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EFFECTS OF MICROMILLING ON MICROHARDNESS AND SPECIFIC CUTTING ENERGY OF ABNT 1045 STEEL

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***Abstract**. This study quantified the influence of the feed per tooth (f) and depth of cut (d_c) on microhardness and specific cutting energy aiming at evaluating the size effect when milling ABNT 1045 steel. The experiments were carried out in a CNC machining center Hermle C800U by adopting simultaneously up/downmilling (slots milling) and no coolant application. 0.8 and 2.0 mm diameter endmills (two flutes) coated with TiAlN were used in tests for micro and macromilling, respectively. Analysis of Variance (ANOVA) allowed determining statistical significances of control factors on response variables. Under the standpoint of workpiece material, the results indicated that the microscale milling caused more size effect than macromilling because reached higher surface microhardness and hardened layer beneath the machined workpiece. However, neither milling conditions nor cutting parameters presented significant differences for both the machining scales. Specific cutting energy depended strongly on cutting parameters and milling conditions mainly in microscale machining. Feed per tooth and depth of cut presented correlation inversely proportional to the specific cutting energy with statistical prevalence of the first over the second.*

***Keywords:** micromilling, microhardness, specific cutting energy, size effect.*

1. INTRODUCTION

The evolution of the technology and manufacturing processes demanded production of miniaturized components in different industry areas, such as automotive, medical, biotechnology, telecommunications, electronics and optics. The miniaturization process aimed to produce micro components with new applications, good performance and high quality, requiring production methods that have reliability and repeatability (Madou, 2002; Chae *et al.* 2006; Dornfeld *et al.* 2006; Câmara *et al.*, 2012; Komatsu *et al.*, 2012). The mechanical micromachining, performed by cutting, has become a good option by using miniaturized cutting tools to promote material removal with good accuracy and surface finish.

Micromilling enables to produce micro components in 3D form with high geometrical complexity in a wide variety of metallic and non-metallic materials, such as polymers and ceramics (Alting *et al.*, 2003; Câmara *et al.*, 2012). However, as the chip volume decreases, the cutting thickness (h) may be compared to the tool edge radius size. As a result, cutting takes place with a highly negative tool rake angle (Bissaco *et al.*, 2005) and the relationship between the cutting thickness and tool edge radius will set the chip removal mechanism.

Chae *et al.* (2006) introduced the concept of minimum chip thickness (h_{min}), whereby the chip will not form unless the cutting thickness is greater than h_{min}. When the cutting thickness is smaller than h_{min}, the part material is subjected to an elastic-plastic deformation (plowing) without effective material removal. As the cutting thickness matches and exceeds h_{min}, plowing decreases considerably and chips are formed completely.

This chip formation mechanism causes the named size effect, a phenomenon characterized by the substantial increase of the specific cutting energy for machining processes with small cutting thicknesses, a reflection of the

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increase in part shear flow stress due to the cutting zone decreasing (Simoneau *et al.*, 2006). According to Liu *et al.* (2004), this phenomenon affects significantly on cutting forces and surface finishing of workpieces. As a result, several studies have been conducted to understand the size effect, investigating the tool edge radius influence on chip formation, and forces and specific cutting energy involved in micromachining operations to ensure that cutting will occur without damage to workpiece surface integrity.

Therefore, the objective of this paper is evaluate the overall effect of machining conditions and cutting parameters feed per tooth (f) and depth of cut (d_c) on microhardness and specific cutting energy in macro and micromilling of ABNT 1045 steel applied in moulds and dies.

2. EXPERIMENTAL PROCEDURES

The milling tests were carried out in a CNC machining center Hermle C800U without cutting fluid. Cutting speed (v = 60 m/min) was kept constant and the width of cut (w) was equal to diameter (d_t) of the endmill cutter. Feed per tooth (f), depth of cut (d_c) and width of cut (w) were the input variables while microhardness and specific cutting energy (u) were the output ones. Table 1 presents the experimental matrix.

Table 1. Experimental matrix for micro and macroscale milling.

