HIGH-SPEED CUTTING AFFECTS THE WORKPIECE INTEGRITY SURFACE

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Abstract. *This work determined the influence of the milling conditions on the microstructure and microhardness of the workpiece. A low carbon steel 0.15%C (200 HV) was machined. Eight different machining conditions were carried out varying cutting speed, feed per tooth, and depth of cut for using the Analysis of Variance (ANOVA), highlighting the machining considered as high-speed cutting (HSC) and another assumed as conventional one. The dry end down milling tests were carried out in a CNC machining center of 11 kW power and 7,500 rpm maximum spindle speed. A 25 mm diameter endmill with two carbide inserts coated with* Al_2O_3 *was used. The results indicated an influence of the machining conditions on response variables. Higher cutting speeds and depths of cut caused deformation of the material's microstructure near the milled surface. The same parameters increased the microhardness and depth of the hardened layer.*

Keywords*: milling, high-speed cutting, surface integrity, low carbon steel*

1. INTRODUCTION

High-Speed Cutting (HSC) can be understood when cutting speed is elevated above a certain critical value intrinsic to each kind of workpiece material in which segmented chips are formed (Flom and Komanduri, 1989). This technique has been useful in aeronautical and molds industries to produce dimensionally precise parts (Brandão *et al*., 2008). Some advantages assumed for HSC such as decrease of temperatures and forces can be decisive for workpiece surface integrity. Despite these supposed benefits, many scientific results are still contradictory mainly about part surface integrity (Rodrigues *et al*. 2010).

When applying manufacturing processes, depending on how the material removal occurs, e. g. involving high shear rates, the machined parts may present changes or damages in their texture caused by manufacturing. Surface Integrity is defined as a set of changes on the surface of parts caused by the manufacturing process. Thus, surface changes were initially classified by the mechanical nature (plastic deformation, cracks, changes in hardness, and residual stress), metallurgical nature (phase transformations, grains size, and recrystallization), and chemical nature (intragranular etching, intragranular corrosion, intragranular oxidation, contamination), among other types of transformations (Becker, Santos e Sales, 2005). Field *et al*. (1989) also mention the changes of thermal nature (heat affected zone, material resolidification, and material remelting), and electrical nature (change in conductivity, magnetic shift).

Machining processes may induce changes in the microstructure. The microstructure is related to the mechanical, physical and chemical properties of the part, and a change may result in loss of performance in any of these properties, which is undesirable for product quality. The plastic deformations are revealed as a microstructure elongation near the surface, toward the deformation flow generated by the shear, characterizing changes in microhardness due to resulting strain hardening. In most cases, these changes occur due to the action of the tool cutting edge on the workpiece. This layer, where there is the possibility of transformations, usually is only about 75 µm deep (Field *et al*. 1989).

This work determined the influence of cutting speed, depth of cut and feed per tooth on the workpiece microstructure and microhardness of a 0.15%C steel.

2. EXPERIMENTAL PROCEDURE

Machining tests were carried out in a vertical CNC machining center ROMI Discovery 560 adopting end down-milling and dry condition. Scanning electron microscopy (SEM) Philips XL 30 TMP was used for evaluation of the cross section's microstructure of the milled surface. Microhardness measurements were done in the Shimadzu ultra-microhardness tester DUH-211.

Table 1 shows the input variables (control factors) and the respective number of variations (levels). It is important to note that the cutting parameters were adopted according to a 2^3 factorial design, whose purpose was to evaluate the isolated effect of the cutting parameters, having as extreme conditions: roughing (conventional machining) and finishing (HSC machining). All quantitative results were statistically treated considering a 5% significance level.

Table 1. Input variables and levels adopted in machining tests.

Machining Parameters	Levels	Machining Conditions							
		C1	C2	C3	C4 (1)	C5 (1)	C6	C7	C8
Cutting speed [m/min]	100 / 600	100	100	100	100	600	600	600	600
Depth of cut [mm]	0.5 / 3.0	0.5	0.5	3.0	3.0	0.5	0.5	3.0	3.0
Feed per tooth [mm/tooth]	0.05 / 0.20	0.05	0.20	0.05	0.20	0.05	0.20	0.05	0.20

(1) Condition adopted as conventional (C4) and HSC (C5).

