

Study of residual stresses from two machining protocols using an indentation method

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Abstract: Although high-speed machining offers a number of advantages over conventional machining, it is possible that the residual stress distributions generated by the former can affect the service life of the processed components. In this paper, a newly developed micro-indent method is used to evaluate different residual stress states, which were introduced in samples of AA 7075-T6 aluminum alloy milled at low and high-speed. Different surfaces were generated by varying the cutting speed in one order of magnitude, from 100 m/min to 1000 m/min. Two machining protocols, which consist of using different machine tools, were evaluated. The results show that it is possible to generate and to evaluate very small residual stresses. Finally, the values and levels obtained for normal components were analyzed in function of mechanical and thermal effects that generated the residual stresses.

Keywords: Residual Stresses, Machining, Aluminum Alloy, Indentation Method

1. Introduction

Residual stresses are inevitably introduced when a mechanical component is machined. These stresses are caused by local plastic deformation generated by the interaction between the cutting tool and the component, and also, by the heat conducted from the primary deformation zone to the new surface [1,2]. In turn, both the local plastic deformation and heat flow depend on the mechanical properties of the machined component, as well as on the process parameters, geometry, design and condition of the cutting tool, and also, on the cooling conditions. It is noteworthy that a small variation in one of the selected process parameters may substantially change the level and/or sign of the residual stress distribution generated in the new surface. Therefore, it is very important to determine these levels and signs in order to know if the machined component has been strengthened or weakened in its surface.

The methods for the measurement of residual stresses can be classified as direct and indirect. The former consist of determining the residual stress components from the

measurement of different physical properties, which are altered by the introduction of these stresses. On the other hand, indirect methods require breaking the equilibrium of forces and moments of the stressed component, which can be obtained by implementing a cutting or the removal of any part of the material evaluated. Among the direct methods, X-ray diffraction has been the most used technique to evaluate residual stresses in surfaces generated by machining [3,4]. Regarding the indirect methods, the most common approach has been the hole-drilling method [5,6].

Moreover, in recent years different techniques have been developed in order to determine residual stresses through the introduction of micro or nano-indents in the surface to be evaluated. Most of these methods compare the contact depth or load-displacement curve of stressed and unstressed specimens, from which the residual stresses can be estimated [7,8]. Recently, Wyatt and Berry [9] developed a technique based on the change that occurs in the distance between micro-indents when the machined component is subjected to a distension treatment. More recently, through an optimized version of this technique, it was possible to conduct different studies in order to analyze the influence

of high-speed machining process parameters on the generation of residual stresses in samples of different aluminum alloys [10-12].

The determination of residual stress values within the range of ± 10 MPa with a very small measurement error is not possible using traditional measurement techniques such as X-ray diffraction or the hole-drilling method. The purpose of this work is to generate very low residual stresses and to evaluate them using the optimized micro-indent technique previously mentioned. Residual stresses were introduced in samples of AA 7075-T6 aluminum alloy. The machining tests were carried out from two protocols, each of which used a particular type of machine tool. The performance of these machines was evaluated using the same cutting tool for both cases. It is noteworthy that such machines, CNC machining center Victor Vc-55 and CNC vertical milling machine Clever CMM-100, have different wear states. The results show that for both protocols residual stresses were compressive, and of low levels. The normal components of the residual stress were extensively analyzed in function of their directions. Finally, the results obtained for these components were correlated in terms of mechanical and thermal effects that generated the residual stresses.

2. Experimental Procedure

In this work we carried out face milling tests through the implementation of central cutting to determine the main effects of different process parameter combinations on the induced residual stresses. These stresses were determined at 3 points of each generated surface. Fig. 1 shows the new surface (63×40 mm) and the location of these points, that lie along the central line separating the conventional cutting zone ($x > 0, y$) from the climb cutting zone ($x < 0, y$). As mentioned previously, these tests were carried out using the same tool and inserts in different machine tools: a numerically controlled vertical machining center (Victor Vc-55) installed in a laboratory, and a numerically controlled vertical milling machine (Clever CMM-100) installed in a high-production industry. Table 1 shows the different combinations of process parameters for each test, and also, the corresponding machine tool.

