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EXPERIMENTAL STUDY ON TURNING OF GRAY CAST IRON USING TEXTURIZED TUNGSTEN CARBIDE INSERTS

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Abstract. *There is an ever increasing interest on the usage of texturized cutting tools in order to improve the performance of various machining processes. This paper investigates the behavior of the cutting force components when turning gray cast iron with uncoated tungsten carbide inserts ISO grade K15 which were previously subjected to laser texturing on their cutting edges. After chamfering by grinding, the cutting edges were laser texturized in order to generate two parallel rows of dimples with an average diameter of 40 μm. By varying the spacing between the dimples in the same row, three sets of tools were prepared to carry out the force measurements and one set of chamfered tools without texturing was used as control in order to allow the analysis of the efficiency of the produced texture in reducing the machining force components. Furthermore, experiments were carried out dry and with the application of minimum quantity lubrication (MQL). The findings indicated that, in general, the combination of tools with textured chamfer (with a spacing of 200 μm between two subsequent dimples) and cutting with MQL at lower and moderate material removal rates were beneficial to the machining force components reduction.*

Keywords: *Texturing; Machining force; Cutting edge preparation; Minimum quantity lubrication.*

1. INTRODUCTION

Increasing the efficiency of manufacturing processes is the main goal of the majority of the research works, including metal cutting operations. One possible approach for these studies is to use cutting tools which have been subjected to a change in the surface texture, generally called surface texturing. The term refers to the peaks and cavities usually found on a surface. The orderly arrangement of these peaks and valleys may change the surface functionality (Viana, 2009). When surface modifications are made in order to obtain a specific function, this is called "engineered surface" (Evans and Bryan, 1999). In machining, textured surfaces may be applied for improving the adhesion of coatings on cutting tools (Viana, 2009) or reducing the machining force, the cutting temperature and tool wear. In dry turning of titanium alloy using uncoated micro-grooved carbide tools, the cutting temperature and cutting force was reduced by 27.2% and 56.1%, respectively, under higher removal rate (11700 mm^3/min), in comparison with non-textured tools (Xie et al., 2013). Furthermore, cutting temperature decreased by 20% and cutting force by 32.7% under lower removal rate. The micro-grooves were produced on the rake face of the cutting tool by micro-grinding with a V-tipped diamond wheel.

The influence of cutting fluids on the performance of textured tools has also received a great deal of attention. Zhang et al. (2015) investigated the behavior of coated cemented carbide inserts when cutting hardened AISI 1045 steel. Laser texturing was employed and the cutting trials were carried out under high and low lubrication conditions. The results showed that the cutting forces were reduced by 34.7% when the highest cutting speed (200 m/min) and high lubrication condition were employed. In the case of low lubrication regime, the cutting forces were reduced by 8% at highest cutting speed (200 m/min).

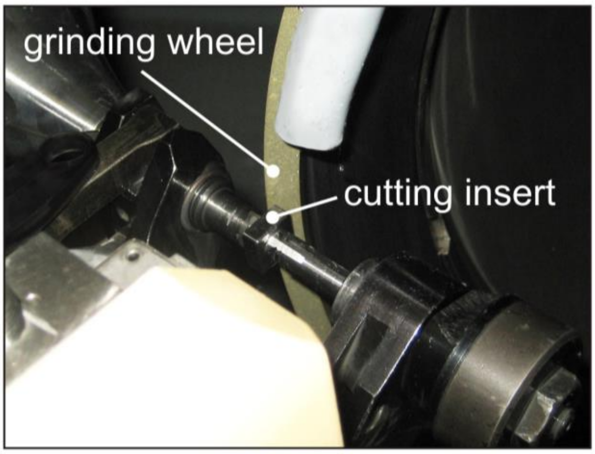
A reduction in the cutting force when wet milling die steel (average hardness of 40 HRC) with textured tools was reported by Chang et al. (2011). Focused ion beam (FIB) was employed to produce micro-grooves on tool’s rake face in three different directions: parallel, perpendicular and at 45° relatively to the cutting edge. The findings indicated that the perpendicularly textured milling cutter provided lower cutting force and flank wear. Kawasegi et al. (2009) used a femtosecond laser to generate micro- and nano-scale textures on the rake face of the tools. As a result, the required cutting forces when turning an aluminum alloy under dry condition and with minimum quantity lubrication (MQL) was reduced, albeit under high cutting speed (above 420 m/min) only. Similarly, the efficiency of the cutting fluid was increased when turning an aluminum alloy with cemented carbide inserts subject to texturing spattering, photolithography and wet etching (Obikawa et al., 2011).

