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STUDY OF THE CUTTING FORCES AND QUALITY PARAMETERS OF THIN-WALLED PARTS MACHINED BY MILLING

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Abstract: *The study in this paper aims to analyze the effect of two factors (i.e., feed rate and cutting speed) on cutting force and two quality parameters of parts (residual stresses in the surface layer and surface roughness) when milling thin-walled parts. It was found that increasing cutting speed and feed rate usually causes an increase in cutting force as well as surface roughness and residual stresses. The measured residual stresses were all of the compressive stress types.*

Keywords: *thin-walled parts, milling forces, residual stresses, surface roughness.*

1. INTRODUCTION

The machining of parts with complex geometrical features is an increasing requirement in manufacturing industry. Thin-wall milling is the most widespread technology currently used for producing such components. It has a wide applicability in different industries, but particularly in the aeronautics industry, because it offers solutions to one of the pressing issues of this field: reducing the weight of components and assemblies without affecting their strength and stiffness. Single-unit components, rather than small welded or riveted parts, primarily compose the aircraft. They are manufactured by thin-wall milling and then joined to the airplane skins, which are previously obtained by the same process [1].

This technology allows obtaining components with very complex geometries (e.g., impellers and blades, fuselage, beam parts, integral panels, etc.), whose wall thickness is usually up to 2 mm [2]. This is possible by removing up to 90-95% of the raw block material to get the final geometry. However, the thickness much smaller than the other two dimensions, poses serious problems during the machining of such components, presenting challenges beyond standard machining practices. The low rigidity and the large size necessitate special machining conditions, such as the use of 5-axis machines that enable the machining of multiple surfaces from one clamping jaw. This prevents the workpiece walls from undergoing elastic deformation, which impact the shape and dimensional accuracy of part. Other options include special clamping systems [3-5], specialized cutting tools [6], and more. The continuous thinning of the part wall thickness during machining causes the stiffness to become increasingly low, predisposing the part to vibration and deformation [7]. It is possible for the material itself to play an important role in these effects [8, 9], mostly because of its high springback (specific to the aeronautics industry alloys), which is caused by residual stresses [10–12].

The cutting force also directly affects the deformation of the workpiece and the quality of the machined surfaces. In turn, it is influenced by different factors, such as the geometry and material of the tool, the material of the workpiece, the cutting depth and speed, the milling method, the lubrication conditions, etc.

The purpose of the current work is to inspect the impact of the two most important parameters in machining thin-wall parts, i.e., cutting speed and feed rate, on the cutting forces and the quality of parts, which was quantified by two parameters, namely residual stresses within the superficial machined layer and machined surface roughness.

The need for the current study resulted from the need to find solutions to a series of issues faced by mechanical processing workshops that do not have the necessary time or personnel specialized in research and development activities and have also limited resources.

2. EXPERIMENTAL METHODOLOGY

2.1 Material, tool, and equipment used for experiments

The experimental tests were carried out on plates of 6061-T651 aluminum alloy, measuring 80 x 60 x 20 mm. This alloy is a high-quality material, renowned for its high corrosion resistance and very good strength/weight ratio, which makes it a very good solution for a broad spectrum of aerospace applications (e.g., wings, fuselages, stabilizers, etc.).

A KNUTH RAPIMILL 700 CNC milling machine, outfitted with a Siemens 802D sinumerik control unit, was used for the experimental testing. The machine's characteristics include a maximum power of 4.7 kW, a continuously variable spindle that can reach 10000 rpm, and feed rates of 24m/min on the Z axis and 30m/min on the X/Y axes, respectively.

An ECA-H3 10-22/40C10CF-R02 ISCAR chatterfree, 3-flute solid carbide endmill with a diameter of 10mm was used to perform the experiments [13].

Each workpiece was fixed in a fixture device that was mounted on a Kistler dynamometer which can measure forces up to 5kN in all three directions (x, y, z) and a momentum. The dynamometer was fixed on the milling machine table (Figure 1).

The roughness of the processed surfaces was measured with a ZeGage Pro profilometer from AMETEK, Germany, equipped with a 10X ocular, which has a field of view (FOV) of 0.83/0.83 mm and lateral resolution of 0.815 μm.

A μ-X360s X-ray residual stresses equipment from PULSTEC Industrial Co., Ltd., Japan, was used to detect residual stresses. Its working principle is based on the cosα law [14, 15].