The workpiece material named as COS AR 60 was supplied by Usiminas-Cubatão S/A. According to the supplier, the workpiece material is a low-carbon steel 0.15%C with 200 HV hardness, 630 MPa tensile strength, 530 MPa yield strength, 26% elongation, and 176 J Charpy energy at 0° C. The chemical specification of workpiece material is given in Tab. 2.

Table 2. Chemical specification of the material used in the machining tests (% in weight).

C	Mn	P	S	Si	Al	Cu	Cr	Ni	Nb	V	Ti	Ceq
0.15	1.49	0.027	0.009	0.27	0.046	0.005	0.276	0.008	0.048	0.044	0.016	0.40

The tests were carried out with two carbide inserts coded R390-11 T3 08M-PM GC 4220, ISO P15 grade and Al_2O_3 coating from Sandvik Coromant. A tool-holder coded R390-025A25-11L for 25 mm diameter endmill from de same tool supplier was also used. The tool path in machining tests was linear (y-direction) in order to mill in 8 passes (2 mm radial depth) a workpiece area (xy) of 16 x 100 mm. Figure 1 shows the experimental setup.

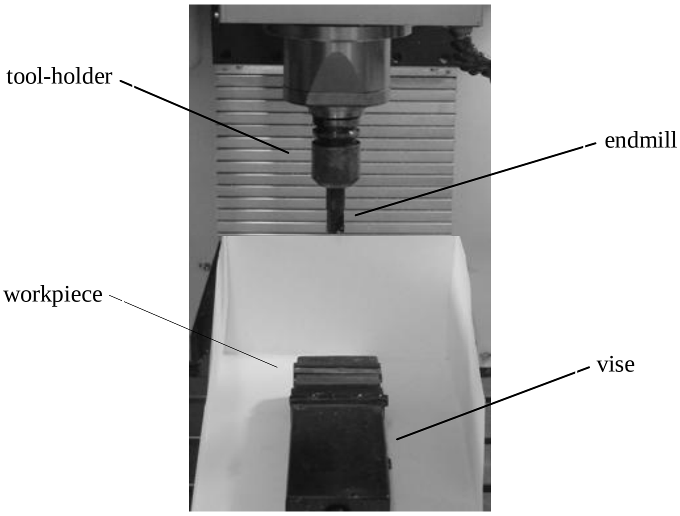

Figure 1. Experimental setup for milling tests.

For microstructural and microhardness analyses after machining, the milled workpieces were cross-sectionally cut, cupped in Bakelite and sanded with 120, 220, 400, 600 and 1000 mesh. After, the specimens were polished with aluminum oxide (1 and 0.3 μm), diamond past (0.25 μm) and etched using reagent Nital 2% by 5 s.

The microhardness measurements were determined according to the ISO standard 14577-1 using the dynamic hardness scale Martens (HM) with Vickers indenter and 20 mN (2 gf) load. The loading-unloading method was chosen and room temperature was controlled (20.8 ± 1.5 °C).

For assuring low variability of measurements, microhardness indentations were done inside ferrite grains only. In addition, four repetitions for each of the eight measurements were considered, whose indentations spaced 20 μm from each other, initiating at 5 μm from border (milled surface) and reaching 145 μm of total depth.

3. RESULTS AND DISCUSSION

3.1. Microstructure

SEM images were chosen to represent groups of conditions where there is only variation of feed, because there was no significant influence of feed on the microstructure deformation near milled surface, but only an increase in cutting speed and depth of cut was the most influential in the deformation. This fact can be proved by microhardness measures presented in next subsection, in which will be showed statistically the non-influence of feed in the increase of the microhardness or the affected layer (hardened by machining).

Figure 2a shows a milled surface not affected by cutting parameters, because strain lines towards feed direction are not observed. Thus, the cutting parameters from conditions C1 and C2 were not able to cause deformations in a noticeable layer of machined surface.

