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Size Effect in Micromilling of Superduplex Stainless Steel

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Abstract

Size effect is a phenomenon which can explain the difference of the behavior of a material in a manufacturing process in reduced scale, that is, the difference between the mechanics of cutting in micro and mesoscale. This phenomenon in micromilling deals principally with the decrease of the ratio undeformed chip thickness (t_c) per cutting edge radius (r_e) and the microstructure of the workpiece. On a previous work, it was presented an experimental study on the influence of cutting parameters in micromilling of superduplex steel, considering only two levels of cutting speed and feed per tooth. The objective of the present work is to verify the influence of the size effect on the specific cutting pressure and on the surface integrity in the micromilling of this steel. The Design of Experiments used two levels of cutting speed and six levels of feed rate. The combined analysis of the results of both studies shows a higher influence of the feed rate on the non-linear increase of the specific cutting pressure and, consequently, on the roughness and burr formation.

Keywords: Micromilling, superduplex UNS S32750, specific cutting pressure, surface roughness, burr formation.

1. Introduction

Size effect is a set of phenomenon capable to describe the material behavior during the fabrication in small scale [1, 2]. The size effect in machining deals especially with the cutting edge radius (r_e) ratio to the undeformed chip thickness (t_c) and the microstructure of the workpiece. It is necessary a t_c higher than a minimum thickness, called t_{cm} in order to occur the formation of the chip. When $t_c < t_{cm}$, the material is pushed in front of the cutting edge by a mechanism called *ploughing*, which ends up conforming the piece surface with no material removal, Ramos et al. [3]. If $t_c \ll t_{cm}$, the chip will not be formed and the workpiece surface will be elastically deformed, recovering its shape after the tool passage [4].

Another important characteristic around the size effect is the microstructure of the workpiece. In micromachining the quantity of removed material at each pass of the cutting edge per surface is a lot smaller than in machining, for the same workpiece material. This way, if for the conventional process the chip formation includes the union of a lot of grains, in the micromilling the chip can be compound of few grains of even of just one. When the cutting process happens inside only one grain, the tensions applied to the tool are dependents of various material factors, causing high frequencies oscillations of the cutting forces, Bissacco *et al.* [1]. This oscillation will influence on the process performance and the workpiece finishing.

Big part of the miniaturized parts is fabricated with materials used in medical, biomedical and dental areas, as titanium alloys and shape memory alloys. Despite this, steels in general have also been studied in micromachining because of its heterogeneous microstructure and to increase its area of application.

Among these steels, stainless duplex and super duplex are strong candidates to micromachining as they have great corrosion resistance and high mechanical resistance values because of its biphasic microstructure, Pardal [6].

Micromachining of the super duplex presents the problems related to its heterogeneity. This way, it becomes important to know the microstructural characteristics of the material, its mechanical properties, the influence of the cutting parameters and conditions during the process and the main factors which have influence on the stability of the process during micromachining.

This way, Mougo *et al.* [7] started an experimental study on the micromilling of UNS S 32750 superduplex steel. On that work it was presented the first results on the variance of the specific cutting pressure influenced by the cutting speed and feed per tooth. It was possible to also observe the increase of the specific cutting pressure with the increase of number of milled channels, indicating a possible wear of the cutting tool.

The actual article presents a sequence of the experimental study of the micromilling of super duplex UNS S32750. It will be added to Mougo *et al.* [7] article the micromilling results of superduplex steel with four more levels of feed per tooth, with the objective of verifying the influence of the cutting speed and of the feed per tooth on the specific cutting pressure and the part integrity through the measure of the roughness and the burr formation

2. Experimental setup

2.1. Material and experimental apparatus

The super duplex UNS S 32750 workpiece has been flatned by milling before the micromilling experiments. The dimension of the flat surface is 40mm x 20mm. The heterogeneous microstructure

can be seen in Fig. 1.

After the metallographic preparation, the images were analysed in the Image-Pro Plus software in order to quantify the volumetric fraction of the ferrite (52%), dark grains, and austenite (48%) phases.

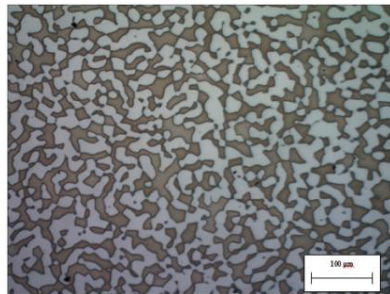


Fig. 1. Super duplex stainless steel microstructure.