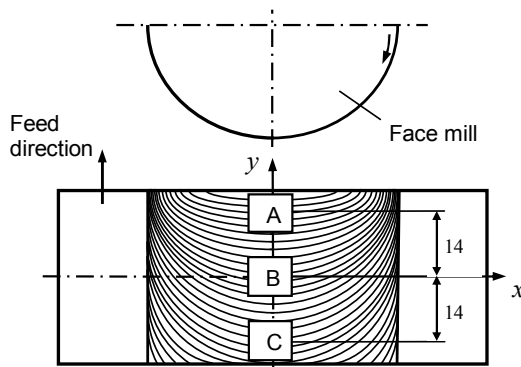


Figure 1. Milled surface. The units are in mm.

Table 1. Selected process parameters

Test number and machine	Process parameters		
	Cutting speed V (m/min)	Feed per tooth f_z (mm/tooth)	Depth of cut d (mm)
1 - Victor	100	0.16	0.40
2 - Victor	1000	0.16	0.40
3 - Clever	1000	0.04	1.00
4 - Clever	1000	0.04	1.25

The material evaluated in this study was AA 7075 - T6 aluminum alloy. Table 2 and 3 show respectively the chemical composition and mechanical properties of this rolled product with 4 mm in thickness. This material was subjected to a distension heat treatment to ensure a residual stress free state before machining. The heat treatment was carried out after preparing the specimen geometry. The values corresponding to this treatment were 573 K and 80 minutes. Finally, the cooling process was carried out in the oven (Dalvo HM2).

The details of the indentation technique used in this work for determining different components of the residual stress can be found in previous studies [10-12]. In general terms, this technique consists of two stages. First, a series of micro-indentations are introduced in the surface to be evaluated. Then, the micro-indent coordinates are measured, before and after a thermal distension treatment, using a universal measuring machine (UMM) of high accuracy. It is noteworthy that these machines are very versatile, allowing to carry out different types of measurements in mechanical components, including the determination of orthogonal coordinates (x, y, z) at any point through the incorporation of a high precision microscope in the main header of the machine [12]. Moreover, to carry out the aforementioned machining tests, we used a face mill of 63 mm in diameter. Five tungsten carbide equally spaced inserts (Palbit Seht AFFN-AL 1204 SM10) were incorporated to the face mill. It is important to note that these inserts were specially designed for machining high strength aluminum alloys.

Table 2. Chemical composition of the investigated aluminum alloy

Chemical composition (wt %)							
Zn	Mg	Cu	Fe	Si	Cr	Mn	Al
5.6	2.52	1.72	0.32	0.2	0.17	0.16	balance

Table 3. Elastic and mechanical properties

Properties					
σ_{II} (MPa)	σ_{yI} (MPa)	A (%)	HV0.5	E (GPa)	ν
564	514	11	186	70	0.33

Fig. 2 shows the state of residual stresses generated in the centroid of the new surface (point B). For obtaining the normal components of the residual stress (σ_x, σ_y) at any

point of the surface, four micro-indenters must be introduced at the corners of a square whose centroid is the point to be evaluated [11]. Then, as mentioned previously, the micro-indent coordinates are measured, before and after a distension treatment, using a precision microscope incorporated to the measuring machine (GSIP MU-314). Afterwards, by processing all micro-indent coordinates associated to the evaluated point, it is possible to obtain the normal components of the residual strain (ε_x , ε_y), which correspond to the centroid of the square [12]. Finally, through these strain components and assuming that the new surface is under plane stress conditions [13], the normal components of the residual stress, in the case of a homogeneous, isotropic and linear elastic material, may be expressed as

$$\begin{aligned}\sigma_x &= k_1 \cdot \varepsilon_x + k_2 \cdot \varepsilon_y \\ \sigma_y &= k_1 \cdot \varepsilon_y + k_2 \cdot \varepsilon_x\end{aligned}\quad (1)$$

where $k_1 = E/(1 - \nu^2)$, $k_2 = \nu \cdot k_1$, E is the elasticity modulus and ν is Poisson's ratio. The error corresponding to this method was estimated in the range of ± 0.9 MPa [10]. It is important to mention that all micro-indent coordinates were measured, before and after the distension treatment, within a temperature range of 20 ± 0.2 °C, with a rate of variation less than 0.01 °C/min. It should be noted that if this rate is higher than the mentioned value, the measurement error will significantly increase. With regard to the distension treatment, this was carried out for a period of 80 minutes at a temperature of 573 K.

