MILLING OF ANNEALED AND HARDENED TOOL STEEL WITH COATED CARBIDE AND CERMET INSERTS

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Abstract. *This paper is concerned with the machinability of VHSuper tool steel in both annealed (174 HV) and hardened (47 HRC) conditions, when subjected to up face milling using three cutting tool grades (two carbide grades coated with TiN+TiCN and TiN+TiCN+*Al_2O_3 *and one uncoated cermet). In addition to tooling and work material hardness, the effect of cutting speed and feed rate per tooth was assessed. Tool life, wear mechanisms and machined surface quality were evaluated. The results indicated that when milling the annealed material the TiN+TiCN+*Al_2O_3 *coated carbide presented longer tool life, whereas when cutting the hardened steel the TiN+TiCN coated carbide was superior. In both cases the cermet gave intermediate results The principal acting wear mechanisms varied with work and tool materials. Surface finish deteriorated as feed rate was increased and significant differences between the tool materials were not observed.*

Keywords*: milling, tool steel, coated carbide, cermet.*

1. INTRODUCTION

Milling of hardened steels, especially tool steels, has gained increasing interest owing to the fact that machining time, and consequently costs, associated to the production of dies and moulds represent a considerable fraction of the total die/mould manufacturing cost. Therefore, the use of technologies such as advanced CAD/CAM systems and high speed machining has been intensively investigated. For instance, the selection of the most appropriate cutter path strategy for milling cavities is critical not only to assure the required surface finish and tolerances, but also to promote best tool performance. According to Toh (2004a), there are three principal tool path strategies: offset milling (the cutter starts from the periphery and moves inwards), raster milling (alternating down and up milling) and single direction raster milling (either down or up milling). These approaches differ substantially in machining time and machined surface quality, nevertheless, Toh (2004b) asserts that raster milling in the most suitable when rough milling hardened steels due to high metal removal rate and low machining time.

With regard to tool wear, Koshy et al. (2002) state that when milling AISI D2 and H13 die steels with coated carbide the principal wear mechanisms observed are chipping and adhesion, whereas when using polycrystalline cubic boron nitride (PCBN) tools tool fracture is principal factor limiting tool life.

According to Ghani et al. (2004), the principal parameters affecting tool life when milling AISI H13 tool steel with ISO grade P10 coated carbide tools are feed rate and depth of cut, whereas cutting speed presented a negligible influence. Apparently, when employing high feed rate and depth of cut values the inserts are subjected to higher mechanical loading, thus resulting in cracks which accelerate tool failure. In contrast, increasing cutting speed results in higher temperatures, which represent a smaller contribution to the reduction in tool life.

The number of teeth per cutter is another aspect deserving investigation. Although increasing the number of teeth allows higher metal removal rates owing to the higher feed speed, Richetti et al. (2004) report that the higher the number of teeth, the higher the flank wear land, probably due to the higher temperatures generated.

The heat produced by plastic deformation due to cutting and the correspondent increase in temperature is critical for both the surface integrity of the machined part and tool strength. When machining hardened steel higher temperatures are expected and therefore, special attention must be paid to the cutting temperature. The selection of inappropriate machining parameters for milling hardened tool steels may result in temperatures high enough to promote the surface annealing of the component, thus reducing its service life.

Wang and Zheng (2003) investigated the influence of the work material hardness on machining forces and surface finish when ball end milling AISI H13 tool steel hardened to 20 and 41 HRC with coated carbide tools. The findings indicated that as far as the surface finish is concerned, best results were obtained milling the harder material, irrespectively of the cutting speed used. When the softer workpiece was milled, built-up edge was observed at lower cutting speeds. In addition to that, higher milling forces were recorded when machining the softer material, probably due to the higher plastic deformation in the primary shear plane and higher contact area.

The changes in the milling forces due to the variation in the undeformed chip thickness result in tool deflection, which in turn will impair surface finish and dimensional tolerances, especially when end milling. Machined surface quality and dimensional accuracy are strongly dependent on tool diameter and length. Reducing depth and width of cut also promote lower forces and tool deflection, particularly when milling corners of cavities. In contrast, Liu et al. (2002) report that the forces on the transversal and longitudinal feed directions increase almost linearly with feed rate and width of cut.