The above mentioned decrease in cutting force is probably due to the reduction in adhesion in the chip/tool interface caused by the reduction in the chip/tool contact area promoted by the presence of lubricant or air in textured tools. Minimum quantity lubrication is particularly recommended in this case owing to the fact that it allows entraining a small amount of lubricant by a compressed air stream which is directed over the cutting area, thus producing lubricant atomization and making its distribution in the cutting region more uniform (Weinert et al., 2004). Improved cutting fluid retention through nano- or micro-texturing of the rake face is essential in order to achieve good anti-adhesive protection when cutting aluminum alloy (Sugihara and Enomoto, 2009).

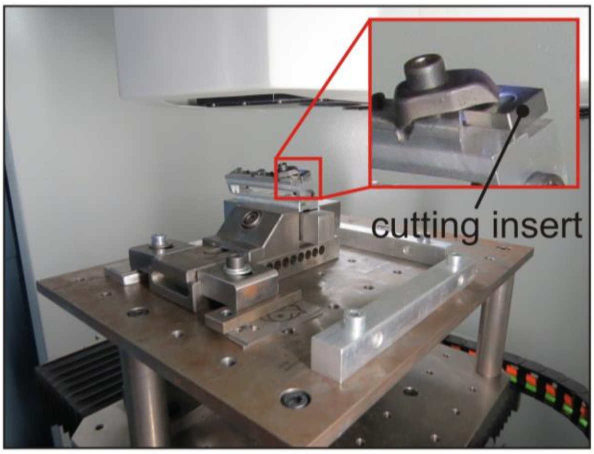
In this work, modifications on the cutting edge chamfer of uncoated tungsten carbide inserts are proposed in order to assess its effect on the behavior of the cutting force components when turning GG30 gray cast iron. Furthermore, dry turning was compared with the application of MQL.

2. CUTTING EDGE PREPARATION

Uncoated tungsten carbide inserts ISO grade K15 and geometry SNMA 120408 (without chip breaker) were used as cutting tools and mounted on a holder code PSBNR 2020K12, thus resulting in a rake angle of -6°, cutting edge inclination angle of -6°, clearance angle of 6° and cutting edge angle of 75°. The inserts were initially ground to produce a chamfer with a width of 100 µm and inclination of 20°. Grinding was performed employing a Wendt WAC715 Centro CNC grinding machine (3 kW of power and maximum rotational speed of 1625 rpm). A vitrified diamond wheel D15 C120 (Winter) was used and dressing was performed with an aluminum oxide wheel (320#). The grinding conditions were as follows: wheel speed v_s = 20 m/s, axial feed speed v_{fa} = 6 mm/min and dressing feed speed v_{fad} = 3 µm/s. Rhenus R-Oil HM7 neat oil was used as grinding fluid. After grinding the inserts were examined in a Mahr Perthometer Concept and then subjected to laser texturing in a Sauer Lasertec 40 machine. The laser equipment operation parameters were: intensity I = 13 W, frequency f = 80 kHz and feed speed v_r = 250 mm/s. The inserts were mounted in a device with an inclination of 20° in order to produce a square angle between the laser beam and the cutting tool chamfer. Two parallel rows 50 µm apart with dimples (semispherical cavities) possessing average diameter of 40 µm and depth of 20 µm were produced on the chamfers of each cutting tool, nevertheless at four distinct steps: step 0 (without laser texturing), step 60 (60 µm between the centers of two subsequent dimples), step 100 (100 µm between the centers of two subsequent dimples) and step 200 (200 µm between the centers of two subsequent dimples). Figure 1(a) shows a detail of cutting insert and wheel mounted on the grinding machine and Fig. 1(b) shows a detail of the laser texturing machine with the device where the cutting inserts were fixed.