A Tungsten Carbide-Cobalt micromilling tool with 0.8 mm diameter and two flutes was used, as shown in Fig. 2. Cutting edge radius (r_e), point radius and helix angle are 2.5 μm , 4 μm and 30°, respectively. The cutting length is coated with Titanium aluminum nitride (TiAlN-F) with thin particles. This tool is recommended for machining steels harder than 48 HRC.

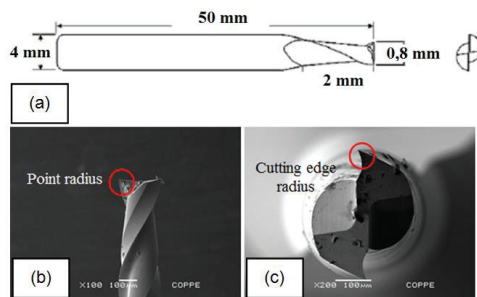


Fig. 2. (a) Dimensions of the micro tool, (b) Point radius and (c) Cutting edge radius.

A micro hardness test on the workpiece surface, as new, was developed applying 1 Kg load for approximately 30 s. The micro hardness average found was 346 HV, that is, 35 HRC, according to the conversion table.

The micro machine-tool which will be used on the experiments is the CNC Mini Mill/GX from Minitech Machinery Corporation. The machine uses NSK 60k RPM precision spindle with 3 axis controller.

A dynamometer was be used for cutting force measurement: the MiniDyn 9256C2 with charge amplifier 5070A10100 and a data acquisition board USB 6251. The dynamometer is calibrated with a sensitivity of -25.61 pC/N on Fx, -12.86 pC/N on Fy and -25.86 pC/N on Fz.

In order to measure the roughness and the burr height, it was used the Form Talysurf Intra. Standard Inductive Gauge, stylus code 112/2009, stylus type 2 μm Standard 60 mm with 90° conisphere diamond was used, as presented in Figure 3. For the surface analysis it was used the Software Ultra Surface Finish V5.

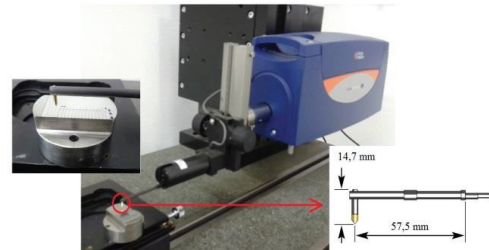


Fig. 3. Profilometer and Standard Inductive Gauge.

2.3. Experimental Procedure

The experiments were planned in order to analyze the influence of two factors on the specific cutting pressure and surface integrity. The factors chosen were the feed per tooth and the cutting velocity with three replicates for each experiment. It was used clockwise spindle speed and cutting fluid. Table 1 presents the cutting parameters used on the experiments.

Table 1

Cutting Data	
Parameter	Levels
Spindle speed (n)	12000 rpm and 20000 rpm
Feed per tooth (f_t)	1, 2, 3, 5, 7 and 10 $\mu\text{m}/\text{th}$
Depth of cut (a_p)	100 μm
Cutting fluid	Microcut 510 F / 1:20

Table 2 presents the cutting parameters of each experiment. Based on r_e value (2.5 μm) and considering initially $t_{cm} \approx r_e$, the experiments from 1 to 8 were made with $t_c > t_{cm}$, ensuring chip formation. In order to complete the analysis of the size effect on the specific cutting pressure, experiments 9 and 10 were carried out with $t_c < t_{cm}$.

Table 2

Cutting parameters for each experiment		
Exp.	f_t ($\mu\text{m}/\text{tooth}$)	n (rpm)
1	10	20000
2	10	12000
3	7	20000
4	7	12000
5	5	20000
6	5	12000
7	3	20000
8	3	12000
9	2	20000
10	1	20000

Surface roughness was measured on the longitudinal direction of the channels, that is, on the same direction of the cutting tool feed. In this stage, three measurements were made for each channel. For the top burr height, 10 measurements were made of the transversal profile of the channels.

3. Results and discussions

3.1 Cutting forces analysis

In order to analyze more precisely the influence of cutting parameters on the cutting force, the

maximum resultant cutting forces of the experiments 1 to 4 were computed.

The maximum resultant force is calculated per cutting edge, which means that for one revolution two values for this vector are added.

The analysis of the results through statistical methods shows that the increase of the cutting speed caused a decrease of the cutting force and the increase of the tool run-out verified by the higher standard deviation, as presented in Fig. 4.

