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**STUDY OF RESIDUAL STRESSES IN MACHINED PARTS WITH
DIFFERENT MACHINING STRATEGIES OF AISI 6351 ALUMINUM
ALLOY**

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Abstract. *The machining of parts using machine tools has undergone many developments over the last few decades. The first machines had low cutting speed, considering that mechatronics had limitations. However, with advances in mechatronics and information technology, these machines can now operate at much higher speeds. In this context, the cutting speeds had a great increase. This change allowed complex machining. This additional potential made it possible to work on a major problem when machining parts with elaborate geometry and thin thickness. This study grows in importance for the manufacture of parts in which warping compromises the functional performance, such as parts of aircraft wing control surface. In this article, we intend to characterize the machining strategy, evaluating machining parameters such as depth, cutting speed and cutting width. The methodology used is the machining of specimens using combinations of relevant cutting parameters with the subsequent evaluation and characterization of geometric and dimensional changes. The results showed a higher residual stress when machining at a greater depth of cut and a smaller width of cut.*

Keywords: *Residual stresses, machining strategy, machining aluminum.*

1. INTRODUCTION

Milling, like other machining methods, can introduce residual stresses into the material. These stresses have significant implications for the material's in-service performance, especially in terms of fatigue resistance, corrosion, and distortion. Aluminum alloys, widely used in the aerospace, automotive, and other industries, are often subjected to milling processes. Residual stress is the internal tension present in the material without the application of external loads (Niku-Lar, 1987). These stresses can be beneficial or detrimental, depending on their magnitude and direction. When milling aluminum alloys, residual stress can arise due to plastic deformation caused by the cutting tool's action, localized heating due to friction and cutting, followed by uneven cooling, and microstructural variations resulting from machining. Several process factors, such as cutting speed, cutting depth, tool type, coolant, and feed, can influence the profile and magnitude of residual stresses (Griffiths, Brian., 2001). Berry *et al.* (2022) examined how the milling-induced residual stresses affect the fatigue life of aluminum alloys. Using commonly engineered 7075 aluminum alloys, samples were milled under three different conditions to induce varying levels of residual stress. The residual stresses were later measured using the drilling technique. The samples were then subjected to cyclic fatigue tests to determine their lifespan. It was discovered that compressive residual stresses were generated due to an increase in feed per tooth combined with a reduction in cutting speed on the material's surface. The fatigue test concluded that this increase in compressive stress improved the fatigue life by delaying the initiation and propagation of cracks.

X-ray diffraction (XRD) is a versatile technique used in many industries to assess residual stresses in crystalline materials and provides information about the mean state of stress in a thin surface layer of the material (Prevý, Paul S. et al., 1986). The basic principle for stress measurement by XRD is since when a crystalline material is controlled to mechanical stresses or temperature variation, the crystalline lattice is distorted (Prevý, Paul S. et al., 1986). This distortion causes changes in the crystallographic properties of the material. By measuring these changes, it is possible to determine the residual stresses present. The most used methodology for measuring residual stress is $\text{Sen}2\psi$. This methodology consists of rotating and tilting the sample at different angles. The prepared sample is placed in a

diffractometer where various diffraction patterns are collected around the upper 2Theta diffracted plane, as this provides greater accuracy for stress measurement (Fitzpatrick, M.E. et al., 2006).