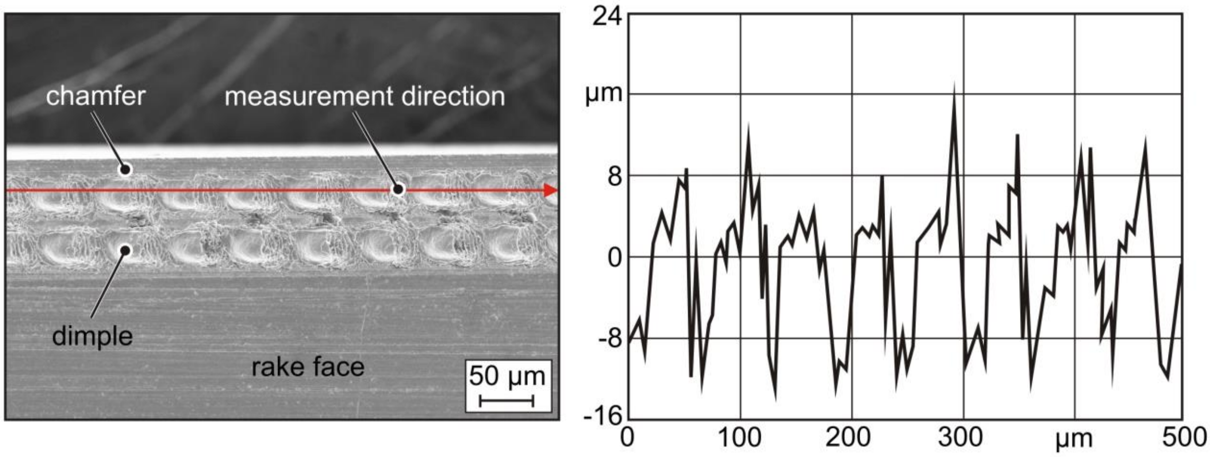
(a) Insert grinding machine



(b) laser texturing machine

Figure 1. Equipment employed for cutting edge preparation: (a) Insert grinding machine and (b) laser texturing machine

A sample of the textures produced on the tools' chamfer is given in Fig. 2. It can be noted on Fig. 2(a) that two parallel rows with dimples were produced on the chamfer by laser texturing. In this particular case, the distance between two subsequent dimples was 60 µm (step 60). Furthermore, resolidified material is present in the neighborhood of each dimple due to the fact that this process was not gas jet-assisted. The chamfer profile obtained through the profilometer is represented in Fig. 2(b), where the scatter in the depth of the dimples and the presence of the resolidified material can be assessed. The distance between two subsequent dimples, however, does not seem to change drastically in the same sample.



(a) SEM photography of the chamfer (b) dimples profile

Figure 2. Textured sample (step60): (a) SEM photography of the chamfer and (b) dimples profile

3. TURNING TRIALS

Bars of GG30 gray cast iron with an average diameter of 82.6 mm and 70 mm long were used as work material. The samples were subjected to annealing under the following condition: heating at 930° C for 5 hours followed by cooling in the furnace. Before the beginning of the tests, the hardness was measured on the surface of three samples selected at random and the average value was 72 HRB. The hardness value was monitored throughout the test program and this value remained unaltered up to 9 mm beneath the surface. Every time this distance was achieved, a new workpiece was used to continue the turning tests. Each cutting edge was used to perform two tests (with a cutting length of 45 mm each) in order to avoid the influence to tool wear on cutting force.

A Romi GL 240M turning center (power of 22.5 kW) was used and the force components of the turning process were measured with a Kistler 9272 piezoelectric dynamometer connected to an amplifier and acquisition board from the same manufacturer. The force components in the cutting, feed and radial directions were recorded at an acquisition rate of 1000 Hz. The cutting conditions tested for each edge preparation are depicted in Tab. 1, where it can be noted that, additionally to the influence of cutting speed, feed rate and depth of cut, the effect of environment (dry turning and cutting with minimal quantity lubrication - MQL) was assessed. One test plus one replicate were conducted for each cutting condition and the average force was calculated and used to plot the graphs. Feed rate was limited to 0.15 mm/rev in order to allow the investigation of the influence of texturing on the chamfers (100 μm wide). Minimal quantity lubrication was applied using an Accu-Lube system set to a pressure of 6 bar and flow rate of 65 ml/h. As cutting fluid, Blaser Vascomill MMS1 was applied through one nozzle pointed at the clearance face of the insert, as shown in Fig. 3.

Table 1. Cutting parameters employed in the turning tests

Cutting speed v_c (m/min)	Feed rate f (mm/rev)	Depth of cut a_p (mm)	Cutting fluid
100	0.05	1.0	Dry
200	0.10	1.5	
300	0.15	2.0	MQL

4. RESULTS AND DISCUSSION

Initially, the results concerned with the cutting (principal) force are presented for both dry and MQL conditions, followed by the feed force and finally by the passive (radial) force component. Figure 4 show the influence of the cutting parameters and chamfer texture on cutting force when dry turning GG30 gray cast iron. In contrast with the expected trend of reduction in the cutting force with the elevation of cutting speed, Fig. 4(a) show an appreciable increase in cutting force when cutting speed is elevated from 100 to 200 m/min, followed by a slight reduction for v_c = 300 m/min. According to Trent and Wright (2000) the drop in the cutting force with the elevation of cutting speed is partly caused by a decrease in contact area and partly by a reduction in shear strength in the flow zone as its temperature rises. Therefore, it may be inferred in the present case that the brittle nature of gray cast iron does not allow a reduction in the shear strength of the work material. In addition to that, the employed feed rate values make chip formation to take place within the chamfer land, which results in a highly negative effective rake angle of -26° (20° from the chamfer plus 6° from the tool holder). Consequently, the otherwise expected reduction in the contact area does not occur and the increase in material removal rate (as cutting speed is elevated) leads to the observed increase in cutting force.