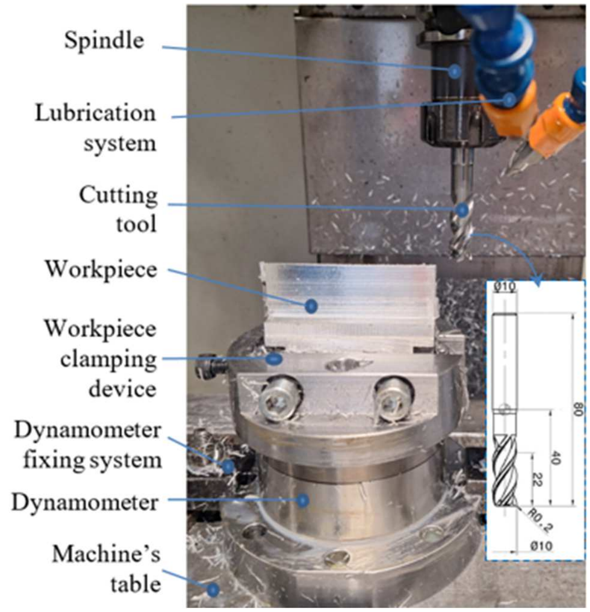


Fig. 1. The experimental setup

2.2 Machining parameters and procedure

The experimental tests were conducted by using the process parameters presented in Table 1.

A T-shaped cantilever (Figure 2) was chosen as the part to be machined using the up-milling strategy, which is recommended in case of unstable conditions, such as thin-wall machining. The cantilever height was obtained in three successive levels, employing a jump-to-jump toolpath in the z-axis direction and a "Christmas tree" routine to reduce vibrations while maximizing productivity. The minimum quantity lubrication (MQL) solution was chosen for lubrication due to its resource-saving nature and environmental friendliness [16, 17].

A mix of water and B-Cool 755 cutting fluid from Blaser Swisslube, which is mineral oil-based and chlorine-free, was sprayed onto the tool surface in a 10:1 ratio, as illustrated in Figure 1.

Table 1

Machining parameters

Variable factors	**Values**		
Feed rate, f_z [mm/tooth]	0,02	0,04	0,06
Cutting speeds, v_c [m/min]	126	188	283
Constant factors	**Values**		
Axial cutting depth, a_p [mm]	9		
Radial cutting depth, a_e [mm	1,3		
Tool diameter, d [mm]	10		
MQL lubrication [ml/hour]	100		

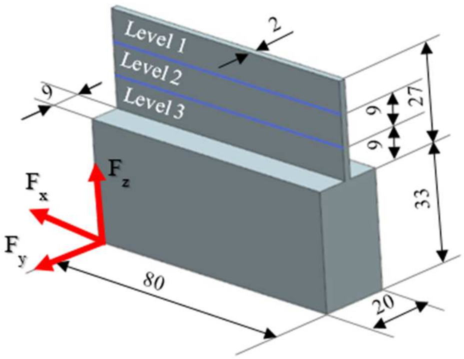


Fig. 2. The geometry of the machined part

The cutting forces on the three directions (F_x, F_y, F_z) were captured during machining process. The obtained data were imported into Excel, where the maximum values of the three components of milling force were extracted. The obtained results in response to the variation of the two considered variables (feed rate and the cutting speed, respectively) are displayed in the Results section.

The residual stresses in the machined superficial layer and the machined surface roughness (Ra) were also measured. Three measurements of each response have been carried out, and the mean of the recorded values was calculated and further used for data processing. The scanned area on each sample for determining the surface roughness was 800 x 5000 µm, obtained by stitching eight separate images/captures, aligned along the y-axis.

A Cr X-ray tube was used to perform the measurement, as it is suitable for aluminum alloys, according to the equipment prescriptions. The system provides a single incident X-ray angle detection using a 2-dimensional sensors and the stresses are then determined by using the Debye-Scherer ring.

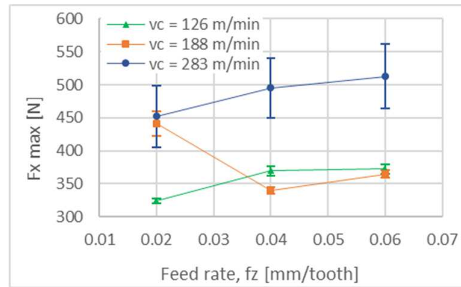
3. RESULTS AND DISCUSSIONS

3.1 Effects of the feed rate and cutting speed on cutting force components

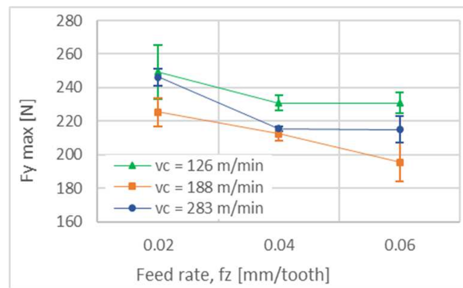
The influence of feed rate on the cutting force components is presented in Figure 3.