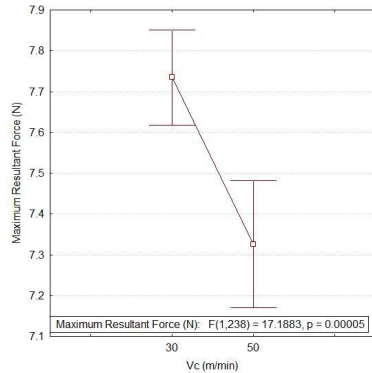


Fig. 4. Variance of the maximum cutting force considering the influence of V_c .

3.2 Specific Cutting Pressure

Using the resultant cutting force results it is possible to calculate the resultant specific cutting pressure (K_t). So, the specific cutting pressure (K_t) is computed as a function of K_r , as shows Eq. 2, where $m_1=0.6$ e $m_2=0.2$ [5]

$$K_t = \frac{K_{resultant}}{\sqrt{1+m_1^2+m_2^2}} \quad (2)$$

K_t values were selected for $f_t=1$ to $10 \mu\text{m/tooth}$ with $V_c=50\text{m/min}$. Figure 5 presents the evolution of the experimental specific cutting pressure when increasing feed per tooth.

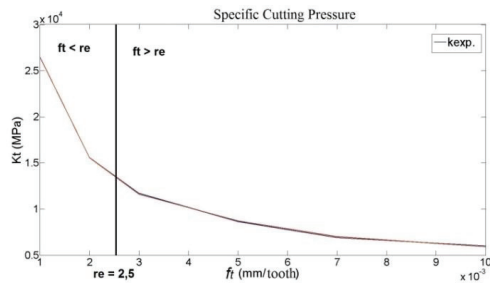


Fig. 5. Evolution of specific cutting pressure as a function of f_t

In order to analyze the influence of the factors in K_t it was made a ANOVA by experiments 1 to 4. The factors are considered independent. This means that the cutting speed does not influence on the feed per tooth value and vice-versa. It was used the following data configuration:

	Parameter	-1	+1
P1	Cutting Speed	12000	20000
P2	Feed	0.007	0.010

The hypotheses tested for each parameter were H_0 (Null Hypothesis) - the specific cutting pressure does not vary with the parameter and H_1 the alternative Hypothesis.

The results are shown in Table 3. Using a significance level α of 0.05, a critical value F of 5.32 is found. It can be seen that feed per tooth has a significant influence on specific cutting pressure, as $F > F_{critical}$.

Table 3 ANOVA K_t : $f_t = 7$ and $10 \mu\text{m/tooth}$

Source	SS	Df	MS	F
n	1880050	1	1880050	18.9
f_t	4242352.1	1	4242352.1	42.64
Error	79890.2	8	99486.3	

From the determination of $F_{critical}$ and F ratio it is possible to observe that both cutting speed and feed per tooth influence K_t value, that is, hypothesis H_0 is rejected and hypothesis H_1 is accepted. However, as it was expected from the metal cutting theory, feed per tooth has more influence on K_t changes than the cutting speed.

Cutting speed can influence K_t in two ways. When V_c increases, workpiece surface can suffer thermal softening, lowering the material hardness and consequently K_t value. With V_c increase, a higher standard deviation. This deviation can increase or decrease the cutting force and specific cutting pressure through the variance of the chip removed thickness.

3.3 Analysis of size effect influence on specific cutting pressure

The results obtained in the last section showed that the cutting speed can modify the cutting force and the specific cutting pressure due to, especially, the tool run-out and the thermal softening.

Feed per tooth, on the other hand, does not need secondary conditions to influence on specific cutting pressure value. This means that the increase or decrease of f_t is sufficient to modify cutting forces and specific cutting pressure values.

The nonlinear increase of the specific cutting pressure was observed when the feed and cutting edge radius values were closer ($f_t < r_e$).

Because f_t is inversely proportional to K_t , when f_t decreases, K_t tends to rise. When $f_t < r_e$, the forces that actuate on the cutting edge and the forces from material deformation through ploughing are summed with shear forces, making K_t values to rapidly increase in a non-linear way. With feed values lower than r_e , the probability of $t_{min} < t_c$ is higher. Therefore, in this region the actuation of size effect will occur through the relation of the cutting edge radius and the chip thickness.

When $f_t > r_e$, the value of f_t increases until it settles K_t . This fact can be explained by the same consideration before, that is, when f_t becomes bigger

than r_e , the chip removal only by shearing also becomes bigger than the other forces, which actuate on the cutting edge.

Besides the increasing of K_t when $f_t < r_e$, it is possible that the lower value of $f_t = 1 \mu\text{m/tooth}$ was not lower than t_{cm} . Some authors studied the relation between t_{cm} and r_e for various types of metallic materials with the objective of verifying the occurrence of size effect and of finding a bottom limit to f_t , when there is not chip formation [10, 11]. The biggest relation was proposed for AISI 1045 steel, where $t_{cm} = 0.3r_e$ [14]. Considering this relation in this work $t_{cm} = 0.75 \mu\text{m}$, indicating that for all experiments $t_c > t_{cm}$.