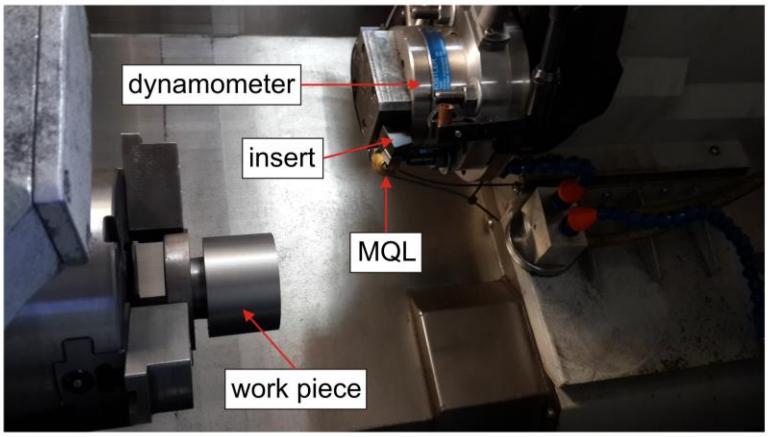


Figure 3. Turning force measurement setup

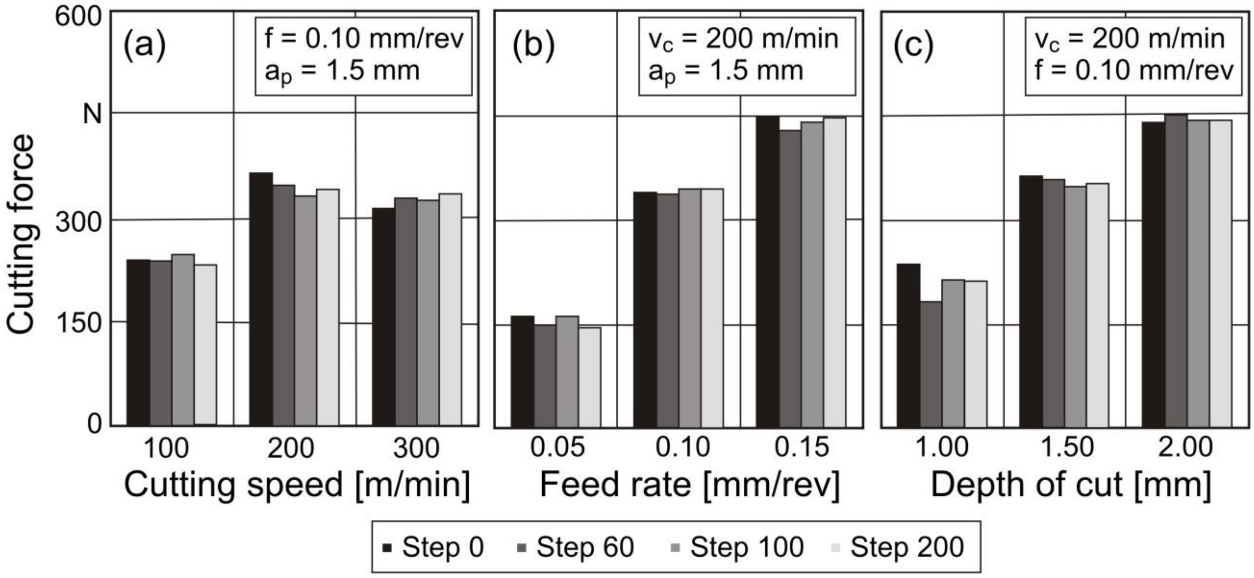


Figure 4. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on cutting force when dry turning GG30 gray cast iron

In the case of feed rate and depth cut, see Fig. 4(b) and 4(c), respectively, the elevation of these parameters lead to higher shear areas, irrespectively of the chamfer geometry. Consequently, the cutting force is increased. With regard to the influence of chamfer texture on cutting force it can be noted that, in general, textured tools provide a marginal decrease in the cutting force in comparison with non-textured tools, notably under intermediate cutting speed of 200 m/min and using lowest feed rate and depth of cut values (f = 0.05 mm/rev and a_p = 1 mm), nevertheless, a clear trend regarding the different textures (steps) cannot be identified in this graph. One possible explanation for the small influence of chamfer texture resides in the fact that the dimples may be filled with material, thus impairing their ability to reduce the contact area between chip and tool rake face.

