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A STUDY OF SPECIFIC CUTTING FORCE IN MICROMILLING OF SUPERDUPLEX STAINLESS STEEL UNS S 32750

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Abstract. *Cutting force, and its modeling, has attracted constant attention of researchers due to its influence in tool life, workpiece quality and other factors related to machine-tool dynamics. The conventional models of cutting force were adapted to the micro scale process considering geometric characteristics, cutting parameters and microstructure. The specific cutting force can be calculated for each tool-piece: both mechanistic and experimental models could predict this important parameter. The objective of this work is to calibrate mechanistic and empirical models determining the cutting pressure coefficients using experimental data and make a critical comparison. The material machined in this experimental work is the superduplex stainless steel UNS S 32750 and the result shows that either models are a good approximation to calculate specific cutting force although they have different applicability.*

Keywords: *micromilling, superduplex UNS S32750, mechanistic model, validation, specific cutting force*

1. INTRODUCTION

The development of new technologies, as electronic devices, monitoring sensors, biomedical and automobilist components, has been stimulating the growth of the miniature products manufacturing. These products can be components or structures with dimensions of hundreds of micrometers with tolerances equal or smaller. Between the micromachining processes used for the manufacturing of these products, micromilling stands out because of the possibility to manufacture structures with complex geometries in 3D using a lot of different materials.

The mechanism of cutting in micromilling should consider "size effect", as claimed by Aramcharoen and Mativenga (2009). Size effect is a set of phenomenon capable to describe the material behavior during the fabrication in small scale (Aramcharoen, et al., 2009; Bissaco, et al., 2008; Mian, et al., 2011). According to Vollertsen et al. (2009), this size effect can occur during the fabrication of any type of material, but it is commonly observed in metallic materials because of its plastic deformation. Due to the small size of the micro tools, which have a diameter smaller than 2 mm, it is very difficult to notice the damage in the cutting edges. Besides, an inappropriate selection of the cutting conditions can cause unexpectedly tool breakage and affect the surface integrity of the workpiece.

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. (2012). 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 (Vogler, et al., 2004; Malekian, et al., 2012).

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 or 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, as crystallographic orientation, polymorphism and present phases, causing high frequencies oscillations of the cutting forces, Bissacco et al. (2008). This oscillation will influence on the process performance and the workpiece finishing.

The predictive models of performance of the machining processes have been under development and integrated to the manufacturing process (Tlustý, 1975; Sabberwal, 1961; Armarego and Deshpande, 1989). Without these models, planning and experimental tests in machining become extremely expensive, because besides the great knowledge of best working conditions, a change in any of the input parameters can cause errors and damages to the process. Several models were developed to predict cutting forces, chip formation and temperature field on the contact region tool-piece. However, cutting force has attracted constant attention of researchers because from these parameters it is possible to analyze tool life, piece quality, besides other factors related to equipment and machine project.

These conventional models of cutting forces were adapted to the micro scale process considering, for example, chip and tool dimensions, dynamics and cutting parameters, material and microstructure of the part (Bissacco, et al., 2008; Bao, et al., 2000; Rodríguez and Labarga, 2013). Between these models, mechanistic models use a series of relation between the process variables and the cutting forces, considering geometric characteristics of the process and the specific cutting force for each tool-piece pair. These models present both mechanistic and experimental characteristics because the equation used to compute the specific cutting force is obtained through experimental data.

The objective of this paper is to calibrate a mechanistic model for a superduplex stainless steel, determining the specific cutting force coefficients using experimental data and, then, validate this model comparing the specific pressure values computed with the experimental ones.

2. CUTTING FORCE MODELLING

The cutting force in micromilling is based on the well-known relation between the chip load area and the specific cutting force. In the micro machining case, the chip load area is adapted and the specific cutting force presents different values compared to the meso-scale machining.

Elemental normal and frictional forces are required to the determination of cutting forces for a given geometry. The mechanistic modeling approach is a combination of analytical and empirical methods in which the forces are proportional to the chip load.