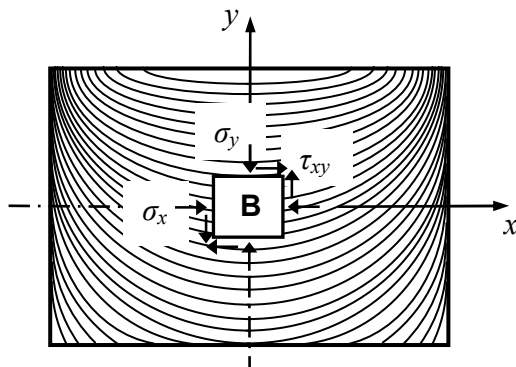


Figure 2. Residual stress components in the centroid B.

3. Results and Discussion

Fig. 3 shows the distributions of the normal components of the residual stress along the symmetry axis parallel to the feed direction. The y -coordinate of the points A, B and C corresponds to 14, 0 and -14 mm, respectively (see Fig. 1). In Fig. 3 (a) we compare the distributions of σ_x differing only in the cutting speed (one order of magnitude) and also those differing only in the depth of cut (25%). As expected, the change in the cutting speed generates a stress level difference higher than that generated by the change of the

depth of cut. When the cutting speed or depth of cut increases, the stresses become more compressive. Moreover, Figure 3 (b) shows the results obtained for the σ_y component. Although the slopes of the distributions corresponding to this component are smaller, the results are similar to those of Fig. 3 (a). The levels of the σ_y component seem to be moved about 4 MPa with respect to those corresponding to σ_x . It is noteworthy that this level displacement is towards a more compressive zone.

Table 4 shows the values obtained by subtracting σ_x from σ_y , for each of the milling tests and at each point evaluated. The average value of this subtraction was 4.25 MPa, with a standard deviation of 0.77 MPa, which corresponds to a coefficient of variation of 18%. These dispersion values, which are possible to obtain by using the present measurement method, help to predict an evident link between the local plastic deformation (mechanical effect) and the heat conducted towards the new surface (thermal effect), for both orthogonal directions.

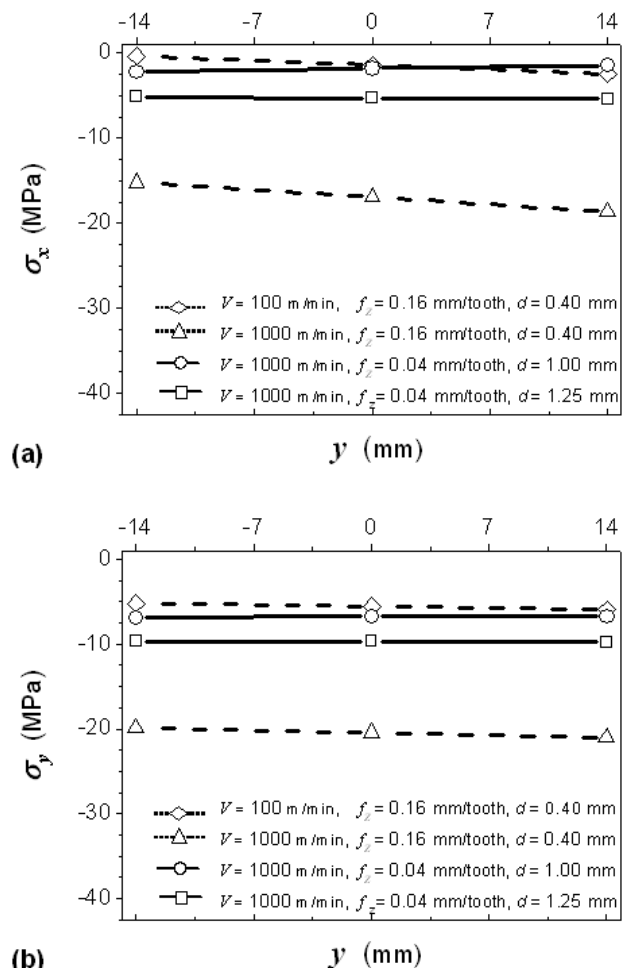


Figure 3. Residual stress components (a) σ_x and (b) σ_y along the axis $x = 0$.