A study conducted by Ullah et al., (2022) numerically and experimentally investigated the thermo-mechanically induced residual stresses during high-speed milling of the Ti-6Al-4V alloy. Advanced numerical models were employed to simulate the milling process and predict the generation of residual stresses. The results showed that high-speed milling induces a complex combination of residual stresses in the material, resulting from thermal and mechanical deformations. It was observed that the cutting speed, feed, and cutting depth play crucial roles in the magnitude and distribution of residual stresses. Another study led by Rahul et al., (2021) the study introduces a novel methodology aimed at predicting the sub-surface residual stress generated during micro end milling of the Ti-6Al-4V alloy. The research employed both experimental and computational techniques. Physical milling experiments were performed on Ti-6Al-4V samples under controlled conditions using micro end mills. The resultant sub-surface residual stresses were then measured using methods like X-ray diffraction. Parallely, a computational model was developed, taking into consideration factors like tool geometry, cutting parameters, material properties, and thermo-mechanical loads. Finite Element Method (FEM) simulations were used to simulate the micro end milling process and predict the resultant stresses. The experimental results showed a significant presence of residual stresses beneath the milled surface, which can be attributed to factors such as the tool's cutting action, heat generated, and material's plastic deformation. The developed computational model was successful in predicting these stresses with good accuracy when compared to experimental results. The study also highlighted the critical parameters that significantly influence the induction of these stresses.

Residual stresses introduced by milling in aluminum alloys can have significant effects on the component's performance. A detailed understanding of these stresses and the process variables that influence them is crucial for optimizing the machining process and ensuring the component's in-service reliability. Thus, with the use of residual stress verification, using the XRD technique, the final objective is to verify the behavior of the surface residual tension after different machining strategies. The main difference in strategies is the variation in cutting depth and cutting width.

2. MATERIALS AND METHODS

The test carried out had the following methodology: an aluminum block was machined, generating 6 new blocks (Figure 1). And in new block a different machining strategy was carried out. Then, each strategy was separated in order to facilitate the installation of the samples in the X-ray diffraction machine. Then the samples were prepared for checking the superficial residual stress.

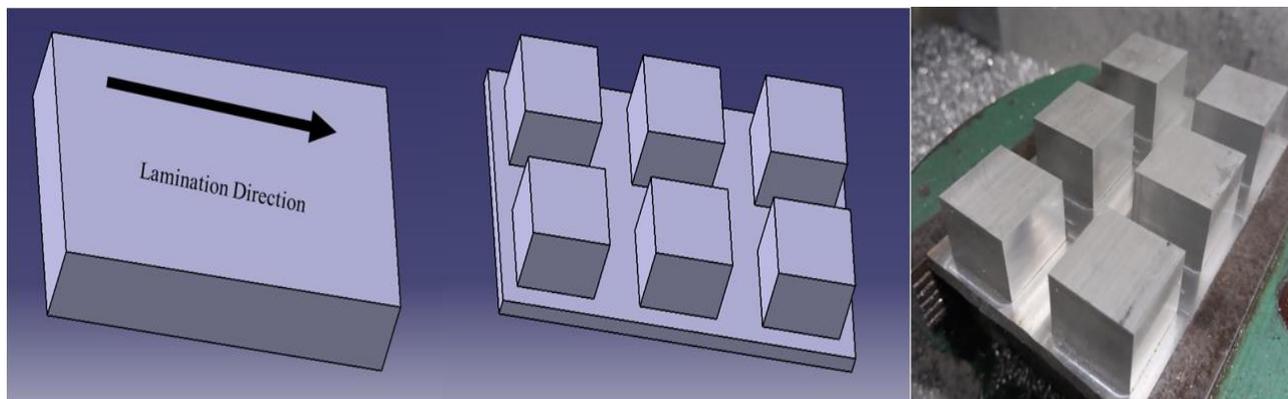


Figure 1. Test specimen.

The material studied in this work is the aluminum alloy AISI 6351. This alloy is an aluminum alloy that belongs to the 6000 series. It has resistance and ductility properties (Table 1), which makes it suitable for several industrial applications (Santos and Machado, 2016). Aluminum alloy 6351 mainly contains aluminum (Al), magnesium (Mg) and silicon (Si) as its main alloying elements. The amount of magnesium in the composition helps to improve the strength of the alloy, while silicon contributes to its responsiveness to heat treatment. This alloy has relatively high mechanical strength which makes it suitable for several industrial applications (Ferry and Kissell, 2002).