The specific cutting force components, K_t , K_r and K_z , have been shown as a function of chip thickness t_c in meso-scale milling process and it is used for calculation of dF_r , dF_t and dF_z on each angular position θ of the discretized cutting edge proportional to the chip load area dA as shown in Eq. (1). Using a semi empirical modeling as Tlustý (1975) relating specific cutting forces by empiric factors m_1 and m_2 .

$$dF_t(\phi) = K_t dA(\phi) \quad (1)$$

$$dF_r(\phi) = m_1 K_t dA(\phi) \quad (2)$$

$$dF_t(\phi) = m_2 K_t dA(\phi) \quad (3)$$

2.1 Chip load Cutting Model for Milling and Micromilling

Chip area for milling is calculated based on uncut chip thickness t_c as a function of the rotation angle ϕ and feed per tooth f_t , that is called Martellotti equation:

$$t_c(\phi) = f_t \sin(\phi) \quad (4)$$

Bao and Tansel (2000) developed a calculation for uncut chip thickness $t_c(\phi)$ for micromilling, as a function of the tool run-out, described with the parameter r , depending on the tool teeth z :

$$t_c(\phi) = f_t \sin(\theta) - \frac{z}{2\pi r} f_t^2 \sin(\theta) \cos(\theta) + \frac{f_t^2}{2f} \cos^2(\theta) \quad (5)$$

Ploughing effect occur under minimum uncut chip thickness, $t_{cm}(\phi)$, which was modeled by different approaches. Liu et al. (2006) modeled considering analytical model using slip line theory and Johnson-Cook model. Malekian et al. (2012) presented an article on micromilling of Aluminum, which is used in this article based on the edge radius r_e and on a critical or stagnant angle, ϕ_m , equal to the friction angle between the material and the rake face, regardless of the other parameters involved in the process.

$$t_{cm}(\phi) = r_e(1 - \cos(\phi_m)) \quad (6)$$

2.2 Specific Cutting Force Modelling

In this paper, two specific cutting forces are presented: the mechanistic model, a curve fitting based on the logarithmic relation between the parameters cutting velocity (V_c) and the maximum chip thickness t_{cm} .

a) Mechanistic Model

The specific cutting force in the mechanic model is calculated as:

$$\ln(K_t(\phi)) = a_0 + a_1 \ln(t_c) + a_2 \ln(V_c) + a_3 \ln(t_c \cdot V_c) \quad (7)$$

The coefficients a_0 , a_1 , a_2 and a_3 are called specific cutting energy coefficients. They are dependent on the tool and workpiece materials and also on the cutting speed and the chip thickness. They are determined from calibration tests for a given tool work piece combination and for a given range of cutting conditions.

b) Empirical Model (DeVor et al., 1982)

Another model was used to calculate specific cutting force is show in Eq. (6) called as Kienzle model, where $p = -0.3$ is a constant obtained experimentally and C is an empiric constant based on material and cutting conditions. As the expression describes, it is a function only by the chip thickness without explicit relation to the cutting velocity.

$$K_t = C \cdot (t_c)^p \quad (8)$$

c) Polynomial Model

In this article, it is used also a generic polynomial model using the calibration of a polynomial curve of degree 2 for comparison with the other machining models, as a function of the chip thickness.

$$K_t = p_1 \cdot f_t^2 + p_2 \cdot f_t + p_3 \quad (9)$$

3. EXPERIMENTAL SETUP

3.1 Material and experimental apparatus

The dimension of the flat surface is 40mm x 20mm, as presented in Fig. 1 (a). The heterogeneous microstructure can be seen in Fig. 1 (b). For the preparation of this sample, sandpapers of 220 to 600 mesh and diamond paste of 3 μm and 1 μm were used, and it was performed an electrolytic attack, with reagent composed of 20 g of NaOH and 100 ml of distilled water, by the immersion method during approximately 2 min. 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.

A Tungsten Carbide-Cobalt micromilling tool with 0.8 mm diameter and two flutes was used, as shown in Fig. 1 (c), (d) and (e). 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). This tool is recommended for machining steels harder than 48 HRC. 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.

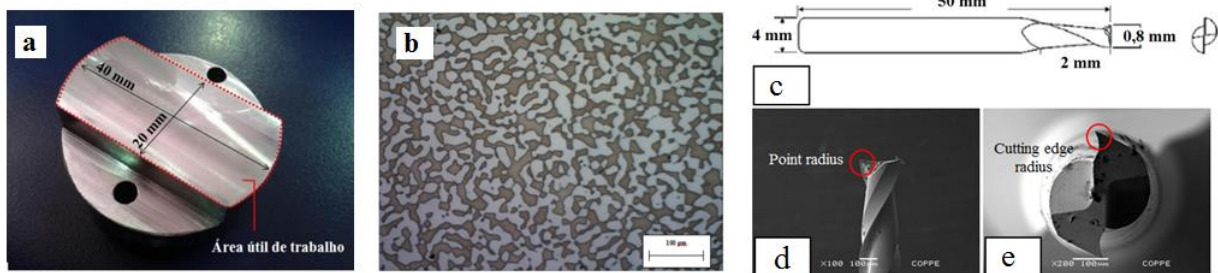


Figure 1: (a) workpiece, (b) microstructure, (c) micromill, (d) point radius and (e) cutting edge radius .

