Effects Of Milling On Surface Integrity Of Low-Carbon Steel

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Abstract. This work measured the effect of milling parameters on the surface integrity of low-carbon alloy steel. The Variance Analysis showed that only depth of cut did not influence on the workpiece roughness and the Pearson´s Coefficient indicated that cutting speed was more influent than tool feed. All cutting parameters introduced tensile residual stress in workpiece surface. The chip formation mechanism depended specially on cutting speed and influenced on the roughness and residual stress of workpiece.

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INTRODUCTION

M. Field and J. F. Kahles in 1967 defined “surface integrity” as a set of modifications in workpiece surface caused by manufacturing processes. The High-Speed Machining (HSM) is industrially defined when cutting speed is elevated and feed per tooth and depth of cut are diminished normally aiming at finishing operations [1]. Some advantages of HSM 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 workpiece surface integrity.

Field, Kahles and Koster [2] stated that milled workpiece surfaces tend to have compression residual stress. Chevrier et al. [3] observed tensile residual stress on workpiece surfaces and Saï et al. [4] obtained compressive residual stress. Blümke, Sahm and Müller [5] concluded that increase of cutting speed elevated of chip segmentation in milling. Rodrigues et al. [6] verified that the chip segmentation depends on workpiece material. Flom and Komanduri [7] indicated that surface finish tends to improve with HSM, but these results are not conclusive.

The objective of this research was to quantify statistically the influence of cutting speed, feed per tooth and depth of cut on the workpiece roughness, residual stress and chip formation of low-carbon steel.

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MATERIALS AND PROCEDURES

The milling tests were carried out in a CNC machining center with 11 kW power and 10,000 rpm spindle rotation. A 25 mm diameter cutter tool with two cemented carbide inserts coated with Al_2O_3 layer (code R390-11 T3 08M-PM 4030 and grade ISO P25) was employed for the endmill operation adopting a down-milling condition.

A low-carbon alloy steel so-called commercially COS AR 60 with 10 x 24 x 100 mm was used for milling tests. The material presents ferritic grain size of 10.8 ± 3.8 μm, 200 ± 2.6 HV hardness, 530 MPa yield strength, 630 MPa tensile strength and 26% elongation. Table 1 shows the chemical elements.

TABLE 1. Workpiece chemical elements (% 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

A 2^3 factorial design using Variance Analysis (ANOVA), significance level α=5% and two replicates was employed considering three factors and two levels i.e. 100 and 600 m/min cutting speed (v_c), 0.5 and 3.0 mm depth of cut (a_p) and 0.05 and 0.2 mm/z feed per tooth (f_z). The main purpose was to quantify the tendencies of results such as recommended by Montgomery and Runger [8].

The machining conditions assumed as conventional and HSM were extracted by combining factors levels with minimum v_c and maximum a_p and f_z, and maximum v_c and minimum a_p and f_z, respectively.

All machining tests were carried out in dry condition with 2 mm width of cut (a_e) and linear tool path in the x-axis direction only. The cutting parameters were based on ranges indicated in Tönshoff [1] and Chevrier et al. [3].

A new cutting edge was used for each test to assure the equal initial conditions since tool wear should not interfere on the tool behavior during milling operations.

The workpiece surface finish was determined considering the Center Line Average R_a [μm]. A portable roughness meter was used for measurements adopting 0.8 mm cut-off and 5 μm needle radius. In addition, the visual characterization of the workpiece surface was also obtained by optical profilometer. The residual stress was measured by adopting X-Ray diffraction through the $\sin^2\psi$ method where the beam deepened at 5 μm beneath milled surface.

The chip formation was evaluated according to its microstructure angle (η) which was measured between the line tangent to the chip-tool interface curvature and the line along microstructure direction. The angle was measured six times for two chips representative from each cutting condition by using CAD software and metallographic images of optical microscope. Thus, the chips were cross-sectionally cupped in polyester resin, sanded with granulometry 400 and 600, polished with aluminum oxide of 1 μm particle size and etched with reagent Nital 2% during 5 s.

RESULTS AND DISCUSSION

Figure 1 shows that roughness increases with feed per tooth and reduces with cutting speed and depth of cut.

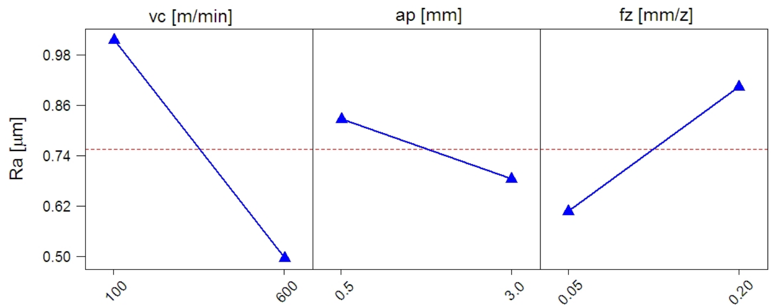

FIGURA 1. ANOVA of the roughness as a function of milling parameters.

