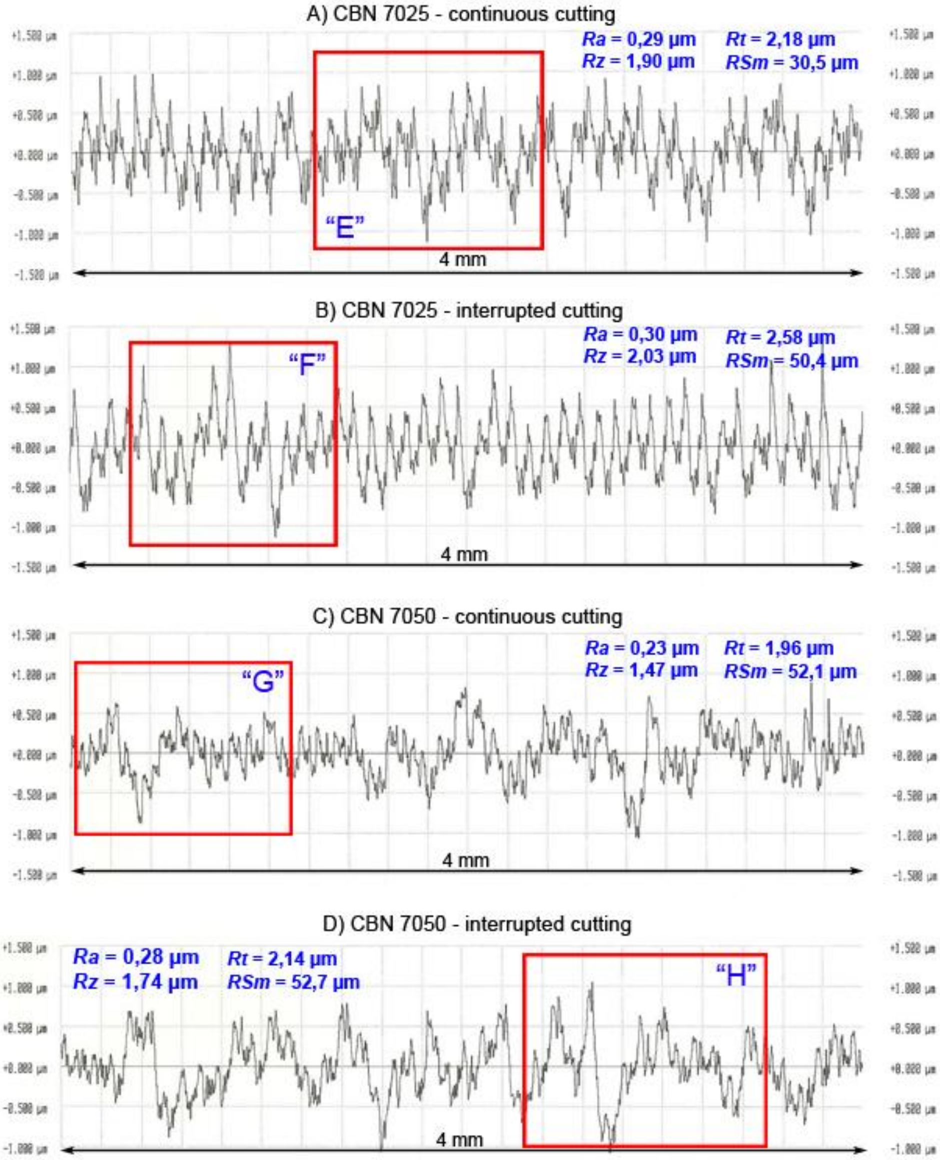


Figure 6. Topographies of the turned surfaces at the beginning of tool life

It is important to state that the roughness profiles showed were similar in all conditions carried out each condition at the beginning of tool life. So, according to Fig. 6, there were no significant differences between the topographies of turned surfaces at the beginning of tool life. Despite the relative movement of the turning operation provides the formation of periodic roughness surface profile, details E, F, G and H in Fig. 6 showed a variation in frequency. As described by Waikar and Guo (2008), these features promote the mixed roughness surface profile (partially period). In this sense, other indicator for the presence of mixed roughness surface profile, also showed inf Fig. 6, is related to the parameter *RSm*. This roughness surface parameter indicates the rate of formation of peaks and valleys in turned surface. Due to the relative motion of the turning operation, roughness surface *RSm* is formed mainly by the feed per revolution used - in this case (f) = 80 µm. In Fig 6a, roughness surface *RSm* was 30.5 µm; while in Fig. 6b, c, and d, was approximately 50 µm. Therefore, it suggested that the microstructure of the turned material, which has a high volume fraction of the carbides, contributes to the generation of the profile roughness surface. As suggested previously, after the tool action, a fraction of carbides, which were fragmented during the chip formation, still remained on the turned surface, influencing the roughness profile.