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. Its standard resolution is 0.78125 μm using dual linear ball bearing slides on each axis, sealed for the table mechanism (THK linear slides - RSR15 series, caged-ball technology). The drive mechanism THK Ball Screw actuator - preloaded and sealed, achieves low torque fluctuation and no backlash.

A dynamometer was 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 F_x , -12.86 pC/N on F_y and -25.86 pC/N on F_z .

Figure 2 shows the positioning of the workpiece on the dynamometer and of the micromilling tool in the machine-tool for the tests. It is also presented in this figure a scheme of the workpiece dimensions where the milled channels of 5 mm length spaced by 1.5 mm of each other can be seen.

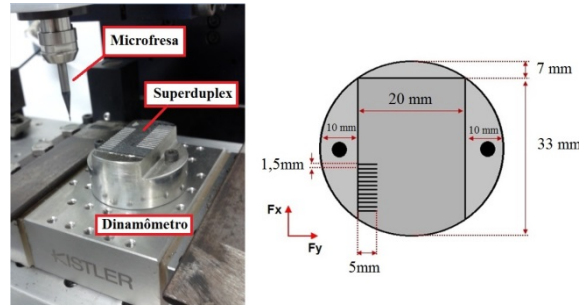


Figure 2: Experimental setup.

3.2 Experimental procedure

The experiments were planned in order to analyze the specific cutting force. 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 (Microcut 510F). Table 1 presents the cutting parameters used on the experiments. Table 2 presents the cutting parameters of each experiment. Based on r_e value (2.5 \AA) and considering initially $t_{cm} \approx r_e$, the experiments from 1 to 8 were made with $t_c > t_{cm}$, ensuring chip formation.

Table 1: Cutting Data.

Parameter	Levels
Spindle speed (n)	12000 rpm and 20000 rpm
Feed per tooth (f_t)	3, 5, 7 and $10 \mu\text{m}/\text{th}$
Depth of cut (a_p)	$100 \mu\text{m}$
Tool	Tungsten carbide, $d=0.8\text{mm}$
Workpiece	Super duplex UNS S 32750
Cutting fluid	Microcut 510 F / 1:20

Table 2: Cutting Parameters of 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

4. RESULTS AND DISCUSSIONS

a) Experimental results using Mechanistic Model

Using the experimental results of Malekian et al. (2009), m_1 and m_2 on Eq. 1 are 0.6 and 0.2, respectively. Using average maximum force and the maximum chip area - feed times depth of cut - was used and the resultant cutting pressure can be calculated, Eq. (8). Then, the experimental specific cutting force for each experiment is given by Eq. (8).

$$K = \frac{F_{res}}{A_{max}} \quad (10)$$

$$K_{exp} = \frac{K_{res}}{\sqrt{(1^2 + m_1^2 + m_2^2)}} \quad (11)$$

Using Eq. (3) and computing the experimental specific cutting force, the coefficients a_0 , a_1 , a_2 and a_3 can be calculated by solving a linear system. Then the numerical specific cutting force can be calculated and compared with the experimental. So the experiments number 1, 2, 7 and 8 are used to calibrate the model and the experiments number 3, 4, 5 and 6 are used to validate the model. After solving the linear system, Eq. (3) becomes:

$$\ln(K_t(\phi)) = 6.8329 + 0.3128 \ln(t_c) + 0.0965 \ln(V_c) - 0.2163 \ln(t_c \cdot V_c) \quad (12)$$

b) Empirical Model Results

Using the same method the Eq. (6) becomes for the different velocities, $v = 30 \text{ m/min}$ and $v = 50 \text{ m/min}$ respectively:

$$K_t = 1.953 \times 10^3 f_t^{-0.3} \quad (13)$$

$$K_t = 1.772 \times 10^3 f_t^{0.3} \quad (14)$$

c) Polynomial Model Results

And the polynomial calibration after solving a linear system becomes for the different velocities, $v = 30 \text{ m/min}$ and $v = 50 \text{ m/min}$ respectively:

$$K_t = 1.8051 \times 10^4 - 2.1571 \times 10^6 f_t + 1.0028 \times 10^8 f_t^2 \quad (15)$$

$$K_t = 1.8230 \times 10^4 - 2.5960 \times 10^6 f_t + 1.3735 \times 10^8 f_t^2 \quad (16)$$

d) Comparison between models

The error between the experimental specific cutting force and the numerical specific cutting force is shown in Tab. 3. Using these models, it was calculated the numerical specific cutting force and put the results in graphics to analyze the validation of the model. In Fig. 3 we have the surface graphic of the model based on Eq. (5) and using two feed per tooth, $3 \mu\text{m}$ and $5 \mu\text{m}$:

Table 3: Comparison between numerical specific cutting force and experimental cutting pressure.

$f_t (\mu\text{m})$	$V_c (\text{m/min})$	K_{exp} (MPa)	K_{sim} (MPa)	Error (%)
Mechanistic Model $\ln(K_t) = a_0 + a_1 \ln(t) + a_2 \ln(t.V_c)$				
5	50	9617.5	9492.5	1.29
5	30	8637.6	8802.8	1.91
7	50	7968.6	7890.4	0.98
7	30	6881.9	7317.5	6.32
Empirical Model $K_t = C.(t_c)^p$				
5	50	8637.5	8685.1	0.55
5	30	9617.5	9573.5	0.45
7	50	6827.7	7851.2	14.99
7	30	7994.1	8654.3	8.25
Polynomial model $K_t = p_1 f_t^2 + p_2 f_t + p_3$				
5	50	8637.589	8684.256	0.540
5	30	9617.517	9772.535	1.610
7	50	6827.639	6788.749	0.569
7	30	7994.193	7865.011	1.610

Using the mechanistic model based on Eq. (6) we have three calibrations differentiating the cutting velocity in 30 m/min and 50 m/min . We obtained the constant C through calibration using these parameters in Matlab. These figures are shown in Fig. 4 respectively.

Using a program that fitting curves in Matlab, we calibration realize that the points of calibration follow a polynomial format. Thus, it was plained a model based on polynomial calibration, using a special program of Matlab, the 'cftool', that it fit curves and through methods of least squares to obtain the coefficients of the curve. It was realized that the polynomial model have the R-square equal 1 showing a great adaptation with model. Figure 5a shows a polynomial calibration with cutting velocity of 30 m/min . Another alternative to improve polynomial model was to pass the coordinates for a logarithmical scale, show in Fig. 5b.

The residuals of the graphics allow concluding that polynomial model is better than the model of Eq. (5). The figure 6 shows show this effect.

5. Conclusion

In this study, it was presented three models for calculated the specific cutting force on the micromilling of an superduplex stainless steel. The error found between the experimental and numerical values of the specific cutting force, it can be seen that the empirical model results are smaller with error 0.45% . This model considers only the feed per tooth as a cutting parameter able to influence the calculation of the specific cutting force.

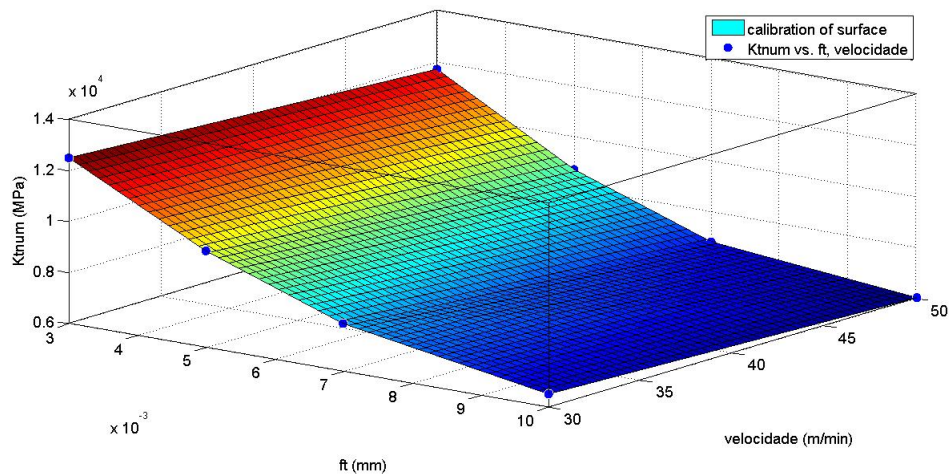
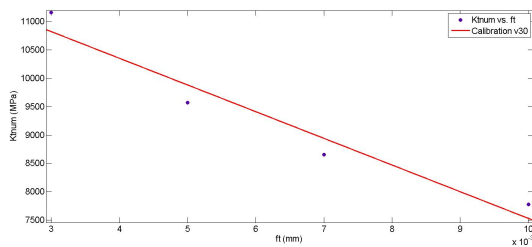
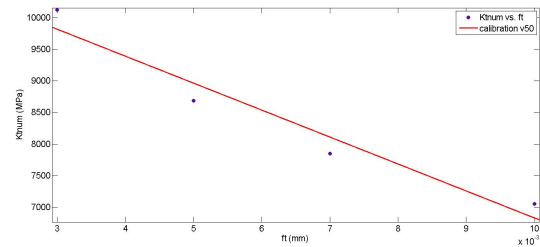