The specimen used was of alloy AISI 6351 T6. The heat treatment involves two main steps: solubilization and aging.

The specimen used was of alloy AISI 6351 T6. The heat treatment involves two main steps: solubilization and aging. In the solubilization step, the material was heated to a high temperature, around 500 °C to 550 °C, and rapidly cooled. In the aging step, the alloy was heated at a relatively lower temperature, between 150 °C and 180 °C, for several hours (ASTM Standards, B597)

This treatment does not include a process for relieving tensions. Therefore, it is more susceptible to post-machining deformations and warping.

Table 1. Characteristics of Aluminum alloy AISI 6351-T6 (matweb.com)

Physical Properties	Value
Hardness, Brinell	95
Hardness, Rockwell A	40
Hardness, Rockwell B	60
Tensile Strength, Ultimate, MPa	310
Tensile Strength, Yield, MPa	283
Elongation At Break	14%
Modulus of Elasticity, GPa	68.9
Poissons Ratio	0.33
Shear Modulus, GPa	26
Shear Strength, MPa	200

This specimen was originated from a 1”x 3” laminated flat bar (25.4 mm x 76.2 mm) (Figure 1). The specimen was divided into 6 blocks, where each block receives a type of machining strategy. The test was performed with 6 different strategies. Each strategy is a combination of 4 factors: rotation of tool (RPM), feed rate (FR), tool cutting depth (a_p) and tool cutting width (a_e) (Figure 2).

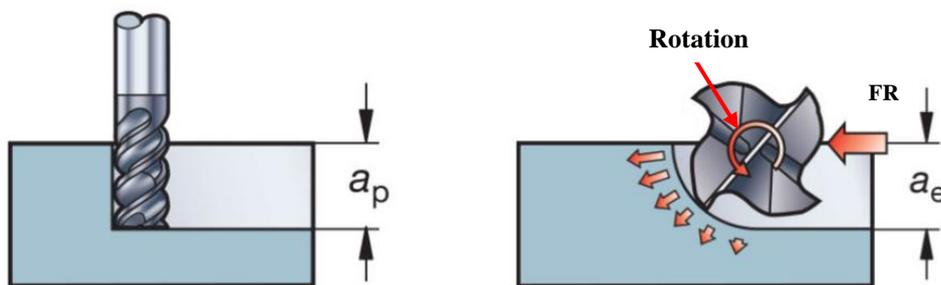


Figure 2. Illustration of milling (detail of cutting depth and cutting width).

Roughing with climb milling was used, as it is a machining technique in which the direction of rotation of the cutting tool is the same as that of the workpiece. In this technique, the cutting tool contacts the material in a direction that matches the feed motion.

This milling has some important characteristics, which is the reduction of cutting forces, because the down-cut milling reduces cutting forces compared to up-cut milling. This occurs because the cutting geometry allows the tool to enter the material smoothly, generating less resistance and less load on the tool.

Therefore, residual stresses in down-face milling are mitigated compared to up-cut milling. This reduction is due to the fact that in the down-cut there is a reduction of plastic deformations during down-cut milling. This is because down milling pulls the material into the cut, while up milling pushes the material out. Thus, the reduction of plastic deformations results in less residual stress flux on the machined surface.

Another advantage of climb milling is better heat dissipation, as the heat generated during the machining process is directed in such a way as to expel the chip along with the energy generated in the cut.

In the test, milling was performed on a CNC milling machine (Computer Numerical Control) with movement in 3 Cartesian axes. The movement is driven by ball screw that are coupled to servomotors. In addition, the spindle rotates the cutting tool (mill) capable of removing material from the part being machined, which can generate different shapes and geometries. However, in this work, only one face milling of the surface was carried out at a depth of 18 mm.

For this process, Solidworks® software was used for CAD/CAM modeling with machine code generation (G Code). This machine code was loaded into the CNC machine, which automatically performed the milling operations according to the instructions. It was performed with 6 different milling strategies as seen in Figure 3 and Table 2.