The complexity of the milling operation results in an unexpected behaviour of the force components (Ko et al., 2002). Therefore, the judicious selection of the most appropriate machining parameters is required in order to ensure minimal tool deflection through the reduction of the the width of cut when machining corners (Law et al., 1999). Mathematical and numerical models capable of predicting the static and dynamic deflections of the tool have been proposed by Kim et al. (2003) and Xu et al. (2003). The latter assert that the dynamic deflection may be neglected. Machine tool vibrations should also been monitored (Fofana, 2003). The analysis of the milling forces behaviour provides information on excessive or undesired vibrations, which make the operation unstable and impair the machined surface quality.

Finally, the principal aim of this work is to assess the machinability of VHSuper tool steel in both annealed and hardened condition when up milling with coated carbide and cermet cutting tools. This evaluation will be carried out in terms of tool life, wear mechanisms and surface finish.

2. EXPERIMENTAL PROCEDURE

Bars of VHSuper tool steel (equivalent to AISI H13 hot work die steel) were tested as work material; one lot was tested in the annealed condition (average hardness of 174 HB) and the other after quenching and tempering to reach an average hardness of 47 HRC. Three cutting tool grades were tested, all of them supplied by Sandvik Coromant: GC 1025 (TiN + TiCN coated carbide ISO grade P10), GC 4040 (TiN + TiCN + Al_2O_3 coated carbide ISO grade P40) and CT 530 (cermet ISO grade P20). The inserts had geometry R300-1032E-PM and they were mounted on a cutter code R300-25T12-10M.

The experimental work was conducted on a machining centre with 9 kW power and 7500 rpm maximum rotational speed. Tool wear was measured with a toolmaker's microscope equipped with micrometer with 0.01mm resolution and a tool life criterion of average flank wear VB_1=0.5 mm was used (ISO 8688-1, 1989). Photographs of the cutting tools used under selected machining conditions were taken with a scanning electron microscope (SEM). The surface roughness parameter R_z was assessed with a portable roughness meter with a stylus radius of 5 µm and adjusted to a cut-off of 0.8mm.

Dry up milling tests were carried out employing distinct cutting parameters for both materials: for the annealed tool steel, cutting speeds (v_c) of 300 - 370 and 440 $m.min^{-1}$ and feed rates (f_z) of 0.10 – 0.15 – 0.20 and 0.25 mm/tooth were used; for the hardened samples, cutting speeds of 120 - 200 and 280 $m.min^{-1}$ and feed rates of 0.10 – 0.15 and 0.20 mm/tooth were tested. The depth and width of cut were kept constant (a_p=0.5 mm and a_e=12.5 mm, respectively) throughout the experimental work.

3. RESULTS AND DISCUSSION

Firstly, the results concerning the annealed tool steel are presented, followed by the hardened tool steel findings.

3.1 Annealed VHSuper tool steel

The effect of cutting speed on tool life (for a constant feed rate of 0.15 mm/tooth) is given in Fig. 1. It can be seen that tool life is reduced as cutting speed is elevated, owing to the fact that higher cutting speeds promote higher temperatures in the cutting zone, which accelerate thermally activated wear mechanisms. Best results (longer tool lives) were obtained when milling with GC 4040 coated carbide, followed by the CT 530 cermet and GC 1025 coated carbide. The superior performance of the GC 4040 tool may be associated to the alumina layer, which possesses lower chemical solubility compared to the other coating materials. Moreover, the use of medium temperature CVD technique results in cutting tools less prone to fracturing. On the other hand, the cermet presents high hardness but low thermal conductivity and high thermal expansion coefficient, which results in cracks and, consequently, in tool failure when subjected to alternating mechanical and thermal loadings.

Figure 2 shows the influence of feed rate on tool life for the three tool grades, using a cutting speed of 370 $m.min^{-1}$. In this case it can be noted that within the cutting range tested, tool life increased with feed rate. Again, longer tool life results were provided by the GC 4040 tool, followed by the CT 530 and GC 1025. The increase in tool life as the feed rate is elevated can be explained by the fact that lower feed rate values result in higher effective contact length between tool and work material. However, the cutting edge must bear the stresses imposed without fracturing. Additionally, the cutting tool action promotes the work hardening of the surface layers of the workpiece, thus, using higher the feed rate, the tool cuts a material which has not been work hardened.