Figure 3: Surface graphic of Mechanistic Model.



(a) $V_c = 30$ m/min



(b) $V_c = 50$ m/min

Figure 4: Calibration curves in Empirical Model.

The polynomial model is not sensitive to the phenomena of the machining process, such as varying the thickness of the chip. Thus, despite having smaller residual error, this model would not be the most appropriate to calculate the specific cutting force.

The mechanistic model showed better results. This model is able to predict the specific cutting force values considering the limits used in the experimental design. The validation results showed the maximum error of 6.32% comparing to the experimental results.

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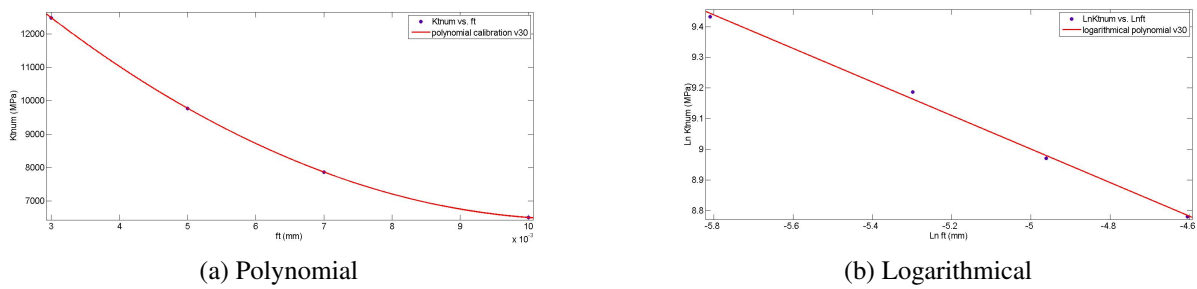
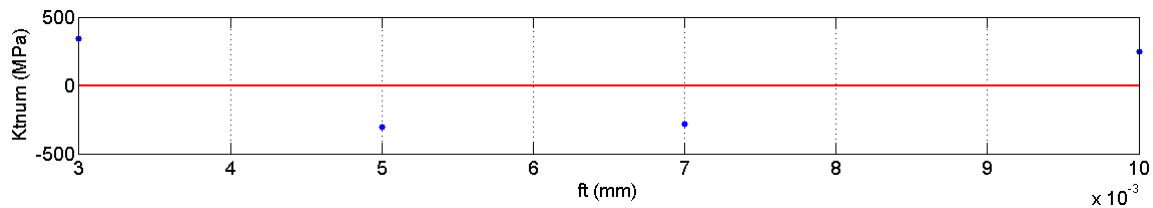
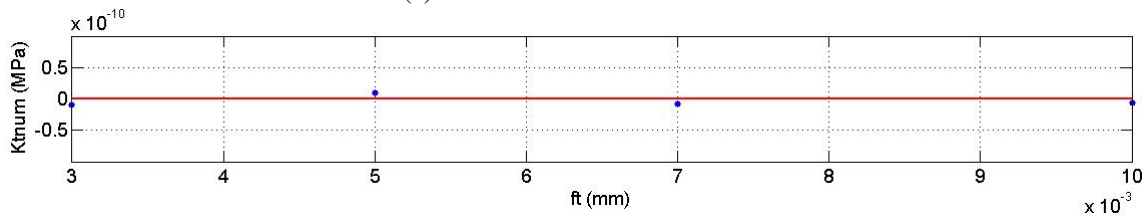


Figure 5: Calibration.



(a) Mechanistic model Residuals.



(b) Polynomial Residuals.

Figure 6: Residual error using different models.

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