Int J Adv Manuf Technol (2017) 88:2485–2495
DOI 10.1007/s00170-016-8964-y

ORIGINAL ARTICLE

Tool vibration in internal turning of hardened steel using cBN tool

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Received: 17 February 2016 / Accepted: 23 May 2016 / Published online: 2 June 2016

Abstract The machining of hardened materials with hardness over 45 HRC has been an alternative to grinding since the 1970s, with the commercial availability of cubic boron nitride (cBN) and ceramic tools. However, the low toughness of these types of tool materials makes them very sensitive to damages caused by vibrations, which are critical for operations like internal turning, where the tool resembles a cantilever beam and therefore is susceptible to large deflections. This work aims to contribute to the study of tool performance in internal turning of long holes in hardened AISI 4340 steel in finishing conditions. Different machining conditions, two different tool holders (steel and carbide), and several tool overhangs were tested. The surface finish, acceleration (vibration) signals, and tool wear of cBN inserts were evaluated. The results show that vibration and the material of the tool holder may play a secondary role in the surface finish for stable turning, but the use of carbide tool holders makes the process stable for longer tool overhangs. Moreover, when the cutting becomes unstable, surface roughness is increased severely.

Keywords Vibration · Boring · Hard machining · Hardened steel · cBN

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1 Introduction

Hard turning is performed on materials with hardness within the 45–68 Rockwell range using a variety of tipped or solid cutting inserts, preferably cubic boron nitride (cBN). Although grinding is known to produce a good surface finish at relatively high feed rates, hard turning may replace grinding in many situations, since it can produce as good or better surface finish at significantly higher material removal rates, as tested by [1] when comparing turning and grinding and stated by [2] in an extensive review of the literature. Although the process is performed with small depths of cut and feed rates, estimates of reduced machining time are as high as 60 % for conventional hard turning against grinding operations [3].

In order to replace grinding by hard turning operations, it is important that the process parameters be chosen correctly. Hard turning parameters are located in a narrower range of values compared to conventional turning, and a failure in their optimization may lead to a combination of short tool life, poor surface finish, unacceptable dimensional accuracy, and the onset of high vibrations (chatter), as observed by [4].

To obtain a successful hard turning operation, some requirements must be observed. Literature [2] compiled some of these requirements:

- The machine tool/ workpiece/tool must have high rigidity, and the machine tool spindle must have a relatively high speed,
- The hardness of the tool material must be very high (much higher than the hardness of the workpiece material) with high wear resistance.
- Hard turning is mostly performed without coolant. For continuous cuts, the high tool tip temperature occurring in dry turning softens the workpiece material close to the

cutting region, which makes the material easier to shear. This explains why, in some cases, it is beneficial to increase the speed when in dry cutting.

Most of the research in hard turning involves the use of cBN or ceramics tools, as mentioned by [5] in their review. However, cBN tools may have a higher performance than whisker-reinforced tools [6] and ceramic tools [7] in hard turning of steels. Pure ceramics have high chemical stability and hardness, but the resistance to fracture is very low. Sialons (Si_4N_3-based ceramics) and the whiskers-reinforced ceramics do not have sufficient chemical stability for turning of hardened steels. Therefore, the cBN is the tool material that best applies to this type of operation. The different chemical compositions of cBN grades make them suitable for operations where high chemical stability of the tool material is demanded (in this case, cBN with a ceramic phase added is used) and also when higher hardness and toughness are demanded (in this case, a high cBN content material is used) [8].

Even having grades with superior toughness, cBNs are characterized by their high hardness and, consequently, low toughness that may lead to edge chipping [9] and may not resist excessive vibrations that are common in internal operations.

Vibrations in machining play an important role in limiting productivity. Excessive vibrations accelerate tool wear, lead to edge chipping and tool breakage, cause poor surface finish, and may damage machine tool parts as spindle bearings [10].

The quality of a machining operation is determined by static and dynamic stiffness of the system, which consists of machine tool, clamping system, tool, and workpiece. Once the overall rigidity is as high (or as low) as the rigidity of the weakest component, the latter should be under investigation, as observed by [11].

Among the elements of the machining system, less rigid components are those that have a free tail (i.e., drills, slender mills, boring, or internal turning bars). If the static/dynamic stiffness of these elements is inadequate, they

- Directly limit the achievable accuracy due to their easy deflection, even under low-magnitude cutting loads, resulting in shape and size deviations.
- Indirectly limit accuracy, since their micro-vibrations at high frequency lead to wear of the inserts during each cutting cycle, resulting in poor surface finish.
- Limit the machining operation due to the generation of self-excited vibration (chatter) when the overhang is four to five times larger than the tool diameter.

The internal turning bar is a good example of a tool that resembles a cantilever beam [12]. It is long and slender and is thus sensitive to excitation forces introduced by the material deformation and chip formation process in the turning operation. According to [13], the internal turning bar is generally the weakest link in the cutting system of the lathe.