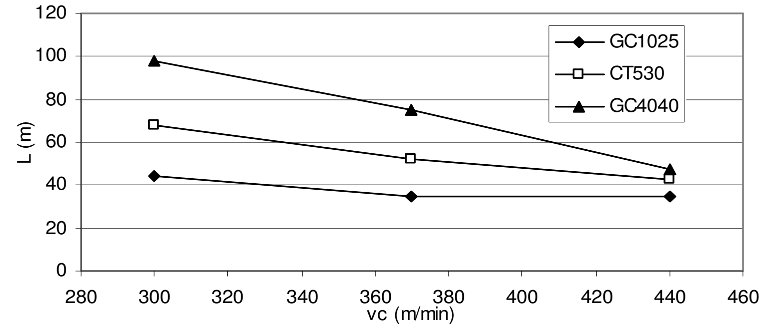


Figure 1. Effect of cutting speed on tool life for a constant feed rate of 0.15 mm/tooth (annealed tool steel).

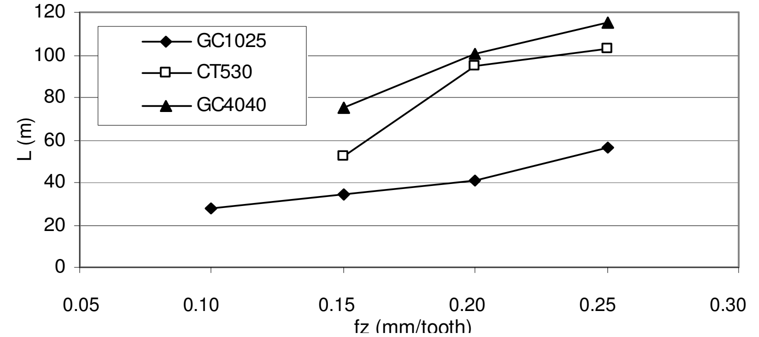
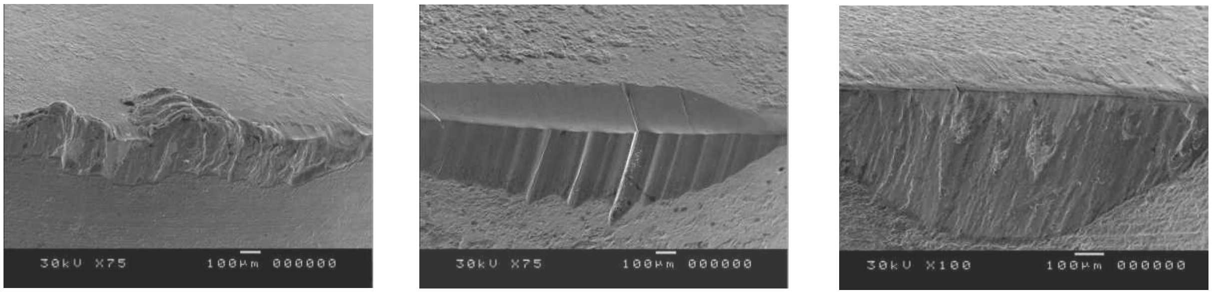


Figure 2. Effect of feed rate on tool life for a constant cutting speed of 370 m.min^{-1} (annealed tool steel).

Figure 3 shows SEM photographs of the wedges (rake and clearance faces) of the three cutting tool materials after reaching the tool life criterion of VB_1=0.5mm. Quite distinctive wear features can be noted in these photographs. Figure 5a shows that when milling with GC 1025 coated carbide at v_c=370 m.min^{-1} and f_z=0.2mm/tooth, after a cutting length of L=40.9 m adhesion of the work material is evident, indicating that the absence of the Al_2O_3 coating is rather detrimental to the performance of the cutting tool. Tool CT 530 is presented in Fig. 5b after milling L=102.5 m at v_c=370 m.min^{-1} and f_z=0.25 mm/tooth. In this case, cracks can be observed in the rake face and clearance faces, suggestive of low thermal shock resistance. Finally, Fig. 5c shows tool GC 4040 carbide after milling using the same parameters as tool GCT 530 for L=114.7 m. It can be seen that gradual wear took place, without evidence of fracture and work material adhesion, thus indicating that diffusion may be the principal wear mechanism involved.