It is possible to infer that cutting speed and feed per tooth are the parameters significant on the roughness due to their variation around average (~0.74 µm). Table 2 below presents the results of the ANOVA and Pearson's Coefficient in order to validate the graphic behavior of surface finish.

TABLE 2. ANOVA for workpiece roughness.

Factor	DF	SS	MS	F	P	PC
v_c	1	2.1788	2.1788	17.67	0.000	-0.579
a_p	1	0.1639	0.1639	1.33	0.259	-0.159
f_z	1	0.7110	0.7110	5.77	0.023	+0.331
Error	27	3.4528	0.1233			
Total	31	6.5066				

DF: Degrees of Freedom; SS: Sum of Squares; MS: Mean Square; F: Test F; P: Probability; PC: Pearson's Coefficient.

Considering data showed in Table 2 it is concluded all factors except depth of cut are significant over roughness once P-Value was smaller than significance level adopted in ANOVA. Cutting speed and feed per tooth have moderate correlation with roughness as well as association inverse and direct, respectively. The correlation between R_a and a_p is weak with no statistical significance.

Figure 2 presents the topography of the milled workpieces at HSM and conventional milling condition.

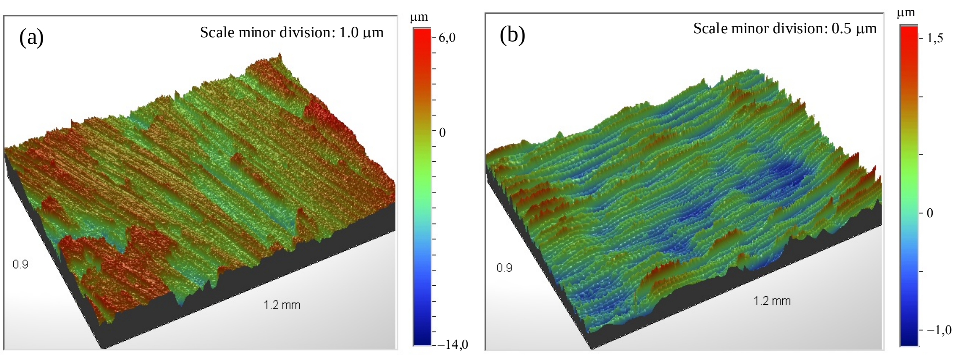

FIGURA 2. Workpiece surface milled at (a) conventional condition and (b) HSM.

The workpiece surface machined at HSM presents better finish than conventional one. Uniform feed marks spaced equally and lower valley-to-peak distance can be viewed. The superior finish generated by HSM it related to the sum of effects such as greater frequency of insert passages over milled workpiece surface given the lower feed per tooth and better chip formation due to higher cutting speed.

Residual Stress of Workpiece

The residual stress evaluation of machined workpiece was done aiming to determine the field and magnification of stresses. Figure 3 shows that residual stress of workpiece increases with all cutting parameters.

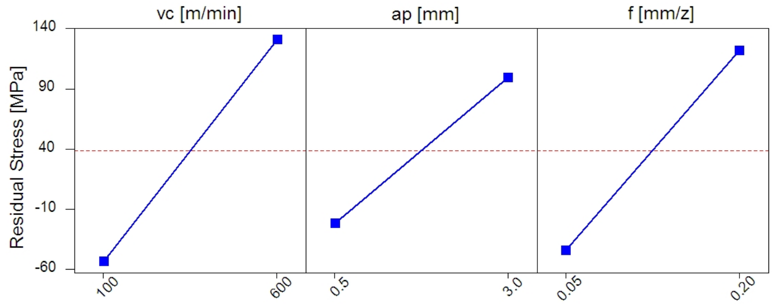

FIGURA 3. ANOVA of the residual stress as a result of milling parameters.

Analogously to the Figure 1, it is possible to infer that all parameters are significant on the residual stress, given the large variation about mean value (~40 MPa). The residual stresses were compression and tensile when milling at gentle and heavy condition respectively. Table 3 contains the results of the ANOVA and Pearson's Coefficient in order to evaluate the graphic behavior of the residual stress.

TABLE 3. ANOVA for residual stress of workpiece.

Factor	DF	SS	MS	F	P	PC
v_c	1	273216	273216	27.40	0.000	+0.553
a_p	1	118526	118526	11.89	0.002	+0.364
f_z	1	221818	221818	22.25	0.000	+0.498
Error	27	279180	9971			
Total	31	892740				

DF: Degrees of Freedom; SS: Sum of Squares; MS: Mean Square; F: Test F; P: Probability; PC: Pearson's Coefficient.