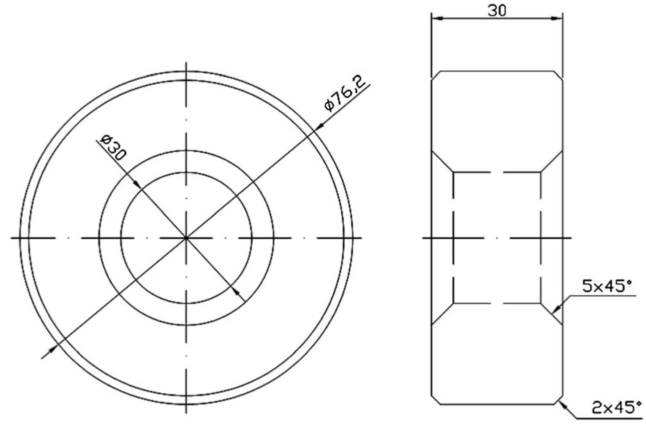

Fig. 1 Workpiece dimensions

As mentioned previously, internal turning bars statically and dynamically deform under the cutting forces during turning operations. If the length of an internal turning bar is L, the static deflection, for a cylindrical bar, in the contact point is given by Eq. (1):

$$\delta = \frac{64 F_r L^3}{3E\pi D^4} \quad (1)$$

where F_r is the radial force, E is the modulus of elasticity, I is the moment of inertia, and D is the diameter of the bar. Cemented carbide tool holders are sometimes used for internal turning bars due to their higher modulus of elasticity compared to the conventional and usual steel bar, which allows the machining of longer holes.

Then, for the same radial force, the greater the length to diameter ratio, the greater the deflection. Excessive static deflections may violate the dimensional tolerance of the hole, and vibrations may lead to poor surface, short tool life, and chipping of the tool. Thus, to obtain a highly accurate hole, the depth of cut must be low in order to have a low radial force [14]. Cutting stability depends mainly on the L/D ratio, independent of the cutting parameters (as modeled by [15], tested in external turning with several overhangs by [16], and also in external turning by [17]).

Several works have aimed at the development of more stable tools ([12] when analyzing clamping conditions [13], by analysis of vibration spectra, and [18] by the introduction

Table 1 Cutting parameters for the preliminary tests using the standard steel holder

Parameter	
Cutting speed (m/min)	360
Feed (mm/rev)	0.08
Depth of cut (mm)	0.1

Table 2 Cutting conditions for the 2^4 full factorial design

Condition	Bar material	Overhang (mm)	Feed (mm/rev)	Cutting speed (m/min)
C1	Standard steel	60	0.06	300
C2	Standard steel	60	0.06	360
C3	Standard steel	60	0.08	300
C4	Standard steel	60	0.08	360
C5	Standard steel	68	0.06	300
C6	Standard steel	68	0.06	360
C7	Standard steel	68	0.08	300
C8	Standard steel	68	0.08	360
C9	Carbide	60	0.06	300
C10	Carbide	60	0.06	360
C11	Carbide	60	0.08	300
C12	Carbide	60	0.08	360
C13	Carbide	68	0.06	300
C14	Carbide	68	0.06	360
C15	Carbide	68	0.08	300
C16	Carbide	68	0.08	360

of absorbers). They allow for working with higher overhangs (or L/D ratios). More stable tools (viz. chatter free tools) make possible machining with deeper cuts, thus leading to a lower number of steps or operations and to greater productivity. These tools also mix better surface finishes with more intense machining regimes and present a lower tool wear ratio due to the reduced high-frequency vibration amplitudes [11].

From a practical point of view, what really matters is if excessive vibrations (or chatter) will occur or not and how they may be avoided, as stated by [19].

When internal turning is made in hardened steel, tool vibration is even more critical, since this is a very accurate operation that aims to replace grinding and therefore requires high precision of the machined hole (i.e., tight dimension and shape tolerances and low surface roughness) and long tool life. Due to the problems of performing internal turning of long holes cited previously, when these holes are made in hardened steel, usually, the last operation is not turning. This work aims to increase the feasibility of using internal turning of long holes in hardened steels. We evaluate the influence of cutting conditions, the material of the tool bar, and tool overhang (L/D ratio) in the workpiece surface roughness and tool life in internal turning of hardened steel.

2 Experimental procedure

2.1 Workpiece

The workpiece material used in the hard internal turning experiments was AISI 4340 steel with a hardness of 53.6 ± 0.6 HRC. It was a 30-mm-long cylinder with a central axial hole

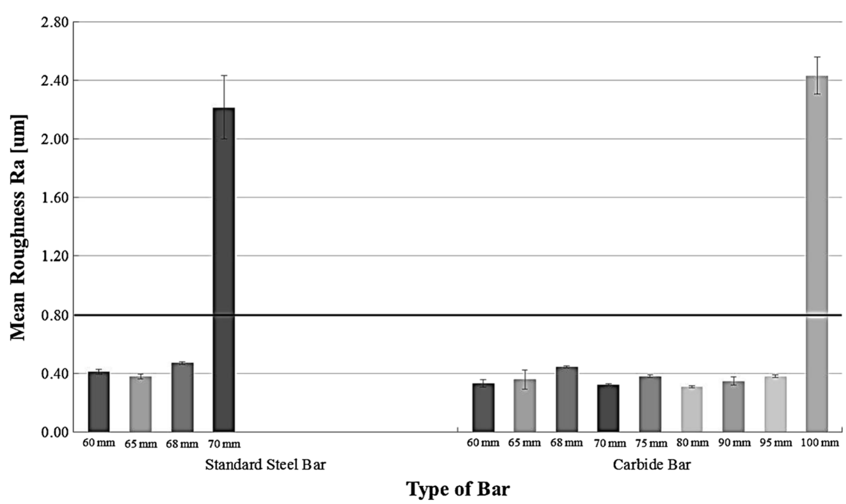

Fig. 2 Workpiece mean roughness, Ra, for increasing overhang in standard steel and carbide bars