According Grzesik (2008a), the factor that still limits the application of PcBN tools in industrial environments is its high cost. Thus, such tools need to be applied to their lifetime limit. Besides this fact, it is pertinent to note that the finishing operation on large parts (such as rolling mill rolls made of white cast iron), a single pass in the external diameter of these components can reach the lifetime criteria. Based on this information, the evaluation of surface roughness parameters at the end of the tool life becomes essential to understand the phenomena of the process. Fig. 7 shows the behavior of the roughness surface *Ra* at the end of tool life.

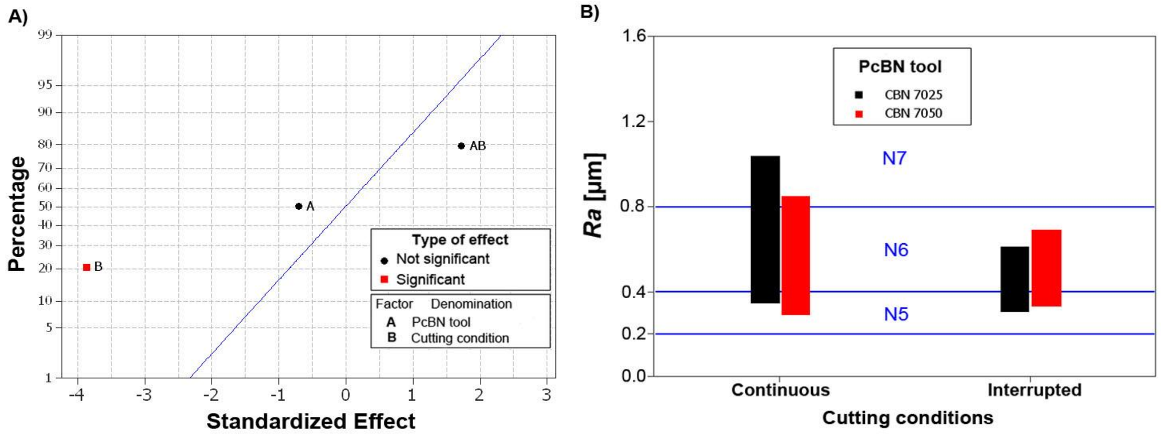


Figure 7. Analysis of the roughness surface parameter *Ra* [μm] at the end of tool life: a) normal probability of effects, b) interaction in the factorial design.

Based on the normal probability of effects for a confidence interval of 90%, shown in Fig. 7a, it appears that the switch the cutting condition from continuous to interrupted generates a significant effect on roughness surface at the end of tool life. Moreover, there is influence, at lower levels, the interaction between these two factors, since this point is away from the line of normal cumulative probability. Only as a reference, when using a confidence interval of 80%, the interaction between the variables used in the experiments is significant.

The influence of cutting conditions on the roughness surface was previously reported by Pavel *et al*. (2005). These authors found out higher values of roughness surface in parameter *Ra* as both the *Rz* for the continuous surfaces when compared with interrupted surface. In continuous cutting, Pavel *et al*. (2005) found out values of both roughness parameters increased during the tool life. On the other hand, in interrupted cutting, roughness value decreases along the tool life due to wear behavior on the cutting edges. This phenomenon on the surface roughness in interrupted cutting was also observed by Ko and Kim (2001). It is important to state that, in this research, the roughness values increase along the tool life.

As shown in Fig. 7b, in the end of tool life, the interrupted cutting promoted lower roughness surface when compared to continuous cutting, evaluated by the parameter *Ra*. A hypothesis for this behavior is connected to the topography of the flank wear of the tool. Based on the analysis of Fig. 7a, it is suggested that the continuous cutting conditions caused greater geometrical alterations on cutting edge geometry (in flank face and rake face), promoting direct consequences on the values of roughness surface. Similar influences of tool wear on roughness parameters were previously reported by Oliveira *et al.* (2009), Penalva *et al*. (2002), Yallese *et al.* (2009) and Grzesik (2008b).