Moreover, Table 5 shows the values of the increments corresponding to the normal components σ_x and σ_y . Regarding the Victor machine, these increases correspond to the change in the cutting speed, while on the Clever machine, they correspond to the change in the depth of cut.

It is important to mention that all increments shown in Table 5 are negative. For the tests carried out in the Victor machine, the mean values for $\Delta\sigma_x$ and $\Delta\sigma_y$ were -15.56 MPa and -14.99 MPa, respectively. For the tests performed in the Clever machine, the mean values for those increments were -3.47 MPa and -2.96 MPa, respectively.

Table 4. Subtraction of residual stress normal components

Evaluated points	$\sigma_y - \sigma_x$ (MPa)			
	Victor		Clever	
	Test 1	Test 2	Test 3	Test 4
A	3.45	2.36	5.20	4.35
B	3.96	3.54	4.96	4.45
C	4.86	4.66	4.72	4.54

Table 5. Increments corresponding to the normal components

Evaluated points	Increments (MPa)			
	Victor		Clever	
	$\Delta\sigma_x$	$\Delta\sigma_y$	$\Delta\sigma_x$	$\Delta\sigma_y$
A	-16.24	-15.15	-3.98	-3.13
B	-15.53	-15.11	-3.47	-2.96
C	-14.90	-14.70	-2.97	-2.79

In both machines, the similarity between increments corresponding to orthogonal directions indicates that the modification in one of the process parameters may generate, for both directions, similar changes in the combination of local plastic deformation and heat conducted to the new surface. Evaluating each of the values shown in Table 5, it is possible to establish the following relationship between increments of orthogonal components

$$\Delta\sigma_x / \Delta\sigma_y \approx 1.1 \quad (2)$$

By observing this relationship it could be added that, in both directions, the normal components of the residual stress show similar sensitivity to the modification in one of the main process parameters, which is true for the tests carried out in both machines.

It is important to note that the pattern corresponding to the subtraction of normal components observed in Table 4 is independent of both the evaluated machine tool and the combination of selected process parameters. Although it is infrequent that the normal component σ_y is greater than σ_x (in absolute value), this has been reported previously in a paper on milled titanium alloy components [14], but not explained. In another study about milling in samples of AISI 4340 steel, Jacobus *et al.* [15] show results where the normal component σ_y is also higher than σ_x but most values obtained are tensile. In contrast, in the present work all stress distributions are compressive. The possible causes generating these compressive stresses along the centerline are analyzed using Fig. 4. The pattern of levels obtained in the different milling tests is shown in Fig 4 (a). Although both levels are compressive, the one corresponding to the

component σ_y is slightly larger in absolute value. Moreover, the levels shown in Fig. 4 (b) represent the relative roles of mechanical and thermal effects in the generation of residual stresses. It is known that in principle compressive stresses are due to mechanical effects, and tensile stresses to thermal effects. At the points evaluated in this work, which correspond to the centerline, the component of the tangential cutting force in the x direction is maximized and the component in the y direction is zero. Moreover, the feed force direction corresponds to the y direction. Besides, this feed force is always smaller than the tangential cutting force [17]. For this reason, local plastic deformation in the x direction should be greater than that corresponding to the y direction. The levels of compressive stresses generated by local plastic deformation (mechanical effects) are shown in the aforementioned Fig. 4 (b). This figure also shows the levels of the thermal stresses. In this case, the tensile levels must be smaller (in absolute value) to their mechanical equivalents, since the final result is compressive. Furthermore, the normal components of residual stress generated by thermal effects must comply with the following expression

$$\sigma_{T_x} > \sigma_{T_y} \quad (3)$$

and also with

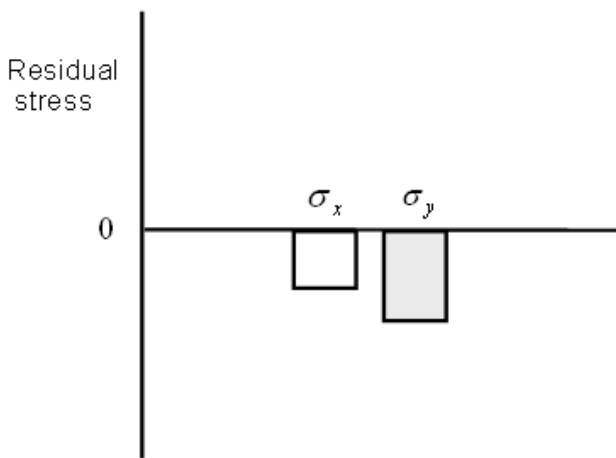
$$\Delta\sigma^T > \Delta\sigma^M \quad (4)$$