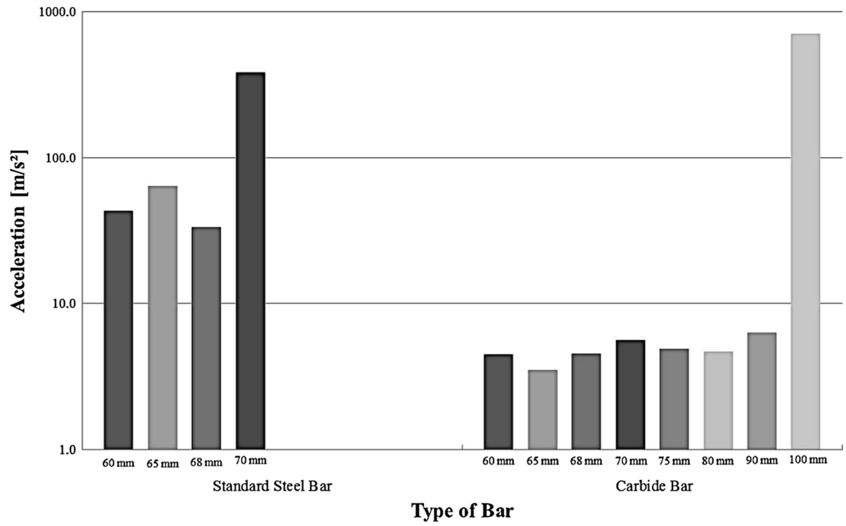

Fig. 3 Log of RMS radial tool acceleration for increasing overhang in standard steel and carbide bars

of 30-mm diameter (shown in Fig. 1) that was turned during the experiments in successive passes with a depth of cut of 0.1 mm, until this diameter reached 38 mm. This was carried out in order to ensure that the hardness of the workpiece did not change significantly.

2.2 Tools and cutting parameters

The ISO code of the cBN inserts used in the experiments was CCGW09T308S1020F 7015 (ISO H10). These inserts have 0.8 mm of nose radius and are made of 50 % cBN and a TiCN and Al_2O_3 ceramic phase and are recommended by the tool supplier for turning hardened steels [20]. The cutting parameters recommended for this insert are as follows: depth of cut from 0.07 to 0.8 mm, feed from 0.05 to 0.3 mm/rev, and cutting speed of 190 m/min.

Two different tool holders were used: a standard steel bar (ISO code A20S-SCLCR 09-R 1M 0866943) recommended for applications in which the tool overhang is up to four times the diameter and a carbide bar (ISO code E20S-SCLCR 09-R 1M 0903414) recommended for applications in which the tool overhang is up to six times the diameter. Both bars had a diameter of 20 mm.

Feeds of 0.06 and 0.08 mm/rev were selected in order to achieve a surface finish similar to those commonly attained in grinding operations, which is the operation that turning of hardened steel is supposed to replace. The depth of cut chosen was 0.1 mm, because this is usually the amount of material removed in grinding operations.

Before the tool life tests, preliminary tests were performed to determine the cutting speed that would result in a tool life close to 15 min. Therefore, a maximum cutting speed of 360 m/min was obtained. These tests were also used for establishing the maximum tool overhang. Since the standard steel bar has lower modulus of elasticity than the carbide bar and, therefore, lower stiffness than the carbide bar (the other tool holder used in the experiments), it was used in these tests. In other words, if the cutting is stable when steel bar is used, it will be also stable when a carbide bar is used. Table 1 shows a summary of the machining parameters.

The surface roughness was evaluated each time that tool overhang was increased. This preliminary test was carried on until mean surface roughness (Ra) was below the limit of 0.8 μm. Results determining the maximum overhang are shown and discussed in the next section.

After the preliminary tests, a 2^4 full factorial design of experiments (DOE) was designed to perform the other experiments. The other input variables besides tool overhang were as follows: cutting speed, feed, and bar material. The cutting conditions used in the experiments are shown in Table 2.

Fig. 4 Generated surface aspect for **a** stable cutting and **b** unstable cutting