Cutting Parameters	**Micromilling / Microscale ($w = d_t = 0.8$ mm)**				**Macromilling / Macroscale ($w = d_t = 2.0$ mm)**			
	C1	C2	C3	C4 *	C1 *	C2	C3	C4
f [mm/tooth]	0.005	0.010	0.005	0.010	0.010	0.020	0.010	0.020
d_c [mm]	0.080	0.080	0.160	0.160	0.160	0.160	0.320	0.320

* Feed per tooth (f) and depth of cut (d_c) adopted as maximum for micromilling and minimum for macromilling.

Analysis of Variance (ANOVA) was applied by considering three replications for each test and 95% confidence interval. A new tool was used in each milling condition to eliminate the influence of the tool wear on output results. Analyses by using optical and scanning electron microscopy, and energy dispersive spectroscopy (EDS) of chips did not identify tool wear with coating loss and built-up edge.

Carbide endmill tools with TiNAl coating, two flutes and 0.8 and 2.0 mm diameters from Seco Tools were used (920ML008-MEGA-T and 920ML020-MEGA-T). The machining tests were performed in commercial ABNT 1045 steel workpieces with 204 HV hardness ("as received" material). Figure 1 presents the workpiece and the endmill used in the milling tests.

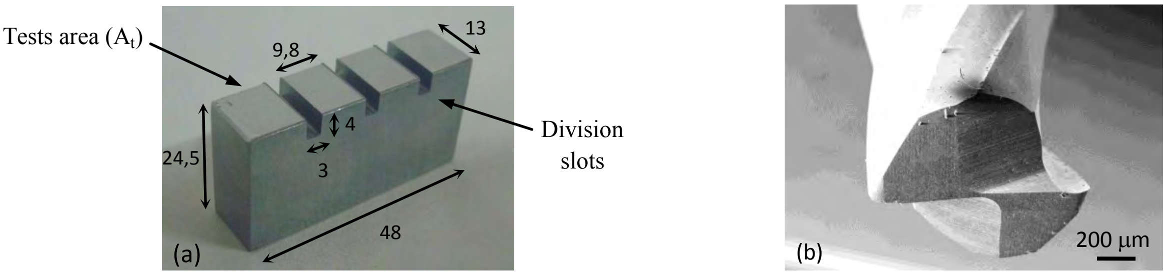

Figure 1. (a) Workpiece geometry for milling tests (millimeters) and (b) endmill.

Microhardness measurements were performed employing a Shimadzu ultra-microhardness tester, DUH-21 model. The microhardness was determined by hardness dynamic Martens scale (HMV) with Vickers indenter, using a 20 mN (2 gf) load. Even using a Vickers indenter, there is not a direct correlation between both Martens and Vickers scales. The Martens hardness includes the plastic and elastic deformation of the material in its measurement and can be calculated for all metallic materials (ISO 14577-1:2002, 2002). Martens scale also allows the use of really small loads, allowing the measurement of the hardness close to the milled surface. Ten replicates for each one of six indentations were made in the cross section of the machined surface, equally spaced, being the first point 10 µm below the machined surface. The following 5 indentations were measured 20 µm equidistant one to another to refine the discretization in a region more susceptible to a microstructural interference. Based on literature and pretests, the total depth evaluated by microhardness was 110 µm.

Specific cutting energy was calculated by numerical integration of cutting force during machining time and multiplied by ratio between cutting speed and removed chip volume (vol = At·dc). The cutting force signals were acquired by using a charge amplifier 5233A and piezoelectric dynamometers 9256C2 and 9257BA from Kistler for micro and macromilling, respectively. Matlab V.7.9.0.529 (R2009b) ™, USB-6216 board and Labview V.7.1 ™ from

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National Instruments were used for post-processing and acquisition of signals by considering a 30 kHz sampling frequency. Figure 2 presents the experimental setup for milling tests.