It is possible note that all factors affect the residual stress including the depth of cut. The Pearson's Coefficients indicate the correlations among cutting parameters and residual stress are moderate and directly proportional. The tensile residual stress is likely originating from higher material removal rate which increases the temperature in primary shear zone and heats the workpiece surface. When contracting over the colder subsurface, the tensile residual stress appears given the reaction of inner material layer against the contracted milled surface. Like the residual stress is tensile in the workpiece surface, the subsurface probably presents compression residual stress in order to reach equilibrium state.

Mechanism of Chip Formation

The analyses of chips indicate that all of them may be classified as continuous, except those from HSM condition. Figure 4a shows clearly the continuity of chip lamellae for conventional milling condition. The saw-tooth type originating from HSM is confirmed by Figure 4b. Despite its shape, the HSM chip presents segmentation degree of 28% only (percentile band ligament height), indicating an initial adiabatic shear process. Thus, the HSM chip can not be classified as segmented one once there is deformation of the microstructure (ferrite-pearlite) inside lamellae and bands with concentrated shear are not clearly defined. Probably the low hardness of the workpiece limited the segmentation process even at higher cutting speed.

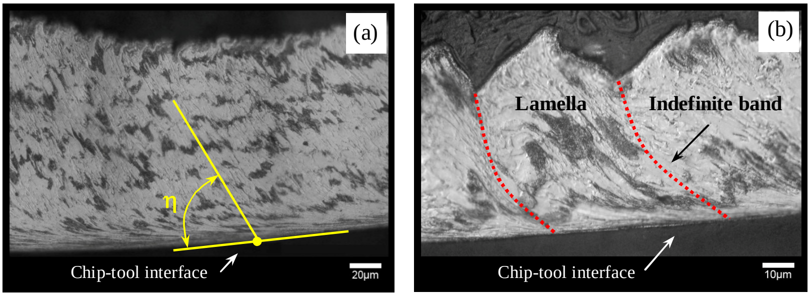

FIGURE 4. Side view of (a) conventional and (b) HSM chips (Nital 2% etching).

Figure 5 shows the variation of the chip microstructure angle with the milling parameters. The relation between the angle and cutting speed as well as feed per tooth is inversely proportional whereas the depth of cut is directly proportional. This parameter varied less around mean angle (~ 55º) indicating to be non-significant.

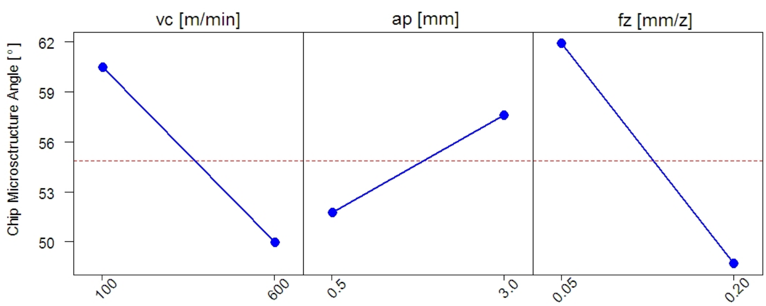

FIGURA 5. ANOVA of the chip microstructure angle as a result of milling parameters.

The variation of chip microstructure angle depends directly on shear angle. When the cutting speed or tool feed rises, the shear angle increases due to the momentum variation in the primary shear zone that reduces the chip thickness for each uncut chip thickness respective. This result was confirmed through HSM chips for which the thickness was 10% lesser than that from conventional milling. Low cutting speeds and tool feeds increase the chip ratio, damaging the workpiece finish given that chips are badly-formed. On the other hand, due to this mechanical effect, the residual stress is favored (compressive field), suggesting that thermal influence is not significant once strain rate for this case is lower.

Table 4 shows the results of the ANOVA and Pearson's Coefficient in order to evaluate the graphic behavior of the chip microstructure angle.

TABLE 4. ANOVA for chip microstructure angle.

Factor	DF	SS	MS	F	P	PC
v_c	1	772.84	772.84	8.45	0.013	-0.511
a_p	1	7.70	7.70	0.08	0.777	+0.051
f_z	1	1081.42	1081.42	11.83	0.005	-0.605
Error	12	1097.20	91.43			
Total	15	2959.17				

DF: Degrees of Freedom; SS: Sum of Squares; MS: Mean Square; F: Test F; P: Probability; PC: Pearson's Coefficient.

All factors except depth of cut are significant on chip microstructure angle once P-Values were smaller than 5%. Cutting speed and feed per tooth have moderate and inverse correlation with the microstructure angle. The correlation between the angle and a_p is weak with no statistical significance.

CONCLUSIONS

The cutting speed and feed per tooth are the milling parameters more significant on surface integrity. Both govern the chip formation which has close relation to the workpiece roughness and residual stress. Besides these cutting parameters, the depth of cut also influences on the residual stress, which is sensitive to a balance between the thermal and mechanical effects. The machining of ductile materials using gentle cutting conditions can also determine the workpiece surface integrity.

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