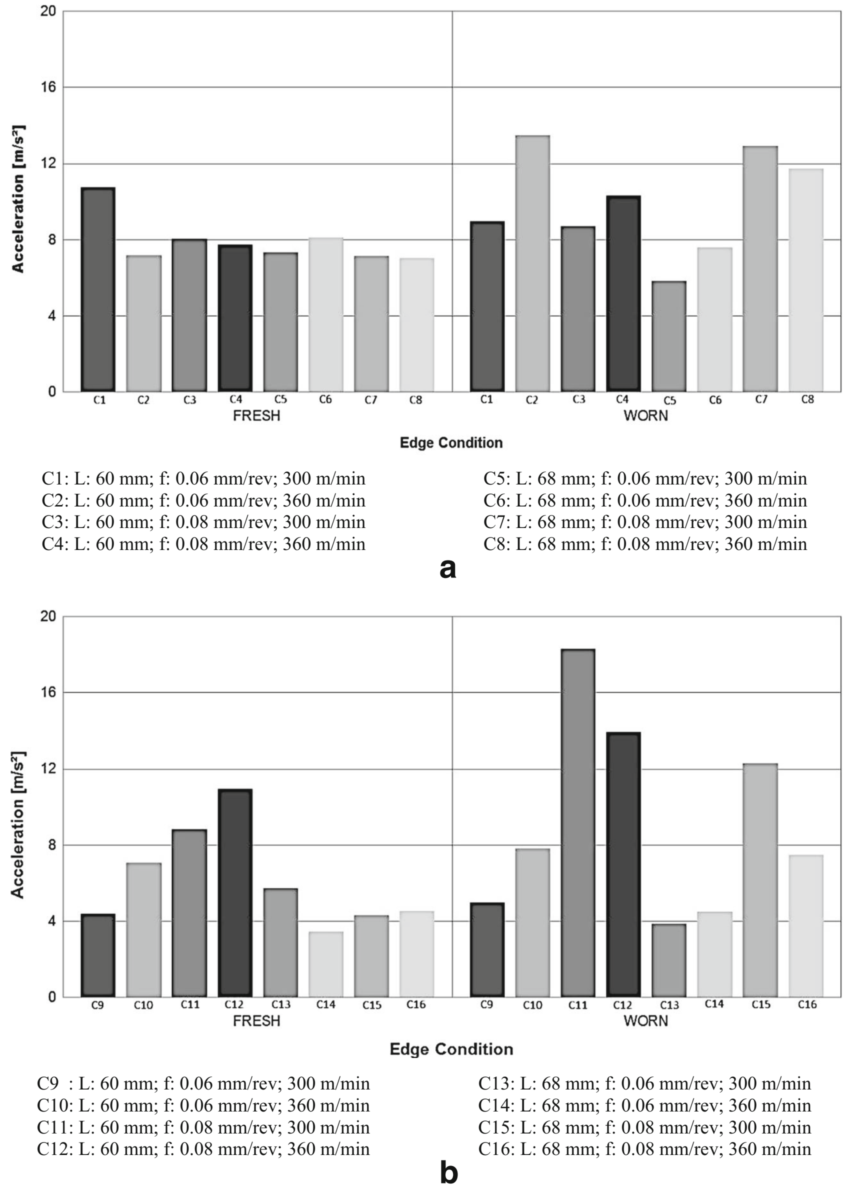

Fig. 5 Acceleration signal RMS for **a** standard steel bar and **b** carbide bar for fresh and worn conditions of tool edge

Next, tool life tests were performed using the conditions above. These tests were interrupted every 3 min of cutting time so that tool wear and surface roughness could be measured. One test finished when the tool flank wear reached 0.2 mm. Tool wear was measured using a stereomicroscope, and surface finish was measured using a Mitutoyo SJ-201 portable surface roughness tester.

The tool vibration signal was acquired using accelerometers attached to the tool holder in radial and tangential directions. However, only the radial vibration was used in the analysis in this work, since it is the most influential on the surface roughness. Acceleration signals were acquired in a Brüel and Kjaer Photon + dynamic signal analyzer using a 10-kHz sampling rate and default anti-aliasing and phase distortion filters. The vibration signals were acquired in tow moments of the experiments, when the tool was fresh (no wear) and also with worn tools (with tool flank wear = 0.2 mm).

Each experiment was performed twice, and the statistical analysis was performed using a confidence level of 95 % ($\alpha = 0.05$).

3 Results and discussion

3.1 Preliminary tests

Grinding operations may be replaced by hard turning since, frequently, the desired finish of a hardened steel surface can be obtained by both turning and grinding.

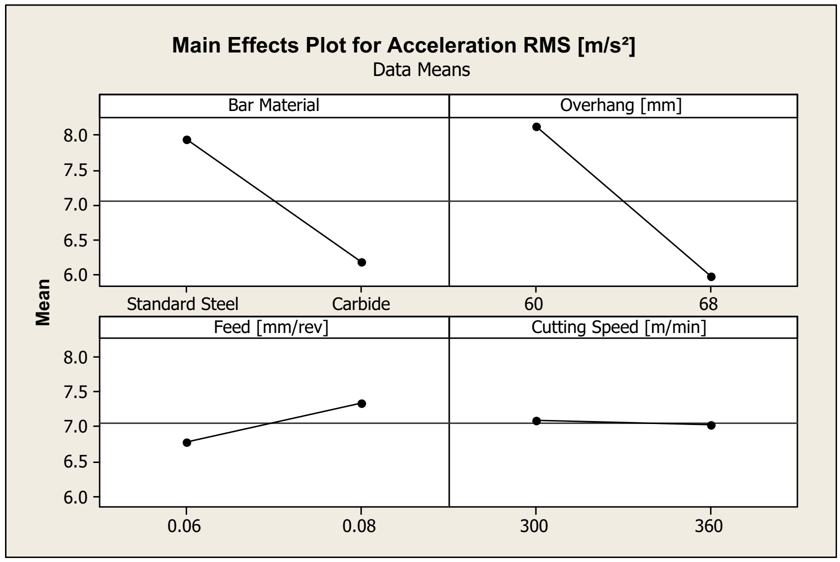

Fig. 6 Main effects plot for tool acceleration

In the preliminary tests, internal turning passes were made on the workpiece with increasing tool overhangs using each of the tool holders until the mean surface roughness of the machined surface, Ra, reached a preset limit of 0.8 μm, which is a value usually obtained in grinding operations. This overhang was then considered the maximum stable overhang. The results of these preliminary tests are shown in Fig. 2.

It can be observed that grinding can be satisfactorily replaced by hard turning unless a particularly low surface finish is required and that there were two distinct regimes: stable and unstable cutting. Moreover, the cutting became unstable suddenly after a small increase of tool overhang (from 68 to 70 mm when the steel bar was used and from 95 to 100 mm when the carbide bar was used). The increase in surface roughness for the unstable cutting is related to tool vibration, according to Fig. 3.