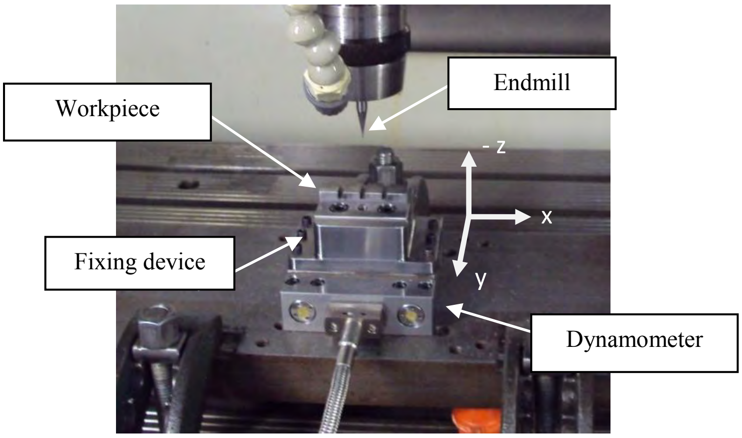

Figure 2. Experimental setup.

3. RESULTS AND DISCUSSION

Figure 3 presents the subsurface microhardness generated after micro and macroscale machining, considering, as comparison, the "as received" (AR) material hardness.

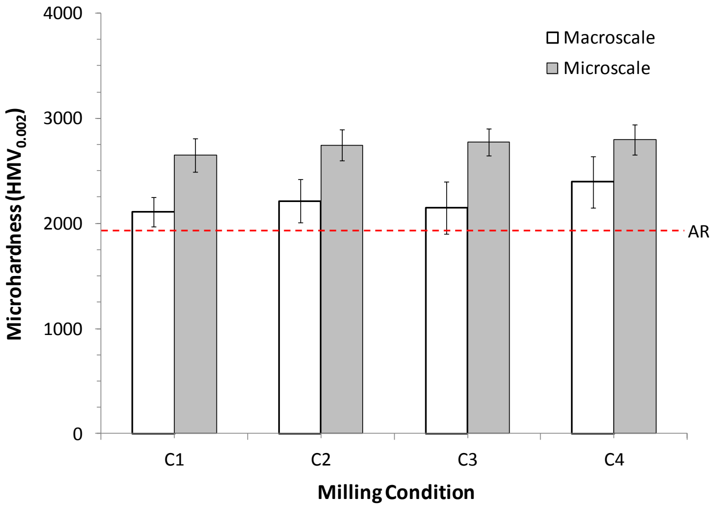

Figure 3. Machining conditions effects on workpiece microhardness next to the milled surface. Indentations performed on the workpiece cross section, 10 µm below the milled surface.

All machining conditions increased the subsurface microhardness, except the condition C3 employed in macroscale machining, since the measurements variability reached the "as received" workpiece material microhardness. Micromilling increased 45.1% on average the microhardness, while the macromilling increased 17.3%, considering "as received" material as the reference. Therefore, micromilling was more significantly to size effect. Despite the high variability associated to the workpiece hardness, there is an indication of increasing on hardness by the increase of the cutting section area (C1 to C4), considering both machining scales.

The ANOVA data shown in Tab. 2 confirm the non-significance of the machining conditions, by analyzing the cutting parameters as control factors on the workpiece subsurface microhardness.

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Table 2. ANOVA of the feed per tooth and depth of cut for microhardness at 10 μm below the milled surface.

Factor	DF	Micromilling				Macromilling			
		SS	MS	F	P	SS	MS	F	P
f	1	10568	10568	1.09	0.323	89840	89840	2.77	0.131
d_c	1	23610	23610	2.44	0.153	36349	36349	1.12	0.318
Error	9	87178	9686			292342	32482		
Total	11	121356				418531			

DF: Degrees of freedom, SS: Sum of squares, MS: Mean square, F: F-Test, P: P-Probability.

None of the factors was significant on microhardness increasing, since the P (P-value) probabilities exceeded the significance level (α = 5%). The ANOVA test was validated by the Kolmogorov-Smirnov Normality Test. Despite the non-significance of the cutting parameters, Fig. 4 shows that the microhardness is directly proportional to the feed per tooth and depth of cut, which confirms the upward trend of microhardness averages shown in Fig. 3, irrespective machining scale employed.