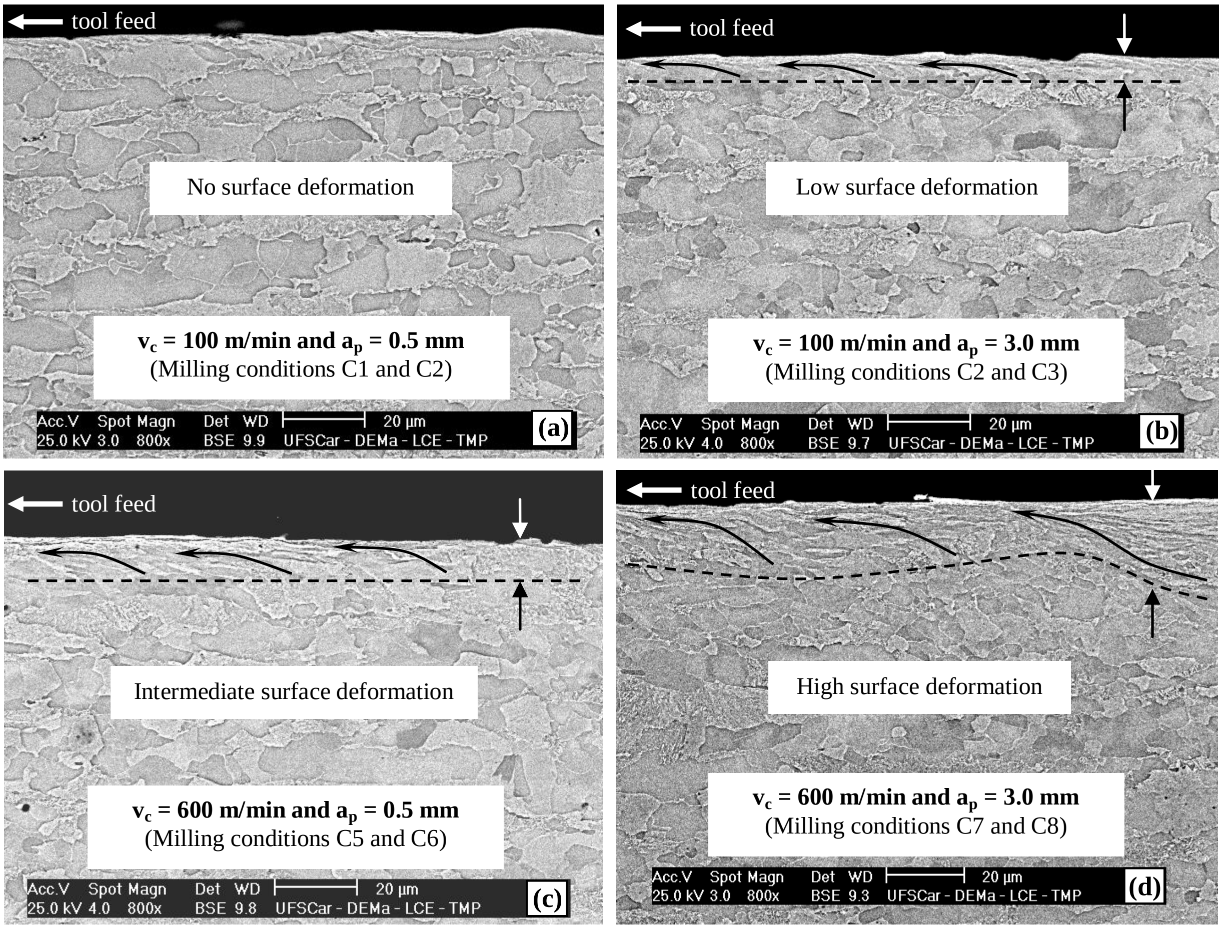

Figure 2. Representative microstructure of the machined border.

Figure 2b shows a deformation pattern of the grains located at the machined border. This effect may be associated to the increase of the depth of cut. This deformation is due to the increase of the cutting force, which in turn depended mainly on the depth of cut, by which exceeded the yield strength causing plastic deformation.