For the stable cutting regimen, although tool deflection increased accordingly to the L/D ratio (Eq. (1)), surface roughness did not show a similar behavior as expected. Moreover, the vibration amplitudes when in the use of the carbide bar were about ten times smaller than the ones when in the use of standard steel bars (related to the modulus of elasticity of the carbide); however, surface roughness was not affected by this level of acceleration. In this regimen, Figs. 2 and 3 show that vibration may play a secondary role in surface finish and that carbide bars are only recommended in situations when standard steel bars are not applicable (once they are more expensive and do not generate better surface finish).

The surfaces achieved in each of these regimes (stable and unstable) are shown in Fig. 4 (the surface aspect achieved in unstable cutting is very similar to those achieved by [15] in boring tests).

The occurrence of stable and unstable cutting shows that the stability is related not only to cutting parameters (depth of cut and feed, for instance), but also to setup conditions (as the overhang). By the results obtained, the maximum overhang that guarantees stability for both tool holder materials is 68 mm, and therefore, this will be the highest overhang value in the tool life tests.

3.2 Tool life full factorial tests

Turning must be performed carefully due to the high hardness of the cBN tool (and its lack of toughness) in order to avoid the premature failure occasioned by edge chipping and breakage. One of the several causes of edge chipping is vibration, which plays a main role in internal turning operations. Then, tool vibration was monitored in two moments of the tool lives (i.e., the beginning and end); the results are shown in Fig. 5.

For the majority of cutting conditions, the acceleration root-mean-square (RMS) value increases at the end of tool life (worn edge condition). This can be explained by the fact that when the flank wear is in the level which characterized the end of tool life (tool flank wear = 0.2 mm), cutting forces were greater than when the tool had no wear and, therefore, the vibration. However, in some cutting conditions, the values of acceleration for fresh and worn edge are very close. Sometimes, the acceleration for the worn edge is lower than the one for fresh edge (for instance, in conditions C5 and C13). This is surely related to the formation of crater wear. Crater wear causes a decrease in the cutting force due to an increase in the effective tool rake angle [21], which is supposed to reduce tool vibration.

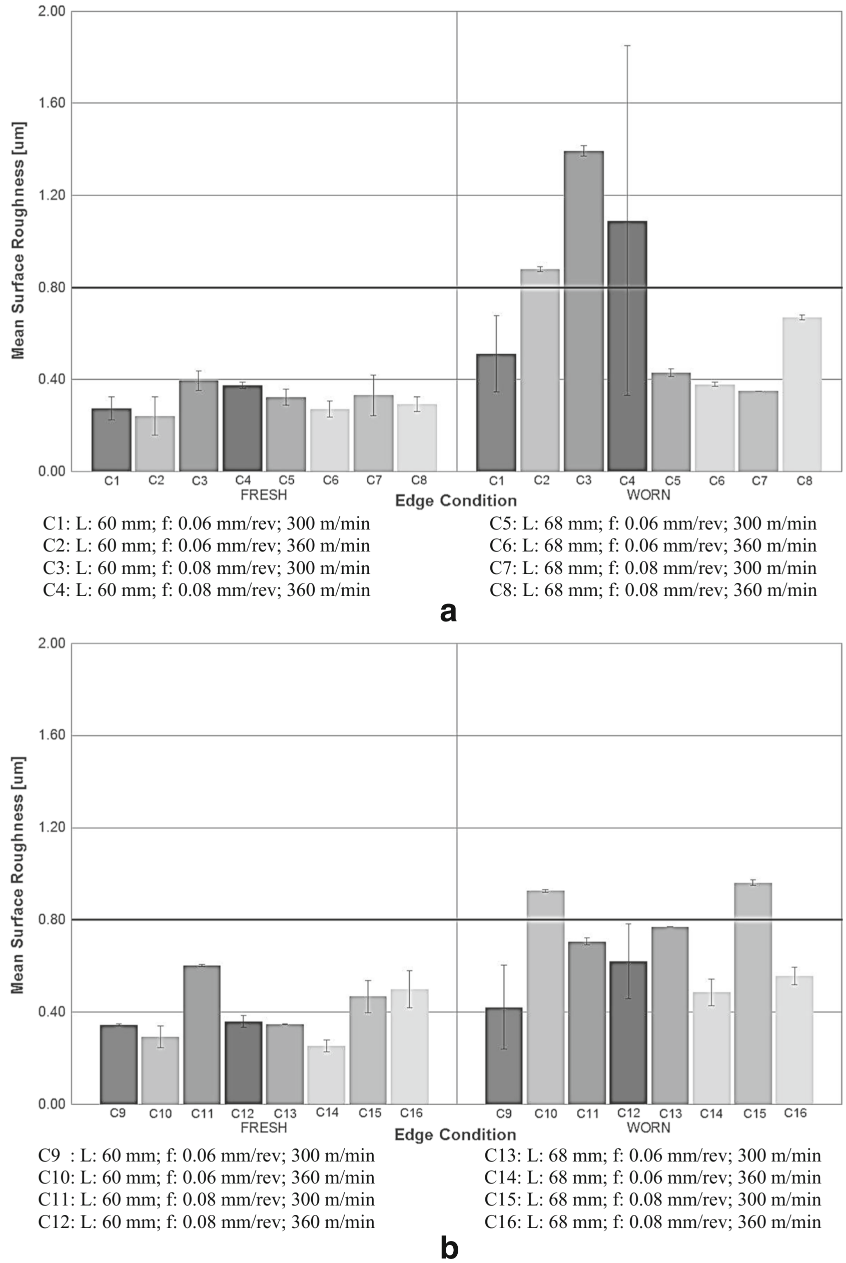

Fig. 7 Mean surface roughness for **a** standard steel bar and **b** carbide bar for fresh and worn conditions of tool edge

When a 2^4 full factorial DOE is carried out, the interaction among its factors is not easily observed just looking at the obtained results. Therefore, statistical analysis was conducted over the acceleration RMS values for fresh edge condition in order to have a better comprehension of the effects of each factor on the tool acceleration (or vibration). The effects are shown in Fig. 6.