(a) GC 1025
(v_c=370 m.min^{-1}; f_z=0.2 mm/tooth)

(b) CT530
(v_c=370 m.min^{-1}; f_z=0.25 mm/tooth)

(c) GC 4040
(v_c=370 m.min^{-1}; f_z=0.25 mm/tooth)

Figure 3. SEM photographs of the cutting wedges after milling annealed tool steel: (a) GC 1025 coated carbide, (b) CT 530 cermet and (c) GC 4040 coated carbide.

Figures 4 and 5 show, respectively, the influence of the cutting length o the surface roughness value (R_z parameter) for the tools CT 530 and GC 4040 and using the intermediate cutting speed value. The results concerning tool grade GC 1025 are not presented owing to the fact that this tool material provided the poorest tool life performance. Observing Fig. 4 it can be noticed that surface roughness increases with feed rate (due to the increase in the feed marks depth) and cutting length (due to the cutting edge deterioration). However, when the lowest feed rate value is employed, the influence of tool wear seems to be insignificant compared to feed rates of 0.20 and 0.25 mm/tooth. Moreover, comparing Fig. 4 and 5 one can note that the surface roughness values produce by tool grades CT 530 and GC 4040 are in the same ballpark, in spite of the fact that tool GC 4040 presented superior wear resistance and, therefore, it would be expected to produce better surface finish.

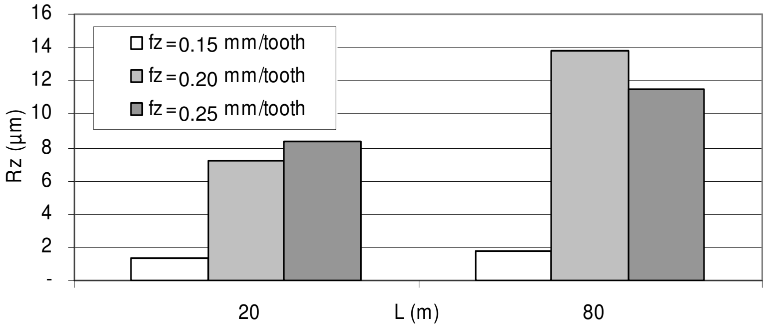


Figure 4. Effect of cutting length on surface roughness for tool CT 530 for a constant cutting speed of 370 m.min^{-1} (annealed tool steel).

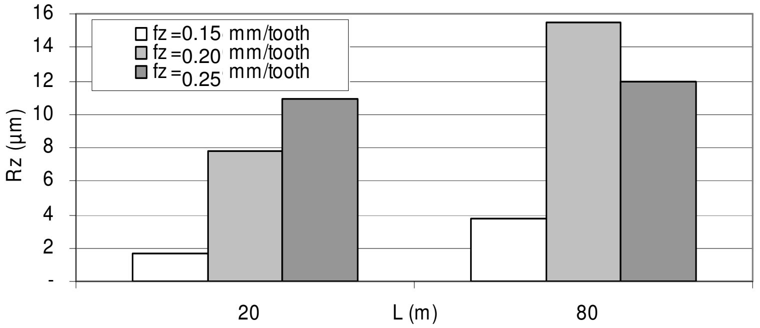


Figure 5. Effect of cutting length on surface roughness for tool GC4040 for a constant cutting speed of 370 m.min^{-1} (annealed tool steel).

3.2 Hardened VHSuper tool steel

Figures 6 and 7 show, respectively, the influence of cutting speed and feed rate on tool life when up face milling hardened VHSuper tool steel. Similarly to Fig. 1, as cutting speed is elevated tool life is reduced, see Fig. 6. Nevertheless, in contrast to Fig. 2, when milling the hardened tool steel an increase in feed rate results in lowering tool life (Fig. 7). Interesting, an inversion on the behaviour of the three cutting tool grades are observed, i.e., tool GC 1025 (which gave the poorest tool life results when milling the annealed tool steel) outperformed tools CT 530 and GC 4040 when hard milling.