For the interrupted cutting condition, roughness surface at the end of the tool life using 7025 grade (low-CBN) and 7050 grade (high-CBN) remained inside the N6 grade (up to 0.8 μm in *Ra* scale). However, in continuous cutting, the 7050 grade reached roughness surface *Ra* values corresponding to the transition region between N6 and N7 grades. Therefore, in continuous cutting, roughness surface values using 7025 grade (low CBN) promote an alteration along tool life from N5 grade, at the beginning of tool life, to N7 grade at the end of tool life (increased two grades along tool life). N6 grade corresponds to typical values of roughness *Ra* found by various authores at the end of tool life, including: Bouacha *et al.* (2010), in turning of AISI 52100 with 64 HRC using low CBN content; Ko and Kim (2001) in with interrupted turning of AISI E52100 with 62 HRC using high and low CBN tools; Yallese *et al*. (2005), in turning of AISI D3 tool steel with low CBN tools.

It is suggested that the roughness values presented in this research for the grade tool of low-CBN (7025 grade) in continuous cutting are connected to the topography of the wear behavior of the tool. Thus, the hypothesis is that especially the grooves formed on the flank face have contributed to the greater roughness surface values found (N7 grade). Figure 8 shows the topographies of turned surfaces at the end of tool life for all conditions.