The steeper the curve, the more influential the factor on the response (in this case, the RMS value of acceleration). Thus, based on Fig. 6, the bar material and overhang are the factors that most influence the acceleration (vibration) followed by the feed with little influence. The effect of cutting speed is not significant, showing that the chip formation frequency has no influence on vibration in internal turning operations.

The use of carbide bars provides lower vibration values than when the steel bar was used due to the increased stiffness of the same, caused by its higher modulus of elasticity.

The behavior of the tool overhang was contrary to what was expected. An increase in the length should decrease the stiffness of the system and thus should have increased vibration. When standard steel bar was used, the decrease in values caused by the increase in overhang is small (compare conditions C1 to C4 to conditions C5 to C8 in Fig. 6a). Therefore, the carbide bar (with its high variation in acceleration RMS values when it went from $L = 60$ mm to $L = 68$ mm—compare

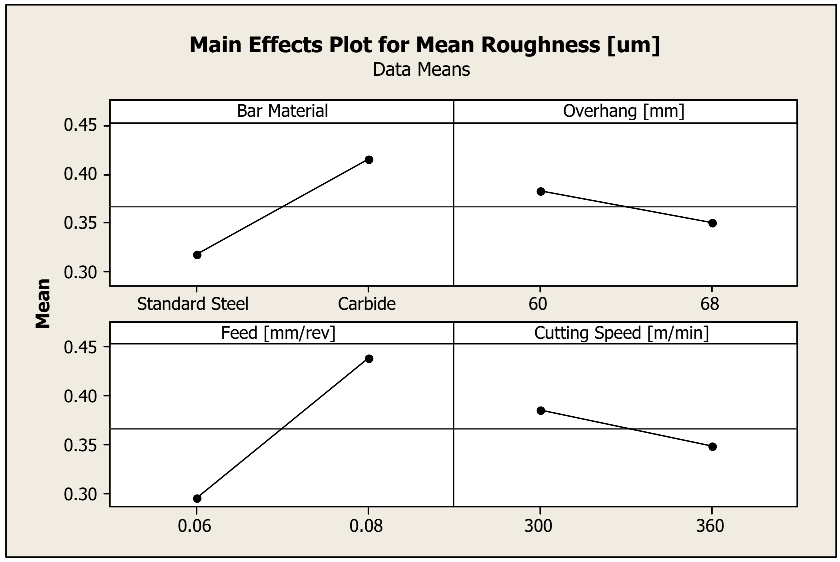

Fig. 8 Main effects plot for mean roughness

conditions C9–C12 to conditions C13–C16 in Fig. 6b) is responsible for this behavior. However, it is noteworthy that even with a greater variation, the absolute acceleration values are low and do not affect tool life or workpiece surface roughness, as will be seen later.

The acceleration values are closely related to the force exerted during the cut. The cutting force is a function of the specific cutting pressure, depth of cut, and feed. When the feed increases, the force also increases, although not in the same proportion. Therefore, the value of the specific pressure (force/chip cross section ratio) decreases. This explains the relatively low influence of feed in acceleration.

This analysis can be used again for the cutting speed. At high speeds, the influence on the specific pressure is small and the increase of the cutting speed results in a slight decrease in the value of specific cutting pressure, explaining the slight drop in acceleration.

The surface finish is influenced by the cutting parameters, vibration, and tool wear suffered by the tip. Since the intent of the hard turning is the replacement of the grinding operation, the mean surface roughness (Ra) could not exceed the stipulated limit of 0.80 μm. Figure 7 shows the Ra values for standard steel bar and carbide bar for fresh and worn edge conditions.

At the beginning of tool life, the standard steel bar provides absolute roughness values lower than the carbide bar, but because of the scale (tenths or even hundredths of a micrometer), a comparison of the two kinds of internal turning bar materials may not be suitable.

At the end of the tool life (tool flank wear of 0.2 mm), this behavior is reversed and the use of the carbide bar leads to lower roughness values than those obtained by the standard steel bar. It is indicative that the inserts used in the carbide bar suffered less damage than those in the standard steel bar, most likely due to less vibration occurring when machined with such a bar, as shown in Figs. 5 and 6.

Due to its dispersive nature, roughness analysis should be performed through the use of statistics. Thus, Fig. 8 shows the main effects plot for mean surface roughness in the fresh edge condition.

Again, the steeper the curve is, the more influential the factor is on the response. Once the cut has been made under stable conditions, the overhang is not an influential factor. In other words, the little vibration that occurs in stable conditions is not able to harm surface roughness.

The cutting speed is not a significant influence on the roughness parameter. However, greater cutting speeds tend to produce finer finishes due to the prevalence of shear over strain on the surface obtained in the process. In addition, the higher temperature due to the higher speeds facilitates chip shearing and chip removal.

Increased feed causes a poor surface finish due to its role in the geometric component of roughness.