The influence of the cutting parameters and chamfer texture on cutting force when turning GG30 gray cast iron with the application of minimal quantity lubrication (MQL) is depicted in Fig 5, where it can be seen that MQL reduces the influence of the assessed cutting parameters on cutting force, i.e., the extension of their influence is smaller compared with dry cutting. In spite of that, the same trends previously reported were again observed: an increase in cutting force when cutting speed is elevated from 100 to 200 m/min followed by a minor reduction for v_c = 300 m/min, as represented in Fig. 5(a), and an elevation in cutting force when feed rate and depth of cut are increased, as can be seen in Fig. 5(b) and Fig. 5(c), respectively. The phenomena responsible for this behavior are the same previously discussed, however, under the presence of MQL the difference between the cutting force recorded using non-textured and textured tools is more evident, apparently when lowest cutting speed, feed rate and depth of cut values are employed, possibly owing to the fact that under this cutting condition the access of the oil droplets to the cutting zone is facilitated.

Moreover, a comparison between the different textures suggests that, in general, cutting force is lowest using the largest step of (200 μm).

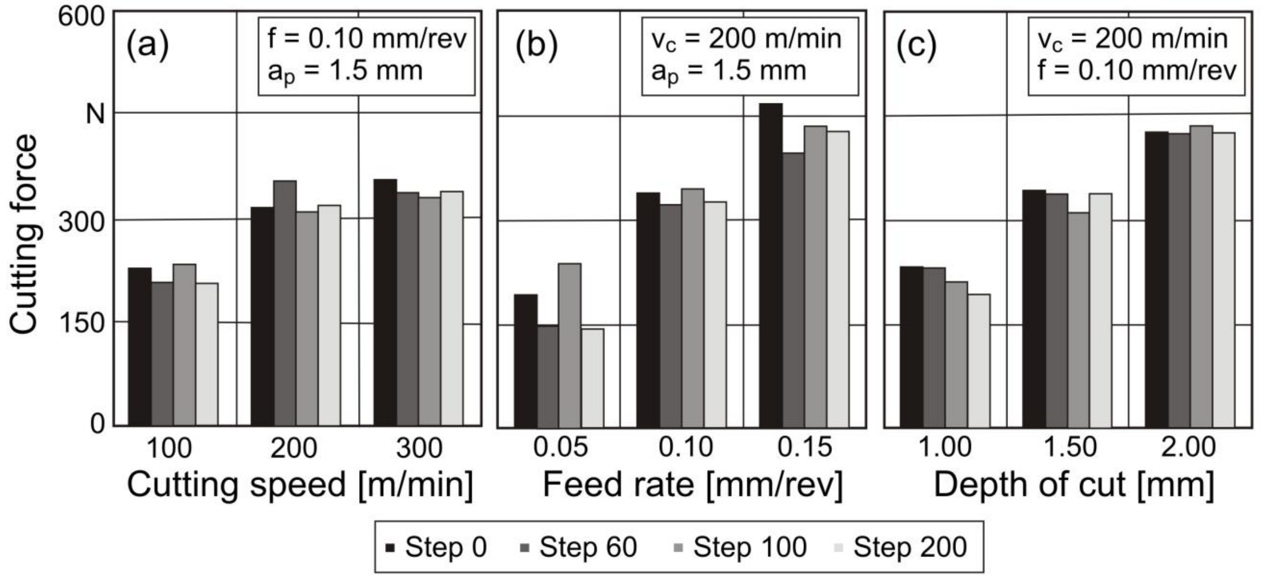


Figure 5. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on cutting force when turning GG30 gray cast iron using MQL

Figures 6 and 7 shows, respectively, the influence of dry cutting and turning with MQL on the feed force when turning GG30 gray cast iron using textured tools under distinct cutting conditions. Despite the fact that lower forces are observed in comparison with Fig. 4(a), the same tendency of maximum feed force for the intermediate cutting speed (v_c = 200 m/min) was recorded, while the elevation of feed rate (Fig. 6b) and depth of cut (Fig. 6c) resulted in highest feed force for the highest values tested (f = 0.15 mm/rev and a_p = 2 mm, respectively). As far as the influence of cutting edge texture is concerned, in general it can be noted that its influence on feed force decreases as the cutting parameters are elevated. In the particular case of employing the highest cutting speed, feed rate and depth of cut values, the non-textured inserts promoted lowest feed force values. Moreover, lower feed force values are typically found when turning with inserts textured with steps of 100 and 200 μm.