where $\Delta\sigma^T$ and $\Delta\sigma^M$ correspond to the differences between the levels of normal components generated by thermal and mechanical effects, respectively. This analysis based on Fig. 4 predicts an orientation effect in terms of the thermal energy conducted from the primary deformation zone to the new surface given that the levels of the thermal origin normal components are different. It is noteworthy that this orientation effect was not included in the work of Jacobus *et al.* [15] due to the fact that the thermal effects are the result of a scalar field of temperatures. In this work, the orientation effect would generate a very small heat flow difference, which could be due to a dynamic effect caused by the movement of the secondary cutting edge [16]. It is important to mention that the movement direction of this cutting edge is parallel to the x axis when it is passing through the line containing the evaluated points.

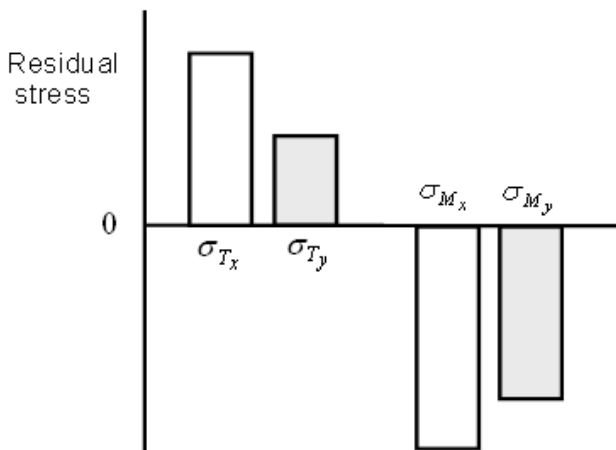
4. Conclusions

The micro-indent method used in this work allowed the determination of very low residual stresses, which were generated via face milling in samples of AA 7075 - T6 aluminum alloy. These stresses were determined along the symmetry axis parallel to the feed direction. Two machining protocols were evaluated through the use of different numerically controlled machine tools. The values corresponding to the subtraction of normal components of the residual stress were independent of both the used machine tool and the combination of selected process

parameters. This would suggest that the difference in local plastic damage and in conducted heat that is established between both orthogonal directions is unchanged. Furthermore, the normal component increments generated through the change of one of the process parameters were similar in each of the protocols, which indicate that the sensitivity to this modification is the same for both directions evaluated. Finally, the fact that in all cases the σ_y component of the residual stress is always greater than σ_x component (in absolute value), predicts an orientation effect regarding the heat flow conducted to the new surface. This effect could be caused by the movement of the secondary cutting edge, which has a specific direction when it passes through the segment containing the points evaluated.



(a)



(b)

Figure 4. (a) Global and (b) thermal and mechanical levels corresponding to normal components of residual stress.

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Nomenclature

A	elongation (%)
d	depth of cut (mm)
E	longitudinal elastic modulus (GPa)
f_z	feed per tooth (mm/tooth)
HV0.5	Vickers micro-hardness (test load: 500 gf)
k_1, k_2	elastic constants
V	cutting speed (m/min)
ϵ_x	residual strain at the x direction
ϵ_y	residual strain at the y direction
ν	Poisson's ratio
σ_x	residual stress at the x direction (MPa)
σ_y	residual stress at the y direction (MPa)
σ_{Mx}	mechanical stress at the x direction (MPa)
σ_{My}	mechanical stress at the y direction (MPa)
σ_{Tx}	thermal stress at the x direction (MPa)
σ_{Ty}	thermal stress at the y direction (MPa)
σ_u	ultimate tensile strength (UTS) (MPa)
σ_{yi}	yield strength (MPa)
$\Delta\sigma_x$	increment of the σ_x component (MPa)
$\Delta\sigma_y$	increment of the σ_y component (MPa)
$\Delta\sigma^M$	mechanical stress level difference (MPa)
$\Delta\sigma^T$	thermal stress level difference (MPa)

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