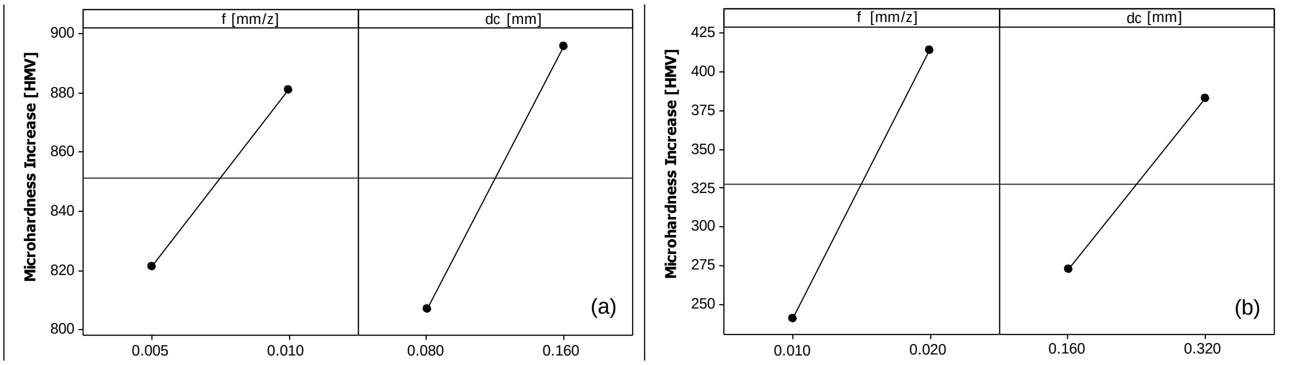

Figure 4. Effect of cutting parameters on workpiece microhardness in (a) microscale and (b) macroscale.

"One-Way" ANOVA was applied to each microhardness measurement to evaluate differences in hardness compared to "as received" material. It can be stated with 95% confidence that the hardening promoted by micromilling reached 50 μm below the machined surface, while macromilling reached only 10 μm. When considering larger depths, there were no statistical differences in relation to “as received” material hardness irrespective scale milling.

The greatest extent of hardened subsurface for the micromilled workpiece (5x) is associated with the size effect and specific cutting energy increase, because lower values of feed per tooth and depth of cut generate deformation forces (plowing) and friction proportionally more representative in relation to the cutting force. Thus, chip formation is hindered due to greater pressure of the tool edge radius on the workpiece material, since the tool edge radius becomes significant compared with the cut thickness, until it reaches the minimum chip thickness.

The dependence of the specific cutting energy on milling conditions and machining scales is shown in Fig. 5.

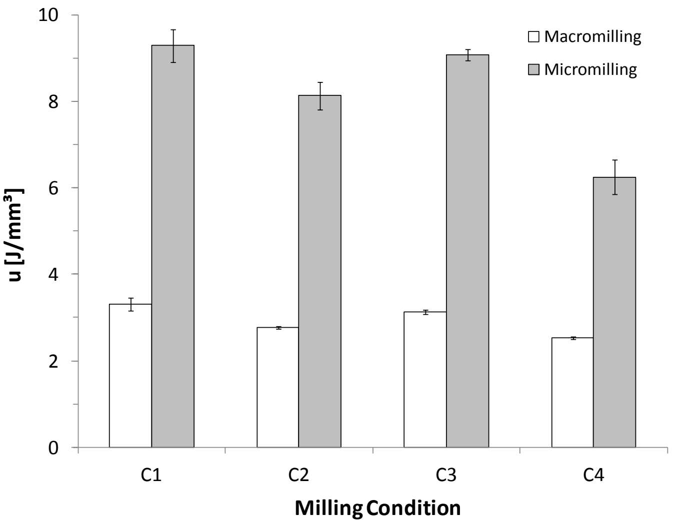

Figure 5. Effect of milling conditions and machining scales on specific cutting energy.