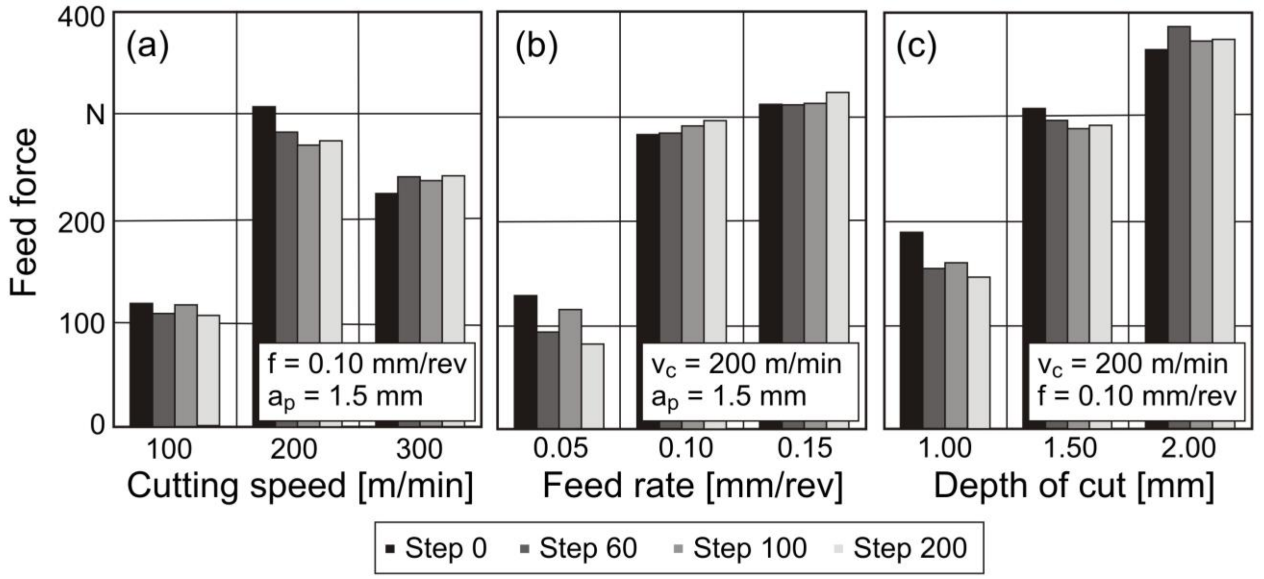


Figure 6. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on feed force when dry turning GG30 gray cast iron

The application of minimal quantity lubrication (MQL) resulted in a more evident variability in the feed force values, see Fig. 7. The influence of chamfer texturing on feed force is more pronounced at lowest cutting speed, feed rate and depth of cut values (v_c = 100 m/min, f = 0.05 mm/rev and a_p = 1 mm, respectively) and, as a general rule, it can be stated that the inserts textured with a step of 200 μm provided lowest feed force values. Moreover, it is worthwhile noting that while the textured tools provided lowest feed forces using MQL under highest feed rate and depht cut (Fig. 7b and 7c, respectively), in the case of dry turning under extreme cutting conditions highest feed forces were recorded for the textured inserts, see Fig. 6(b) and 6(c).