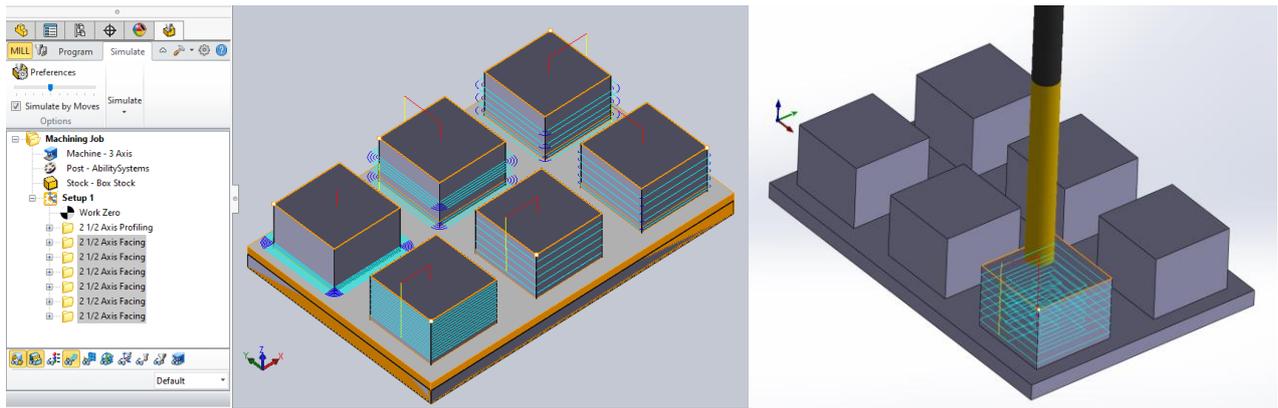


Figure 3. Image of the Solidwork® Software used to generate the machine code.

Table 2. Strategies used on milling.

Strategy	RPM	Feed Rate (FR) (mm/min)	Cutting Depth (a_p) (mm)	Cutting Width (a_e) (mm)	Time of Milling (s)	Volume Milling (FR x a_p x a_e) mm^3/min
1	12000	500	18	0.8	5.48	7200
2	12000	500	9	1.6	5.59	7200
3	12000	400	6	2.4	4.36	7680
4	12000	400	3	4.8	3.44	5760
5	12000	300	2	6	4.94	3600
6	12000	300	1	6	9.89	1800

In this machining, an 8.0 mm diameter cutter with 3 cutting edge and a 55° helix was used. This tool (end mill) started the first strategy in new state. For machining, the aluminum block was fixed in a vise, being completely attached to the router table (Figure 4). Figure 5 shows the specimens after milling.



Figure 4. Machining of specimens for analysis of residual stress.

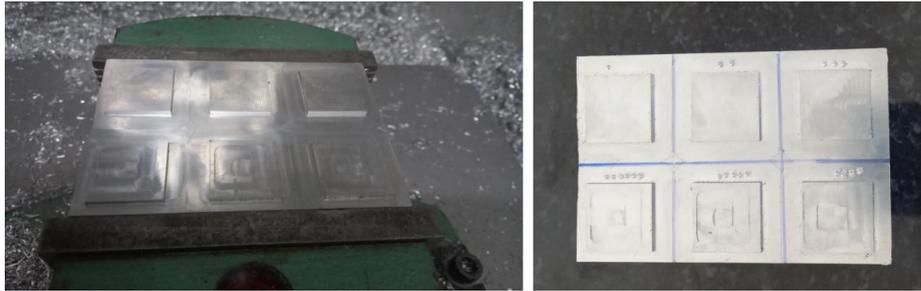


Figure 5. Photo of the specimens after milling.

a. Specimen test preparation

The samples to be analyzed by XRD were ground, mechanically polished with diamond paste and chemically polished with a solution containing 10% of HNO₃.

b. Residual stress measurements

The residual stress measurements by XRD, with Sen²ψ methodology were performed using PANalytical X'PERT PRO MRD diffractometer. The voltage and current were 40 kV and 40 mA, respectively, with cobalt radiation (Co-Kα). Measurements were performed on the surface of the samples. The peak analyzed was the one with the greatest angle 2Theta (77°). The X'Pert Stress software was used for the post-processing of the stress measurements. The values of 68.9 GPa and 0.33 were used as the modulus of elasticity and Poisson's ratio, respectively.