In Figure 2c, the region next to the milled surface with higher cutting speed presented grain deformation due to the high shear rate.

For extreme cutting conditions, a combined effect between higher cutting speed and depth of cut took place since a significant deformation of the grains near the surface can be clearly seen (Fig. 2d).

The images whose deformations were noted show direct effect on the surface and subsurface microhardness of the workpiece, because generated strain hardening and, consequently, raised the hardness of the ferrite grains. The difference of the deformation levels is related to the feed movement of the tool, since the more pronounced deformations occurred in that direction.

3.2. Microhardness

The graphs in Figure 3 show the microhardness profiles only for conditions C4 ad C5 since these two graphs represent the set of curves from other machining conditions. To better visualize the effect of the cutting parameters, the graphs are presented with trend lines, showing clearly two distinct regions i.e. layer affected by milling (slope line) and steady level of the workpiece bulk (horizontal line).

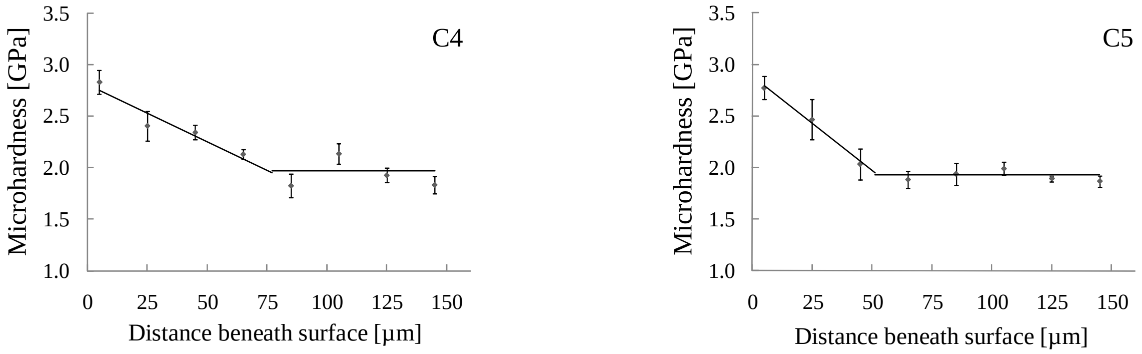

Figure 3. Microhardness profiles of samples machined in condition C4 and C5.

Microhardness profiles presented low scattering when considering the points at the same depth. The linear increase of microhardness was more and/or less pronounced as a consequence of cutting parameters. In general, the increase of cutting speed elevated the microhardness when comparing the conditions C1/C5, C2/C6, C3/C7, and C4/C8. The feed per tooth did not influence statistically on microhardness (C1/C2, C3/C4, C5/C6, and C7/C8) as well as depth of cut, but it was decisive in the affected layer (C1/C3, C2/C4, C5/C7, and C6/C8). This result is in accordance to the Fig. 2d, and Fig. 3 (C4), where microhardness variation was deeper. In order to have statistical validation for abovementioned conclusions, ANOVA table is shown in Tab. 3.

Table 3. ANOVA table for the increase of microhardness and affected layer.

Factor	DF	Increase in Microhardness [GPa]				Affected Layer [µm]			
		SS	MS	F	P	SS	MS	F	P
Cutting speed	1	0.20070	0.20070	5.88	0.032	229.7	229.7	2.50	0.140
Feed per tooth	1	0.00109	0.00109	0.03	0.861	3.0	3.0	0.03	0.860
Depth of cut	1	0.00689	0.00689	0.20	0.661	4542.8	4542.8	49.48	0.000
Error	12	0.40974	0.03414			1101.8	91.8		
Total	15	0.61842				5877.2			

DF: Degrees of Freedom; SS: Sum of Squares; MS: Mean Square; F: Test F; P: Probability.

By applying ANOVA, the cutting speed was significant in increase of the microhardness, since the P-Probability was lower than the 5% significance level. On the other hand, the depth of cut increased the affected layer and the other parameters did not cause significant differences in the affected layer. Figures 4 and 5 also allow evaluating the behavior of the control factors as main effects acting upon the increase of microhardness and layer affected.