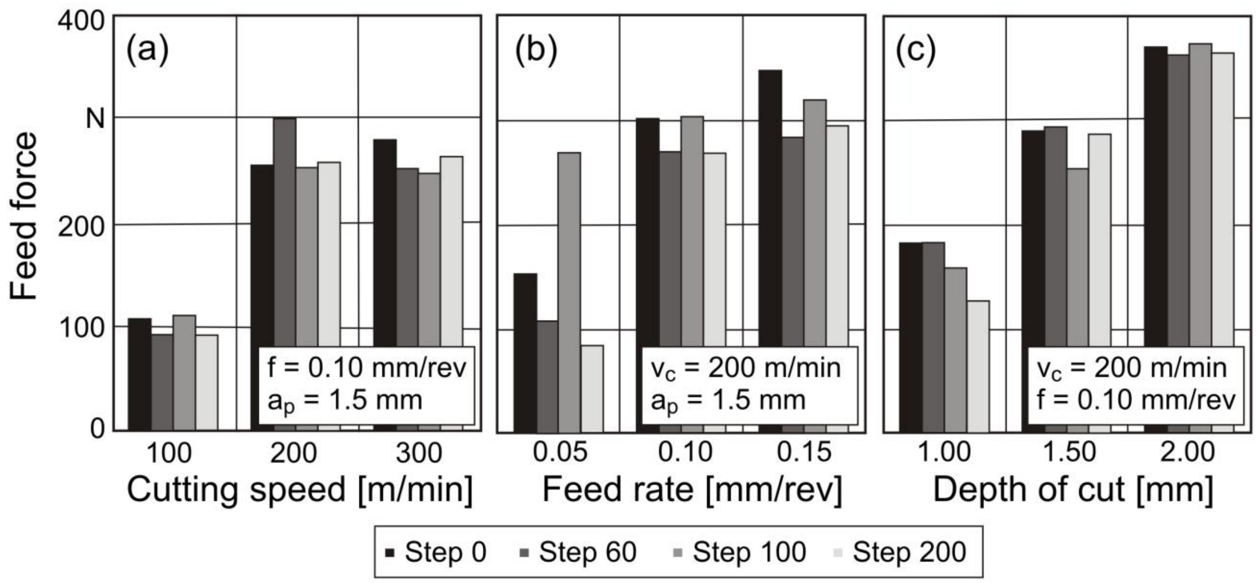


Figure 7. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on feed force when turning GG30 gray cast iron using MQL

The results concerning the passive force are presented in Fig. 8 and Fig. 9, where the former shows the influence of the cutting conditions and chamfer texturing when dry machining and the latter for turning in the presence of MQL. This force component presented lower values compared with the feed force and such behavior can be explained by the cutting edge angle of the tool-holder pair ($\chi_r = 75°$). An increase in this angle makes the cutting edge more perpendicular in relation to the feed direction and more parallel to the radial direction. As a consequence, the higher the cutting edge angle, the higher the feed force and the lower the passive force (which is expected to approach zero when $\chi_r = 90°$). Figure 8 shows the same trends previously noted in Fig. 4 and 6, i.e., the highest passive force is recorded under an intermediate cutting speed of v_c = 200 m/min and the elevation of feed rate and depth of cut leads to higher forces. Furthermore, texturing the inserts does not cause a substantial decrease in passive force under higher removal rates.

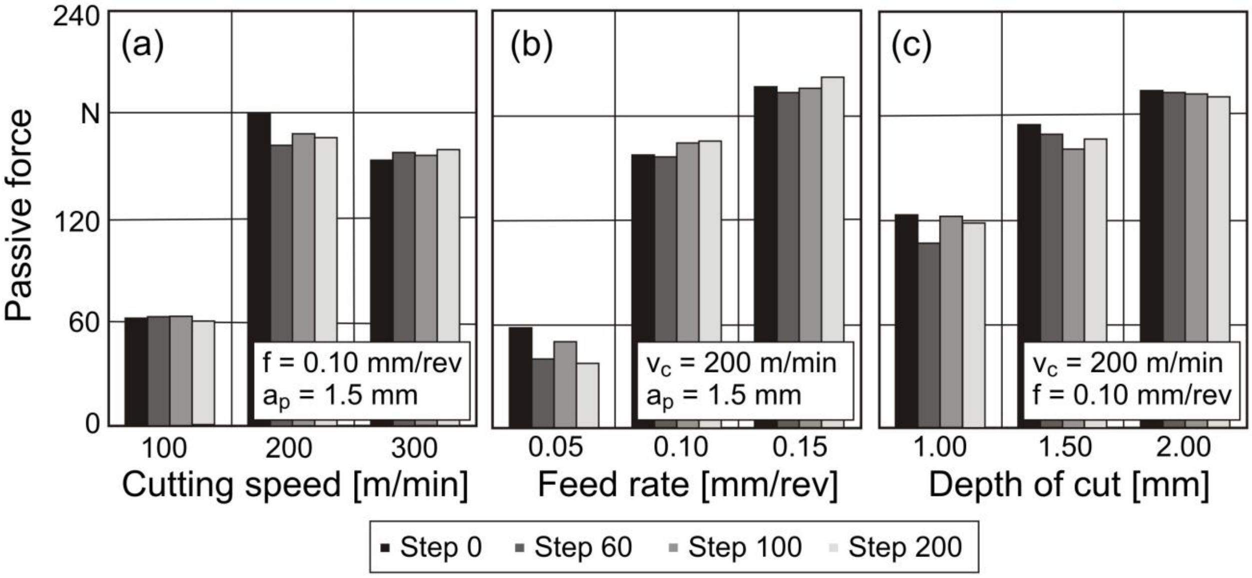


Figure 8. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on passive force when dry turning GG30 gray cast iron

The influence of the cutting conditions and chamfer texturing on passive force when turning with MQL is shown in Fig. 9. Increasing cutting speed, feed rate and depth of cut promoted the same effect noticed in Fig. 5 and Fig. 7, while employing textured tools resulted in lower passive force values compared with non-textured inserts. Generally speaking, the tools textured with a step of 200 μm provided lower passive force values.