It can be observed from the graphs that when feed rate (f_z) increases:

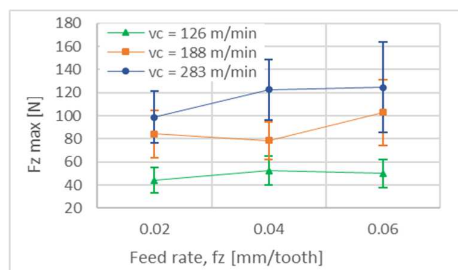
- the F_x force increases for v_c = 126 m/min and 283 m/min, and decreases for v_c = 188 m/min;
- decreases the force F_y for the three values of cutting speed;



a. effect of feed rate on the force F_x



b. effect of feed rate on the force F_y



c. effect of feed rate on the force F_z

Fig. 3. Effects of feed rate on cutting force components.

- increases the force F_z for the three values of the cutting speed.

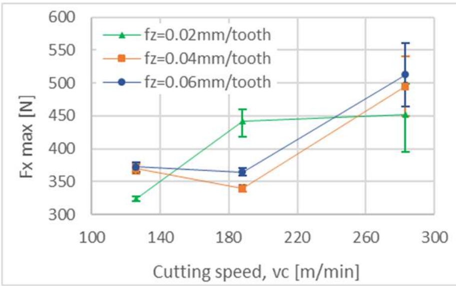
Similar tendencies of variation were reported in [18] for similar ranges of working regimes.

The effects of cutting speed on the cutting force components is presented in Figure 4.

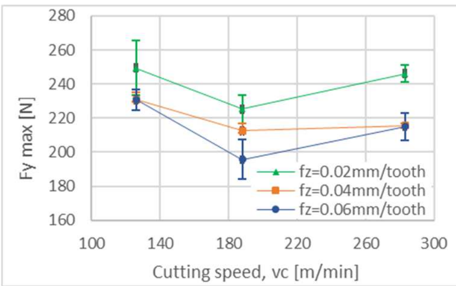
It was found that increasing of the cutting speed (v_c) determines:

- increasing of the force component in the machining direction, F_x;
- decreasing of force în y direction, F_y;
- increasing of force in z direction, F_z;
- for the F_x and F_z force components, the highest measured values were recorded for the highest value of the cutting speed, v_c = 283 m/min, while the highest value for F_y was measured

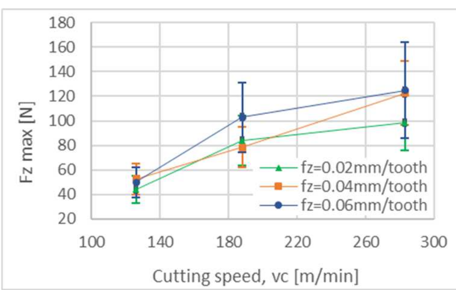
when machining using the smallest cutting speed, v_c = 126 m/min.



a. effect of cutting speed on the force F_x



b. effect of cutting speed on the force F_y



c. effect of cutting speed on the force F_z

Fig. 4. Effects of cutting speed on cutting force components.

It was noticed that higher working speeds led to larger standard deviations from the mean of the Fx and Fz forces measured on each part. This is due to lower forces' values as the tool descends towards the fixing base of the workpiece (forces recorded on level 3 of the part wall were up to 23% lower than those recorded on level 1). This emphasizes the importance of the presence of a part wall stiffening system to decrease vibrations during machining [4].

3.2 Effects of the feed rate and cutting speed on residual stresses

The variation of residual stresses as a function of feed rate and cutting speed is shown in Figure 5 and Figure 6, respectively.

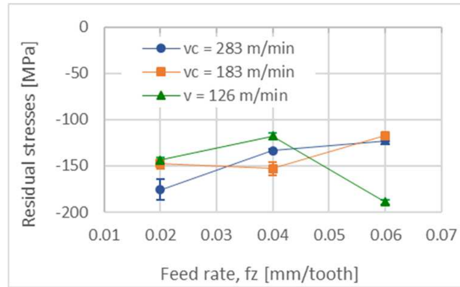


Fig. 5. Effects of feed rate on residual stresses.