For micromilling, specific cutting energy reduced 22% when feed per tooth doubled. On the other hand, the duplication of depth of cut decreased about 13% the mean specific cutting energy. The same relationships for macromilling attained only 18% and 7%, respectively. Thus, the reduction of specific cutting energy as feed or depth of cut increases (size effect) is more pronounced in micro scale and also more sensible to the feed per tooth.

To validate the distinct sensibilities of feed per tooth (f) and depth of cut (d_c) upon specific cutting energy, Tab. 3 presents the ANOVA data and the Pearson Correlation Coefficient.

Table 3. ANOVA and Pearson Correlation of the feed per tooth and depth of cut upon specific cutting energy.

Factor	DF	Micromilling					Macromilling				
		SS	MS	F	P	PC	SS	MS	F	P	PC
f	1	377.95	377.95	83.01	~0.000	-0.862	0.948	0.948	141.67	~0.000	-0.913
d_c	1	87.71	87.71	19.27	0.002	-0.416	0.129	0.129	19.28	0.002	-0.337
Error	9	40.98	4.55				0.060	0.007			
Total	11	506.63					1.137				

DF: Degrees of freedom, SS: Sum of squares, MS: Mean square, F: F-Test, P: P-Probability, PC: Pearson Coefficient.

The ANOVA proves that feed per tooth and depth of cut are significant upon specific cutting energy for macro and micromilling once P-value was smaller than adopted significance level ($\alpha = 0.05$). This statistical analysis was validated by normality test of Kolmogorov-Smirnov without interaction among control factors. Indicated by the Pearson Coefficient, feed per tooth presents major influence on specific cutting energy than depth of cut and both cutting parameters are inversely proportional to the response, which means that as the control factors increases, the specific cutting energy reduces. Figure 6 shows graphically this effect for micro and macromilling.

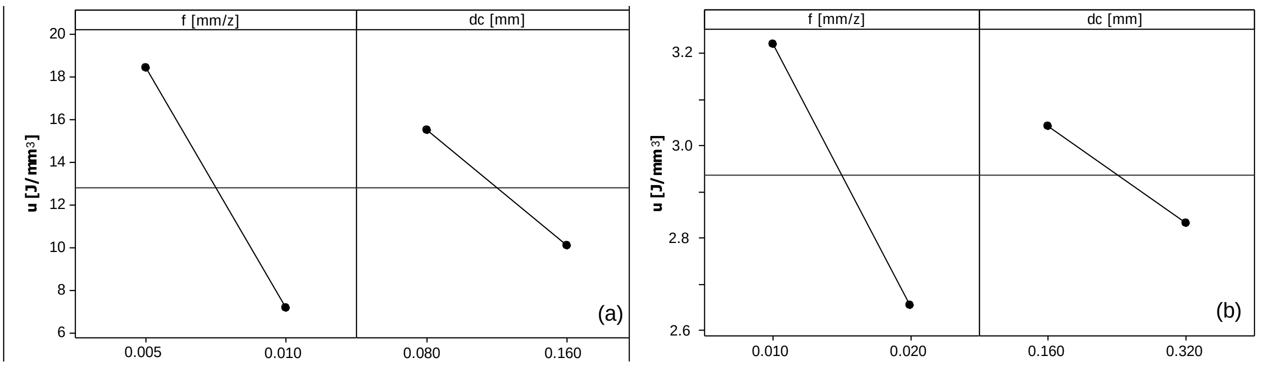

Figure 6. Effect of cutting parameters on specific cutting energy in (a) microscale and (b) macroscale.

4. CONCLUSIONS

The size effect, represented by specific cutting energy, proves to be governed by the mechanism of surface and subsurface hardening in the workpiece, caused by increasing of tensions in the primary shear zone, which is reflected in the workpiece machined surface through the plastic deformation zone around the tool-workpiece contact. The size effect can occur in both macro and microscale machining, but is more pronounced in micromilling, given the reduced cutting parameters feed per tooth and depth of cut, and more influenced by feed per tooth.

5. ACKNOWLEDGEMENTS

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