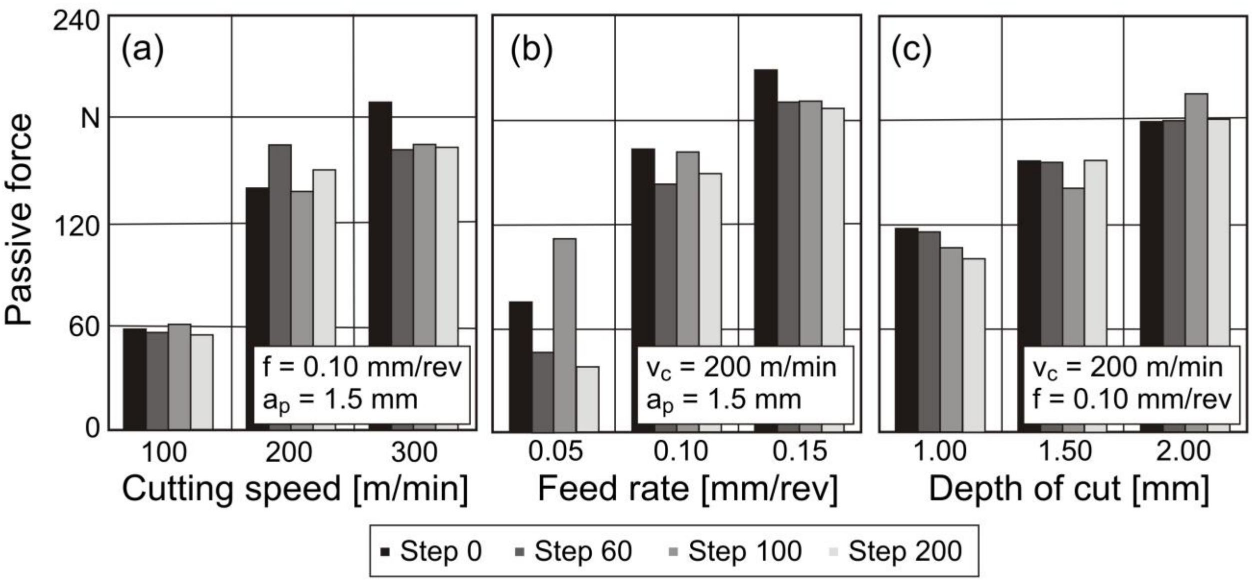


Figure 9. Effect of: (a) cutting speed, (b) feed rate, (c) depth of cut and chamfer texture on passive force when turning GG30 gray cast iron using MQL

Finally, a comparison on the influence of the cutting enviroment (dry or under MQL) was carried out for the intermediate cutting condition (v_c = 200 m/min, f = 0.10 mm/rev and a_p = 1.50 mm). These results are not presented for the sake of conciseness, nevertheless, they indicate that MQL promotes larger scatter in the data recorded for all edge preparations. In adddition to that, the minimum cutting, feed and passive forces are allways lower under MQL.

5. CONCLUSIONS

Tungsten carbide inserts were ground and had their chamfers laser textured under distinct conditions (different dimples spacing). After conducting turning test on GG30 gray cast iron without cutting fluid and employing minimal quantity lubrication and assessing the behavior of the turning force components, the following conclusions can be drawn:

- The cutting, feed and passive forces increased with the elevation of cutting speed, feed rate and depth of cut. The unexpected influence of cutting speed was attributed to the brittle nature of the material (leading to fracture instead of softening by shearing) associated with the highly negative effective rake angle, which did not allow a reduction in the contact length between chip and rake face as cutting speed was elevated. The increase in the force components with feed rate and depth of cut can be explained by the elevation of the shear plane area;
- When dry turning at lowest cutting speed, feed rate and depth of cut, the higher the dimples spacing, the lower the force values. As the cutting parameters were elevated, the effect of texturing in reducing the turning force components was diminished;
- Using MQL, the beneficial influence of chamfer texturing on the reduction of the force components is more evident, with lower forces recorded for dimple spacing value of 200 μm;
- Comparing the forces obtained when dry cutting and turning with MQL, it can be noticed that the former promoted less scatter in the data collected during each test;
- In general, the combination of tools with textured chamfer (spacing with step of 200 μm) and cutting with MQL at lower and moderate material removal rates resulted in the reduction of the turning force components;
- Reducing the dimples spacing did not promote a reduction in the cutting, feed or passive force, thus indicating that the ability to reduce friction and the contact area between chip and rake face cannot be solely associated to the volume available for fluid retention.

6. ACKNOWLEDGEMENTS

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