3. RESULTS AND DISCUSSION

Table 3 and Figure 6 show residual stress values obtained by XRD.

Table 3. Measurement with Ray-X diffraction.

Test Specimen	Cutting Depth (a _p) (mm)	Residual Stress (MPa)	Deviation (MPa)
1	18	26.4	6.4
2	9	7.5	7.7
3	6	10.1	5.6
4	3	10.4	5.3
5	2	6.1	7.6
6	1	9.6	7.0

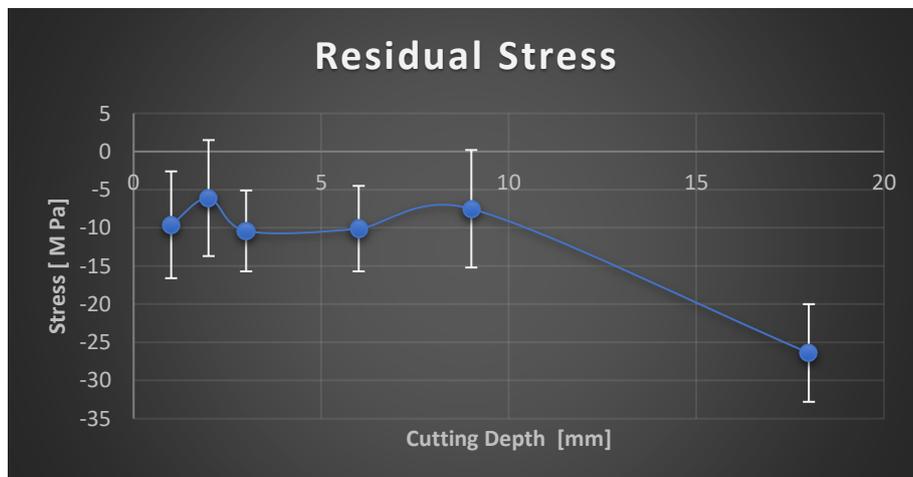


Figure 6. Graphic results.

The choice of cutting depths (18 mm, 9 mm, 6 mm, 3 mm, 2 mm and 1 mm) for the test were chosen because they are widely used in the industry in general. The results showed that machining with a cutting depth of 18 mm caused a higher surface tension than other strategies. This type of machining (greater depth and smaller cutting width) is used for HEM (High Efficient Machining), which is based on the theory involving radial chipping. In this theory, the reduction in chip thickness allows the use of higher cutting speeds. In this machining, the general trend is a decrease in surface tension, however, for the 6351 T6 aluminum alloy this relationship was not observed.

Another observation is that a similar combination of $a_p = 3$ mm and $a_e = 4.8$ mm resulted in shorter machining time, but without compromising the final residual stress.

4. CONCLUSION

From the results obtained in this work, it can be concluded that:

- The machining strategy with a depth of cut of 18 mm caused the condition of higher residual stress tension;
- The combination of $a_p = 3$ mm and $a_e = 4.8$ mm resulted in a shorter machining time, but without compromising the final residual stress;
- This greater residual stress can lead to warping in the case of parts with small thickness and complex geometry.

Finally, for rougher and initial machining, the use of greater cutting depths with a smaller cutting width, which better distributes the energy on the toll shank, can be used. However, when carrying out finishing machining, it is recommended to use smaller cutting depths to avoid large residual stresses and warping for thin parts.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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