The wedges of the three cutting tools after reaching VB_1=0.5 mm can be seen in Fig. 8. In this case the machining parameters employed were cutting speed of 120 m.min^{-1} and feed rate of 0.1 mm/tooth. Increasing the work material hardness resulted in distinct wear mechanisms compared to the annealed tool steel. Figure 8a shows a groove on the rake face (probably caused by the swarf) and a uniform wear pattern after milling for a cutting length of L=73. 9 m. In contrast, tools CT 530 (Fig. 8b) and GC 4040 (Fig. 8c) show evidence of chipping after L=42.7 m and L=13.4 m, respectively. These photographs suggest that when the hardness of the workpiece is elevated its toughness is reduced and therefore, the tool-chip contact length is reduced minimizing the efficiency of the coatings. In opposition to that, the substrate plays a critical role, i.e., tool GC 1025 is harder than GC 4040 (ISO grade P10 against P40) and the coatings were deposited through physical vapour deposition in the former, which induces compressive residual stresses, whereas tool GC4040 is coated through medium temperature chemical deposition.

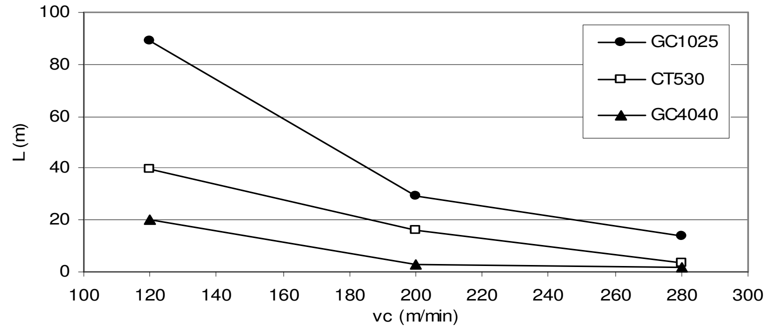


Figure 6. Effect of cutting speed on tool life for a constant feed rate of 0.15 mm/tooth (hardened tool steel).

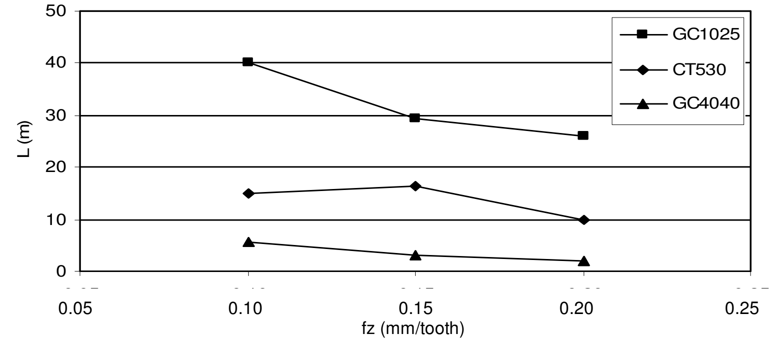
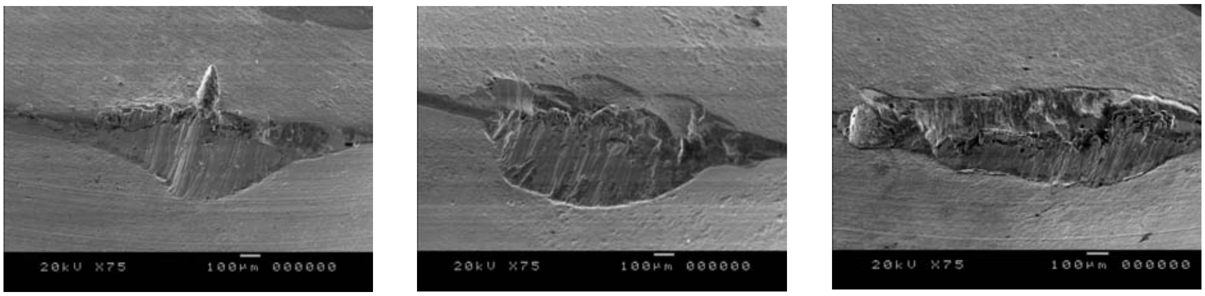


Figure 7. Effect of feed rate on tool life for a constant cutting speed of 200 $m.min^{-1}$ (hardened tool steel).