The relationship between tool vibration and workpiece roughness is conflicting. When the bar material was changed from steel to carbide, tool vibration decreased (see Fig. 6) and surface roughness increased (Fig. 8), which was not expected. When the tool overhang increased, tool vibration decreased significantly (again see Fig. 6) and the roughness decreased just a little (not significantly). Thus, it can be concluded that in these vibration levels (stable cutting), vibration does not influence roughness and the roughness behavior due to the variation in tool holder material and tool overhang being explained by other mechanisms.

One possible explanation is the fact that these variations in roughness have the order of magnitude of tenths of micrometers: a very small variation. Small changes caused by factors such as irregular chip flow that can cause small scratches in

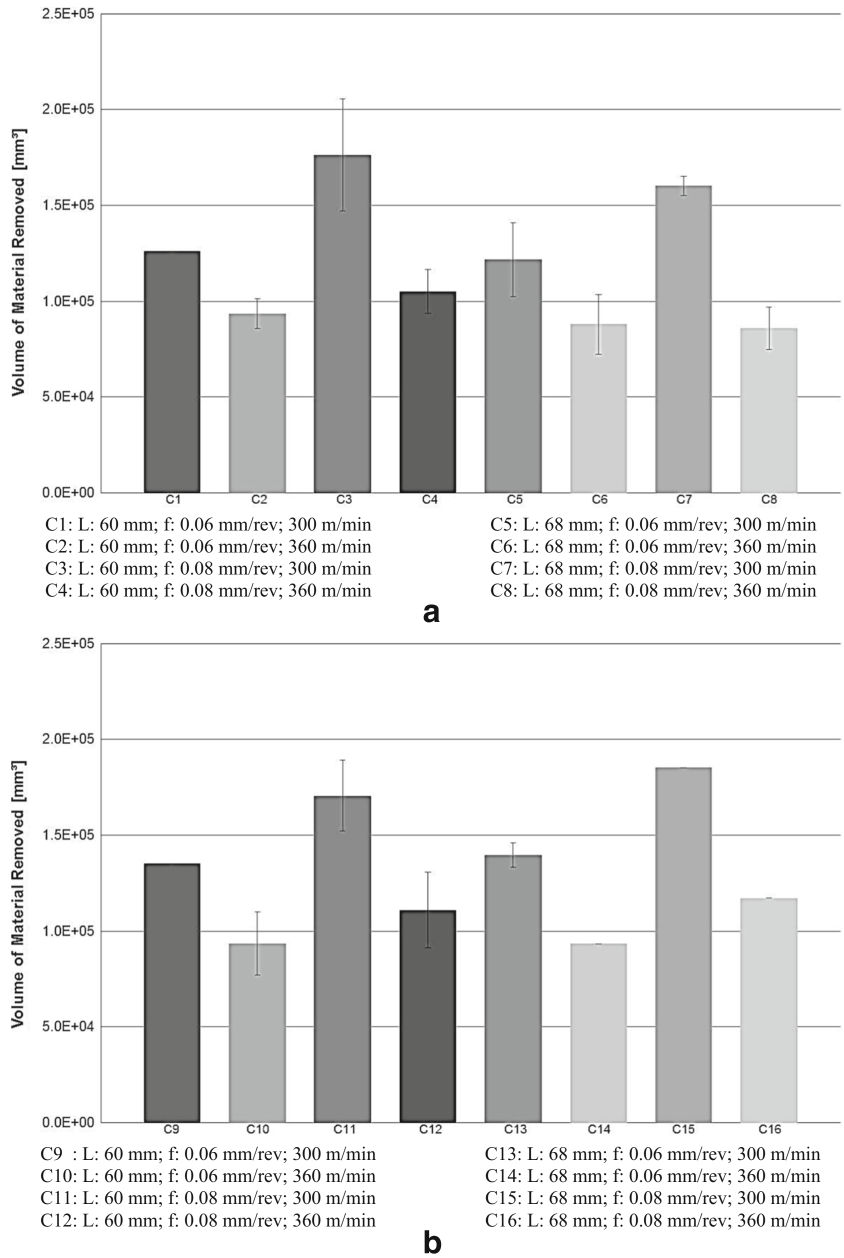

Fig. 9 Volume of material removed for **a** standard steel bar and **b** carbide bar for fresh and worn conditions of tool edge

the generated surface, small variations of the actual depth of cut caused by imprecision of the tool tip positioning, etc., cannot be controlled. These factors may have caused these inconsistencies in the relationship of bar material, overhang, and the surface roughness. However, one conclusion can be extracted from these results: when the vibration is low and the cutting is stable, vibration is not an influential factor on the surface roughness formation (as can be seen in [22] for external turning).

Figure 9 shows the tool lives in terms of volume of material removed for both bars in the different tested conditions. The end of the tool life was reached when the tool flank wear reached 0.2 mm. The use of the chip volume removed by life enables a better comparison of the tool life in the cases where there are variations in cutting speed and feed.

Figure 10 shows the main effects plot for tool lives extracted from the results shown in Fig. 9. It can be seen that the tool life is influenced by cutting speed, feed, and the bar material, in this sequence of significance. It is seen also from this figure that, for stable cuts, the overhang (L/D ratio) did not affect tool life.