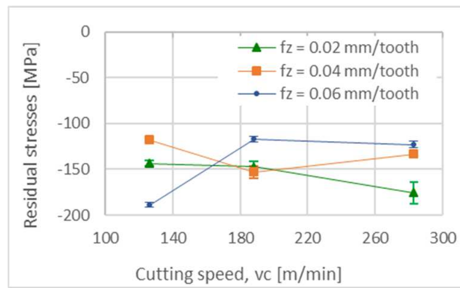


Fig. 6. Effects of cutting speed on residual stresses.

As the graphs indicates, it was found that:

- when using low feed rates, residual stresses get higher as the value of cutting speed increases. Conversely, when using high feed rates, higher values of cutting speed leads to a decrease of the residual stresses.
- at low values of the cutting speed, if the feed rate increases, residual stresses increase. For high values of the cutting speed, the increased feed rate decreases residual stresses.

Similar findings were reported in [19]. The explanation for why residual stresses increase when using either low cutting speeds and high feed rates or low feed rates and high cutting speeds is because the tool and workpiece are in contact for a longer time (the residual stresses measured in the machined surface layer are all compressive stresses).

3.3 Effects of the feed rate and cutting speed on surface roughness

The effects of the feed rate and the cutting speed on the machined surfaces' roughness is shown in Figure 7 and Figure 8.

The graphs reveal that increasing both feed rate and cutting speed lead to the increasing of surface roughness.

Normally, increasing the value of cutting speed should have resulted in a decrease of surface roughness.

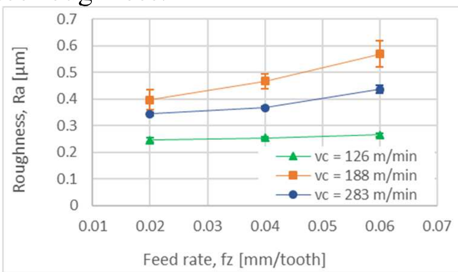


Fig. 7. Effects of feed rate on surface roughness.

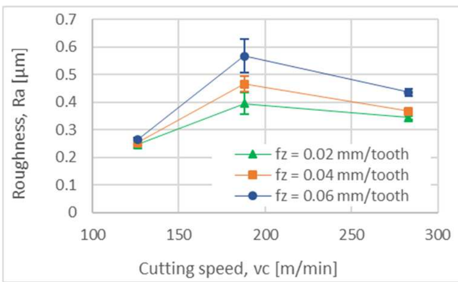


Fig. 8. Effects of cutting speed on surface roughness.

One reason why the roughness might have gotten worse in this case could be related to the dynamics of the process, which get stronger as the cutting speed goes up. This makes the vibrations stronger in parts with thin walls and hence higher roughness.

4. CONCLUSIONS

The current paper presents the results of a study on the effects of two factors (i.e., cutting speed and feed rate) on cutting force, residual stresses within the superficial layer, and surface roughness (Ra) when milling thin-walled parts.

For the machining regimes used, the findings were that increasings the values of feed rate and cutting speed has the following effects on the process performance:

- generally, the total cutting forces increase; it was also noted that cutting force in the feed direction (F_x) drops up as the tool gets closer to the blank's fixing base for high machining speeds.
- the residual stresses in the superficial layer are getting higher, when low values of the cutting speed (v_c = 126 m/min) and, respectively, low values of the feed rate (f_z = 0,02 and 0,04 mm/tooth) are used;
- the increase of the surface roughness.

As a result, low machining speeds are recommended for the tested working regimes for the quality improvement of both the milling process and the parts that are made. This is because they result in lower forces, smoother surfaces and higher compressive residual stresses which improve the functional reliability of parts.

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Studiul forțelor de așchiere și al parametrilor de calitate ai pieselor cu pereți subțiri prelucrate prin frezare

Studiul prezentat în această lucrare a avut drept scop analiza impactului a doi parametri de proces (viteza de avans și viteza de așchiere) asupra forțelor de așchiere și a doi parametri de calitate ai pieselor (tensiunile reziduale în stratul superficial și rugozitatea suprafeței) la frezarea pieselor cu pereți subțiri. S-a constatat că, la creșterea vitezei de așchiere și a vitezei de avans se obține, de obicei, o creștere a forței de așchiere, precum și a rugozității suprafeței și a tensiunilor reziduale. Tensiunile reziduale măsurate au fost toate tensiuni de compresiune.

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