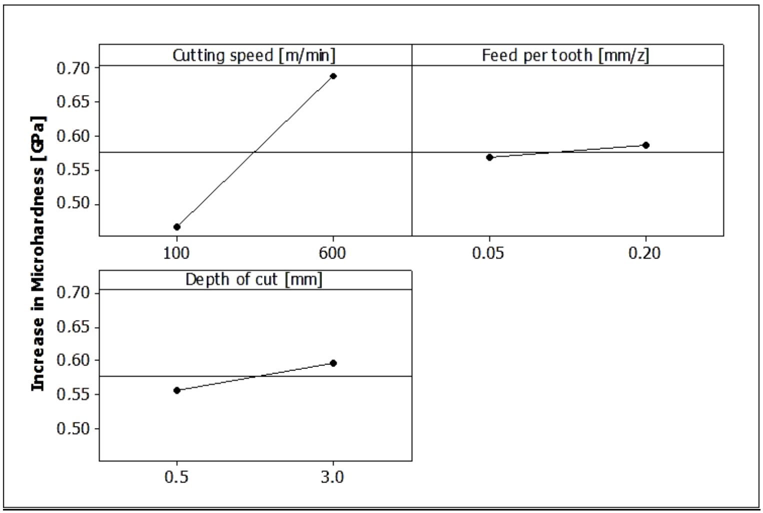

Figure 4. Isolated control factors over the increase in microhardness.

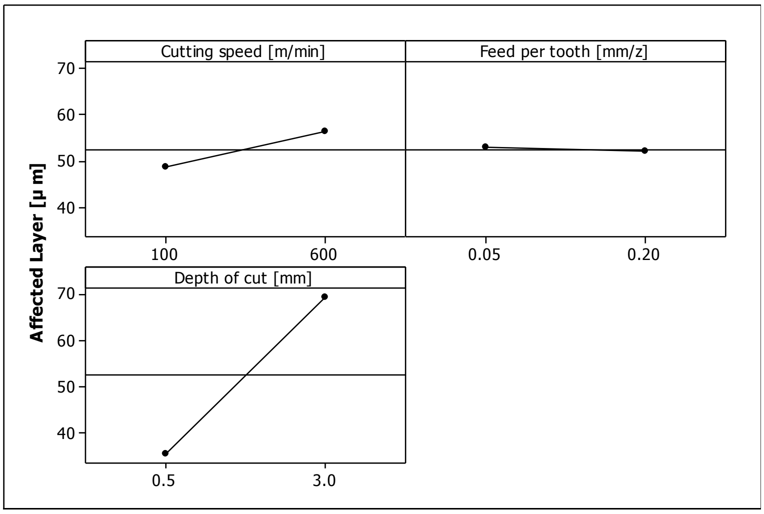

Figure 5. Isolated control factors over the increase in affected layer.

The qualitative ANOVA analysis of a control factor over the response is based on the factor variation around the average. It is observed that the cutting speed in Figure 4 and the depth of cut in Figure 5 were the parameters that had the higher variation around their average, pointing that they were the most influent factors, ratified in the ANOVA table by the P-Probability (< 5%). It can also be noted that the increase of these variables leads to an increase of responses, thus, the higher the cutting speed and depth of cut, the greater the increase in microhardness and affected layer, respectively.

4. CONCLUSIONS

The increase in cutting speed and depth of cut caused the deformation of grains near the milled workpiece surface, noted by SEM images. The machining conditions caused an increase of surface and subsurface microhardness in all machined samples. The cutting speed influenced the increase of the microhardness while the depth of cut governed the extent of the layer affected by the increase in microhardness. Due to the differentiated cutting dynamic, given by the increase in cutting speed and reduction in the tool feed and depth of cut, the HSC condition gave better results compared to other milling conditions. Therefore, cutting parameters are decisive on the surface integrity of the product.

5. ACKNOWLEDGEMENTS

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7. STATEMENT OF RESPONSIBILITY

The authors are solely responsible for the material contained in this article.