(a) GC1025 (b) CT530 (c) GC4040

Figure 8. SEM photographs of the cutting wedges after milling hardened tool steel at v_c=120 $m.min^{-1}$ and f_z=0.10 mm/tooth: (a) GC 1025 coated carbide, (b) CT 530 cermet and (c) GC 4040 coated carbide.

Figures 9 and 10 show the roughness of the hardened tool steel surface machined with the tool grades which presented best performance concerning tool life (tools GC 1025 and CT 530, respectively). The R_z values were collected after milling for a cutting length of L=10 m. Observing Figures 9 and 10 it can be noted that the roughness values increase with feed rate and cutting speed. The elevation of R_z with feed rate is attributed to the increase in the feed marks depth, whereas the effect of cutting speed is owing to vibrations of the cutting head at high rotational speeds. Similarly to the results concerning the annealed material, both tool grades provided equivalent R_z values.

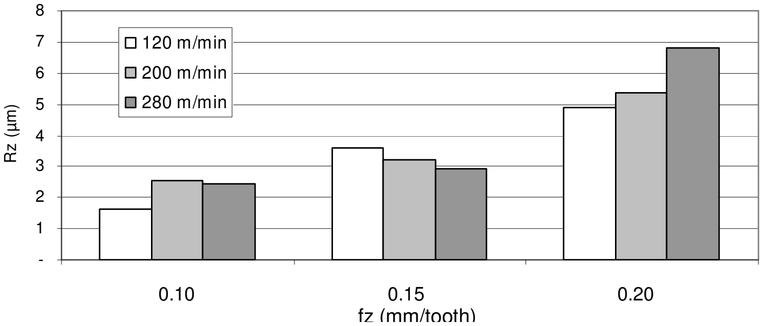


Figure 9. Effect of feed rate and cutting speed on surface roughness for tool GC 1025 (hardened tool steel).

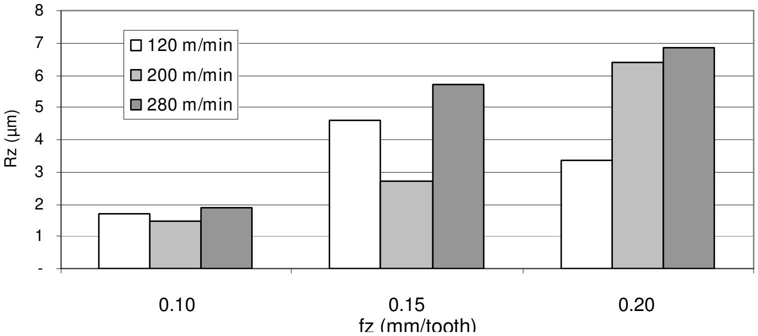


Figure 10. Effect of feed rate and cutting speed on surface roughness for tool CT 530 (hardened tool steel).

4. CONCLUSIONS

After face milling annealed VHSuper tool steel (174 HB) with coated carbide and cermet inserts the following conclusions can be drawn:

- Within the cutting range tested, tool life decreased with cutting speed and increased with feed rate. Longer tool lives were obtained using tool GC 4040 (TiN + TiCN + Al_2O_3 coated carbide) followed by CT 530 (cermet) and GC 1025 (TiCN +TiN coated carbide);
- The principal wear mechanism observed were diffusion (tool GC 4040), cracks (tool CT 530) and adhesion (tool GC 1025);
- The surface roughness values increased with feed rate and cutting length (tool wear) and no appreciable differences in the R_z values were observed for the tools tested.

With regard to milling hardened VHSuper tool steel (47 HRC) the following conclusions can be extracted:

- In contrast to the annealed steel, tool life decrease as both cutting speed and feed rate were elevated. Moreover, tool GC 1025 was responsible for longer tool lives, followed by CT 530 and GC 4040;
- SEM photographs of worn cutting wedges suggest that the presence of the coatings does alter the wear mechanisms involved. Furthermore, the hardness of the substrate seems to possess a more relevant role;
- The R_z values increased with feed rate and cutting speed and significant differences between the tools were not recorded.

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