Tool life is greatly affected by temperature, as seen in [21]. Thus, every factor that causes a rise in temperature will cause a decrease in life. Therefore, cutting speed was the strongest influence in tool life; once when it increases, the amount of material removed per unit of time also increases, but the area

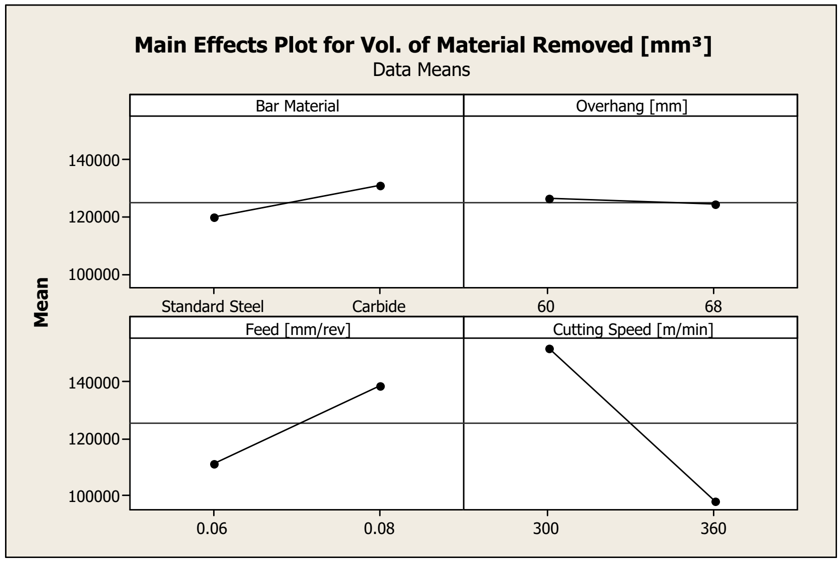

Fig. 10 Main effects plot for volume of material removed

on the tool that has a contact with the chip and workpiece does not change, which make the tool temperature increase and tool life decrease.

Increasing the feed used causes an increase in the volume of removed chip per minute and thus increases heat generated, which reportedly reduces the life of the tool. However, since the area occupied on the tool by the chip also increases, the tool temperature does not increase in the same proportion to the increased heat. On the other hand, increasing the feed decreases the amount of workpiece revolutions required to achieve the same machined length, reducing the contact time (and therefore, the friction generated) between the workpiece and the tool, which allegedly increases the tool life. Thus, as the tool life increased with feed, it follows that this second factor was predominant.

The two longest tool lives for both tool bars were obtained when the highest feed and lowest cutting speed were used (conditions C3 and C7 for steel bar and C11 and C15 for carbide bar—see Fig. 9). This result is interesting because this condition was not the one that presented the lowest chip removal rate. On the contrary, it was the second highest removal rate among those used in the experiments (of course, the highest feed and the highest cutting speed were the condition with the highest removal rate). Therefore, the use of this condition guarantees long tool life with good chip removal rate (but the cutting time not so long). However, if conditions C3 and C15 are used, the end of tool life may not be based on the value of flank wear since, in these conditions, when tool flank wear was 0.2 mm, the surface roughness was greater than 0.8 μm, which is a suitable limit of surface roughness for turning of hardened steels. Consequently, in these conditions, the tool life may be shorter than those shown in Fig. 9. In other words, a specific value of flank wear may not be the only criterion of tool life for processes that require very good surface roughness, like internal turning of hardened steel. Together with flank wear, workpiece surface roughness must be also another criterion to establish the end of tool life.

The use of a carbide bar promotes a slight increase in the volume of chip removed. It must remembered that tool vibration is lower for the carbide bar (Fig. 5). This lower level of vibration was the cause of this small tool life increase. However, it must be pointed out that the influence of the bar material on tool life was not statistically significant. When comparing the tool life values for the two bars in Fig. 9a, b, it is seen that in nearly all of them, there is no difference between the life obtained with steel and carbide bars for the same machining conditions. The carbide bar only provided a longer tool life when comparing the C7 experiment with C15 and C8 to C16 (particularly the latter comparison), that is, only when it had the highest tool overhang and feed among the tests. In other words, the carbide tool bar only generated a longer life than the tool steel bar when it was applied in combination with a lower tool stiffness (due to the higher overhang) and the higher cutting force (due to higher feed).

Based on this analysis, it can be said that for stable cuts, the material of the bar has no effect or too little influence on tool life. Therefore, if a tool overhang is used that provides stable cuts for both steel and carbide bars, the steel bar should be used, since it is cheaper and its use does not significantly reduce tool life (Figs. 9 and 10) and could even reduce workpiece surface roughness (Figs. 7 and 8).

The variation in tool overhang had no significant influence on the tool life because, as also seen, while cutting is stable, increasing the balance did not increase vibration and did not affect the generation of heat during cutting (since the cutting speed does not change).

4 Conclusions

From the results, it can be concluded that, for the internal turning of hardened steel in conditions similar to those used in these experiments,

- In conditions where cutting is stable, the surface finish is mainly influenced by the geometry of the insert and the machining parameters (especially feed).
- The carbide bars should be recommended only for tool overhangs greater than that one that causes instability in the cutting with steel bars. When the cutting with both bar materials is stable, tool life and surface roughness are the same, regardless of the bar material.
- The transition between stable and unstable cutting occurs suddenly after an overhang threshold value rather than in a gradual way.
- More conservative cutting conditions (viz. lower cutting speed and higher feed) promote greater material removal per edge (i.e., longer tool life).
- If the highest value of surface roughness allowed for the holes is Ra = 0.8 μm, in some cases, tool flank wear of 0.2 mm is not a suitable tool life criterion and the surface roughness value may be used as the limit of tool life.

Acknowledgments The authors would like to thank São Paulo Research Foundation (FAPESP-Grant 2010/08457-1) and Sandvik Coromant for supporting this research.

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