3.4 Surface integrity

In order to verify the influence of cutting parameters on R_a , it was made an Analysis of Variance (ANOVA) with the results obtained from the experiments 1 to 4. The configuration of the parameters is the same presented in section 3.2. The results are presented on Table 4.

Table 4
ANOVA R_a : $f_t = 7$ and $10 \mu\text{m/tooth}$

Source	SS	Df	MS	F
N	0.00037	1	0.00037	0.64
f_t	0.02241	1	0.02241	38.8
Error	0.00462	8	0.00058	

Using a significance level $\alpha = 0.05$ it is possible to obtain in a distribution table the value of $F_{\text{Critical}} = 5.32$. So, roughness suffer greater influence of f_t , being this direction of measurement the same of the tool feed.

After the measurement of the top burr height, it was performed an ANOVA to verify which cutting parameters contributes more for the increase of the burrs. In this stage, it was used the experiments 1 to 4. The results are presented on Table 5.

Table 5
ANOVA Top burr: $f_t = 7$ and $10 \mu\text{m/tooth}$

Source	SS	Df	MS	F
N	0.881	1	0.881	0.05
f_t	67.09	1	67.09	4.01
Error	133.841	8	167.302	

As $F < F_{\text{Critical}}$, the null hypothesis H_0 cannot be discarded for the two parameters analyzed. However, it is possible to note that f_t can have more influence on the top burr height than V_c .

4. Conclusions

This work presented a continuation of the study on the micromilling of superduplex stainless steel [16].

The increase of the cutting speed caused the decrease of the cutting forces. Higher cutting speed tends to increase the friction in the chip-tool contact region, causing the thermal softening of the steel during micromilling. Thermal softening decreases the steel hardness and also the force needed for chip removal.

The increase of the cutting speed leads to an

increase of the maximum cutting force standard deviation, indicating the occurrence of tool run-out and, consequently, the variance of the removed chip dimension. The tool run-out can be caused by vibrations of the machine-tool.

From the analysis of variance, it was possible to observe that the feed per tooth influences more on the specific cutting pressure than the cutting speed what can be explained by the relation between feed and chip area. So, the lower the feed, higher will be the energy consumed to remove a unity of material and, therefore, higher will be the specific cutting pressure.

From the experimental results obtained with feed per tooth of $10 \mu\text{m/tooth}$ to $1 \mu\text{m/tooth}$, it was verified a non-linear increase of the specific cutting pressure. This increase is more accentuated when feed is lower than cutting edge radius.

From the analysis of variance, it was observed that the feed per tooth if the factor which most influences on the average roughness of the milled channels. When $f_t > r_e$, R_a increases and when $f_t < r_e$, R_a decreases because of the elastic recuperation of the workpiece surface.

The analysis of variance of the top burr profile did not show influence from the cutting parameters. It is possible that the profilometer and/or the stylus are not indicating for this type of measurement.

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References

- [1] G. Bissacco, H. Hansen, J. Slunsky, "Modelling the cutting edge radius size effect for the force prediction in micro milling", CIRP Annals - Manufacturing Technology, 2008, No. 1; V57: 113-116.
- [2] A. Aramcharoen et al., "Size effect and tool geometry in micromilling of tool steel". Prec. Eng., 2009; Vol. 33, pp. 402-407.
- [3] A. C. Ramos et al., "Characterization of the transition from ploughing to cutting in micro machining and evaluation of the minimum thickness of cut". J. of Mat. Proc. Tech., 2012; Vol. 212, No. 3, pp. 594 – 600.
- [4] M. P. Vogler et al., "On the modeling and analysis of machining performance in micro-endmilling, Part II: Cutting force prediction", J. of Man. Sci. and Eng., 2004; V126: 695-705.
- [5] M. Malekian et al., "Modeling of minimum uncut chip thickness in micro machining of aluminum", J. of Mat. Proc. Tech., 2012; V212: 553-559.
- [6] J. M. Parda, "Aços Inoxidáveis Superduplex. Efeitos dos tratamentos térmicos nas propriedades mecânicas, magnéticas e resistência à corrosão", 2012. Editora Blücher.
- [7] A. L. Mougo, F. O. Campos and A. C. Araujo, "Experimental Analysis of Micromilling Cutting Forces on Super Duplex Stainless Steel", 2014, 9th International Conference on MicroManufacturing (ICOMM 2014).