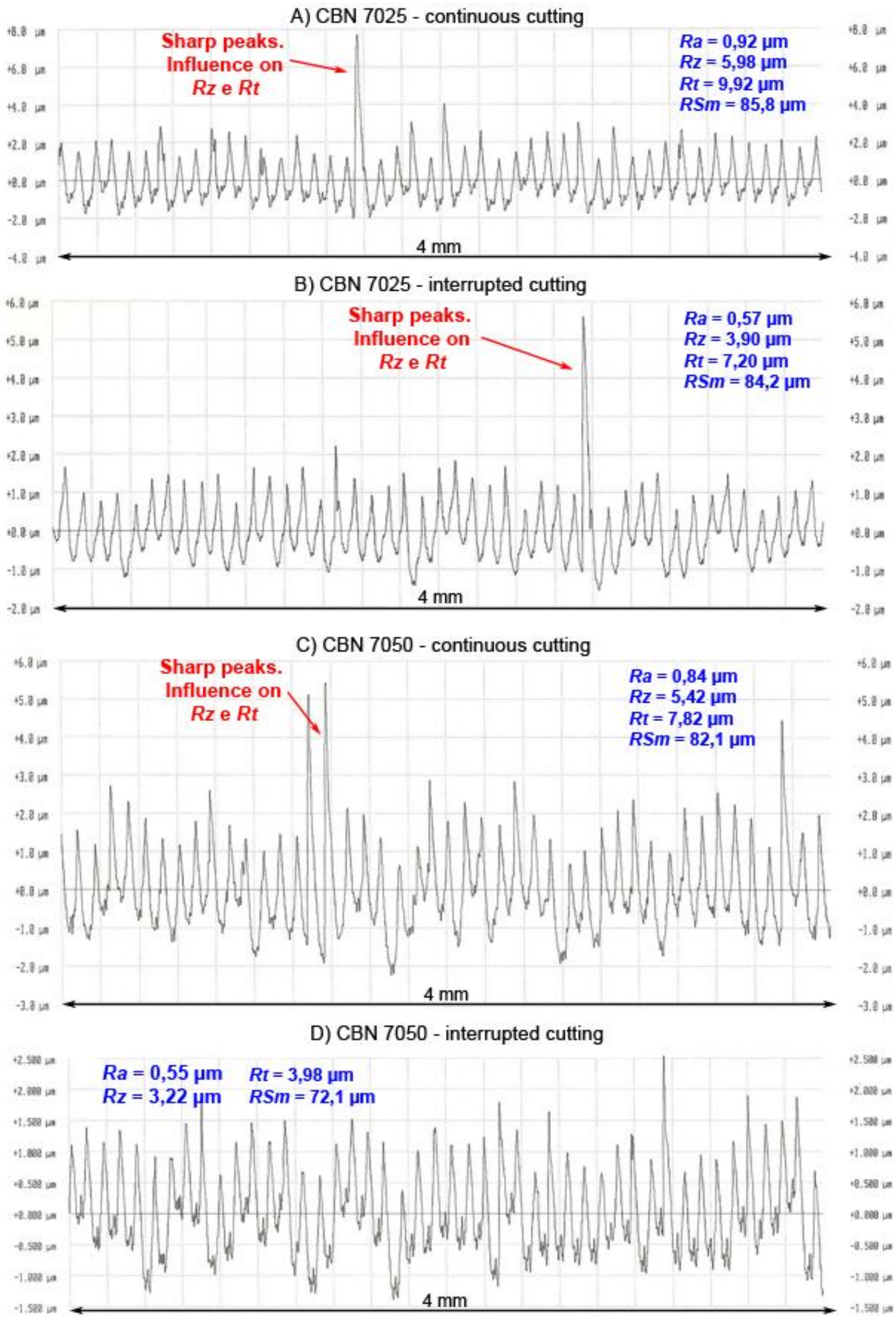


Figure 8. Topography of the turned surface at the end of tool life

Again, it is important to state that, at the end of tool life, roughness profiles showed similar behavior for each condition along the experiments. Figure 8 shows the turned surface profile at the end of tool life and the main roughness surface parameters analyzed. It was identify the sharp peaks of the roughness profile for all conditions. The sharp peaks in the profile roughness directly influence the roughness parameters *Rz* and *Rt*. Thus, the results for the roughness *Rz* are strongly influenced by the defect of the roughness surface profile. Therefore, the statistical analysis of parameter *Rz* does not allow a consistent analysis on the basis of random behavior. It is noteworthy that these sharp peaks were not seen in Fig. 8d. However, analysis of the roughness surface in parameter *Rz* during the experiments showed the same behavior than the other conditions.

Despite the sharp peaks in the profile in the topographies of turned surfaces showed in Fig. 8, the roughness surface profile show a symmetric and periodic variation of the peaks and valleys, which characters a periodic surface profile. An important indicator that supports this phenomenon is the observation of roughness surface *RSm* that, this condition presents similar value to the feed per revolution used (f = 80 µm).

Comparing the Fig. 6 and Fig. 8 is clear that in all conditions carried out, profile roughness surface shifted from the beginning to the end of tool life. It suggested that such change was promoted by the wear mechanisms on cutting edges. One hypothesis for this phenomenon is related to the loss of tool material because of flank and crater wear. It provided greater contact area between the cutting edge and workpiece. Based on the hypothesis suggested, in the critical limit of the tool life (at the end of tool life), the carbides of the microstructure of the material are not sheared with the same efficiency as compared at the beginning of the cut. This fact promotes a tendency to fragmentation and carbides compression between the workpiece and the flank face, causing peaks in the topography of turned surfaces.

From the viewpoint of roughness surface, values obtained during the turning in continuous and interrupted cutting of white cast iron using PcBN tools are compatible with several applications. Agostinho et al. (1977) described some examples of application to the roughness visualizes in this research. According to the authors, N5 grade is applied to guides surface and accuracy elements, guides and tables of machine tools, to the flanks of gears, among others. Moreover, N6 grade is applied to ball valves and brake drums. Finally, N7 grade is applied in piston heads and seats of bearings for shafts. Thus, with the turned surface values obtained in high chromium white cast iron showed on this research, it allows a new material applications and expand the area of activity of the studied material, which may replace less durable materials such as ductile iron, even the gray cast iron and tool steels (depending of application).

The roughness surface at the end of tool life can be further improved. With this goal, studies can be carry out in the application of turning tools with new inserts geometries, i.e. round geometries or wiper, which have a larger contact area of the secondary region of cut (part of the cutting edge with greater importance in the formation of roughness surface) with turned material. Thus, the maintenance of class of roughness surface less than N6 at the end of tool life could be verified.

4. CONCLUSIONS

Based on the results obtained during the experiments for turning high chromium white cast iron, using two grades of tool material in continuous and interrupted cutting, it can be concluded that:

a) turning operation of material with high volume fraction of carbides in the microstructure promotes, along the tool life, roughness values similar to those obtained by the grinding process;

b) at the beginning of tool life, tool grade and cutting condition there are no significant influence on roughness values and there are no evidence of sharp peaks and valleys on the turned surface;

c) at the end of tool life, the cutting condition shows a significant influence on roughness values and there is presence of sharp peaks (strong influence on the parameter *Rz*) in all conditions carried out.

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