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**Research Article**

# Analysis of Residual Deformations and Stresses in a Rolled Sheet of AA 6082-T6 Aluminium Alloy Using a Micro-indent Method

[1]F.V. Díaz, [1]F.N. Rosso, [1]A.C. Walker, [1]C.A. Mammana and [2]A.P.M. Guidobono
[1]Departamento de Ingeniería Electromecánica-Departamento de Ingeniería Industrial, Facultad Regional Rafaela, Universidad Tecnológica Nacional, Acuña 49, 2300 Rafaela, Argentina
[2]División Metrología Dimensional, Centro Regional Rosario (INTI), Ocampo y Esmeralda, 2000 Rosario, Argentina

**Abstract:** The residual deformation and stress states, corresponding to a rolled product of AA 6082-T6 aluminium alloy used in naval structures, were comprehensively analyzed from data obtained using an optimized micro-indent method. A great advantage of using this method, which needs a measuring machine, is to avoid specific equipments and qualified personnel. Furthermore, the absolute measurement error of this technique is very small (±0.9 MPa). The results obtained through the analysis of Mohr's circles reveal compressive normal components prevailing in the residual deformation and stress states. A very important aspect is that the direction of the more compressive component is very close to the rolling direction. This may indicate the importance of the rolling process, which is previous to the thermal hardening process T6, in the final states of residual deformation and stress. Finally, the residual stress state of the evaluated material, which is quasi-isotropic, was compared with the failure stress by using the von Mises yield criterion for ductile materials.

**Keywords:** Micro-indent method, naval alloy, rolling, residual deformations, residual stresses

## INTRODUCTION

High-performance aluminium alloy sheets and plates show a broad range of industrial applications. For example, medium-strength sheets and plates are used in ship manufacturing and high-strength plates are employed in the automotive and aerospace industry. More specifically, medium-strength aluminium alloys, such as AA 6082-T6, are widely used for lightweight structural applications, especially in shipbuilding. In the lightweight ship industry, they are used in the structural members of the ship, namely in the stiffeners of reinforced panels (Almeida Bugio *et al*., 2013).

For preventing fatigue cracking in these structural members and to avoid past pitfalls (Sielski, 2007), it is imperative to perform rigorous evaluations of residual stresses. In the first place it is important to determine the sign of residual stresses. If this is positive, the tensile stresses can generate and propagate cracks in the surface of the member (Toribio, 1998; Schwach and Guo, 2006). On the contrary, if the sign is negative, the compressive stresses do not generate these problems. Then, it is very important to determine the values of the tensile or compressive stresses because the residual stresses must be added to those generated by service loads. If the addition of stresses is unknown and gets close to the failure stress of the material, it is possible that the collapse of the member occurs at the beginning of its service life (Rowlands, 1987; Withers, 2007).

In the last decades, two approaches have been extensively used for determining residual stresses: the hole drilling method (Rendler and Vigness, 1966; Gupta, 1973; Díaz *et al*., 2000) and X-ray diffraction (Noyan and Cohen, 1987; Prevéy, 1987). However, residual stresses can also be determined through instrumented indentation. Most approaches compare the contact depth or load-displacement curve of stressed and unstressed specimens, from which the residual stresses can be estimated (Suresh and Giannakopoulos, 1998; Swadener *et al*., 2001).

A more recent approach is based on the modification of distances between micro-indents (Wyatt and Berry, 2006). The change of these distances occurs when residual stresses are relaxed by means of a thermal distension treatment. This micro-indent method has the great advantage of being simple and inexpensive because it does not need specific equipment. For measuring the residual displacements, this approach only requires a universal measuring machine (Dotson *et al*., 2003; Curtis and Farago, 2007), a micro-hardness tester and an oven, which are commonly available in many workshops.

**Corresponding Author:** F.V. Díaz, Departamento de Ingeniería Electromecánica-Departamento de Ingeniería Industrial, Facultad Regional Rafaela, Universidad Tecnológica Nacional, Acuña 49, 2300 Rafaela, Argentina, Tel.: + 54 3492 432710; Fax: + 54 3492 422880

Table 1: Chemical composition (wt %) of the investigated aluminium alloy

| Mg | Si | Mn | Fe | Cr | Zn | Cu | Al |
|---|---|---|---|---|---|---|---|
| 0.9 | 0.9 | 0.6 | 0.5 | 0.22 | 0.2 | 0.15 | balance |

Table 2: Elastic and mechanical properties of the investigated aluminium alloy

| | Properties | | | | |
|---|---|---|---|---|---|
| $\sigma_u$ (MPa) | $\sigma_{y_{0.2}}$ (MPa) | A (%) | HV0.5 | $E$ (GPa) | $\nu$ |
| 290 | 250 | 11 | 108 | 70 | 0.33 |

The purpose of this study is to determine and evaluate comprehensively the residual deformations and stresses in a flat sheet of AA 6082-T6 aluminium alloy by using an optimized micro-indent method. It is important to note that this naval alloy is relatively new and, in literature, there are very few exhaustive studies about the residual deformations and stresses generated during the different kinds of processing to which is subjected this material (Díaz *et al*., 2010, 2011, 2012; Mammana *et al*., 2010). Regarding the above-mentioned optimized micro-indent method, a mechanical device of indentation is incorporated to the measuring machine, which allows reducing the absolute error of measurement to just ±0.9 MPa (Díaz *et al*., 2010). The absolute error of the more commonly used techniques, the afore mentioned hole drilling method and X-ray diffraction, is approximately ±25 MPa, therefore the present study would not be possible to accomplish by using these techniques. The obtained results show that the normal components are compressive independently of the evaluated direction and, in turn, appreciably larger than the tangential components, which are very low. A detailed analysis of these results was performed using a graphical tool denominated Mohr's circle (Gere, 2001). Through this tool it was possible to detect that the direction associated with the more compressive principal component is very close to the original rolling direction of the evaluated alloy. Therefore, in spite of the subsequent thermal hardening process T6, the rolling may have a very important role in the generation of the final states of residual deformation and stress. Finally, by using the maximum distortion energy criterion of von Mises (Budynas and Nisbett, 2008), the final state of residual stress was compared with the failure stress. Through this comparison it was detected that the value obtained for the von Mises stress represents an appreciable fraction of the failure stress, which would lead to serious difficulties when the evaluated component is subjected to service loads.

## EXPERIMENTAL PROCEDURE

The material evaluated in this study is a hot-rolled sheet of AA 6082-T6 aluminium alloy. The thickness of this rolled sheet is 4 mm. The T6 tempering process consisted of three phases: solution heat treating (550°C, 2 hours), quenching in water to room temperature and artificial aging (175°C, 8 h). Due to an optimized distribution of precipitate particles of $AlMg_2$ in the aluminium matrix, this alloy has the higher mechanical strength of the 6000 aluminium alloy series. In relation to the main features, they include very good mechanical properties and excellent corrosion resistance. Both the values of chemical composition and, elastic and mechanical properties of this material are reported in Table 1 and 2 respectively.

The dimensions of the sample evaluated in this study were 30×30×4 mm. With respect to the measuring method, in first place it consists in performing a micro-indent distribution in the surface to be evaluated. Then, the micro-indent coordinates are optically measured, before and after a thermal relaxation treatment (300°C, 80 min), using a special microscope assembled in the measuring machine (GSIP MU- 314), which is shown in Fig. 1. It should be noted that if the relaxation treatment is performed below the recrystallization temperature (Mao, 2003), the dimensional changes at the specimen will be governed only by the elastic relaxation of the lattice (the plastic

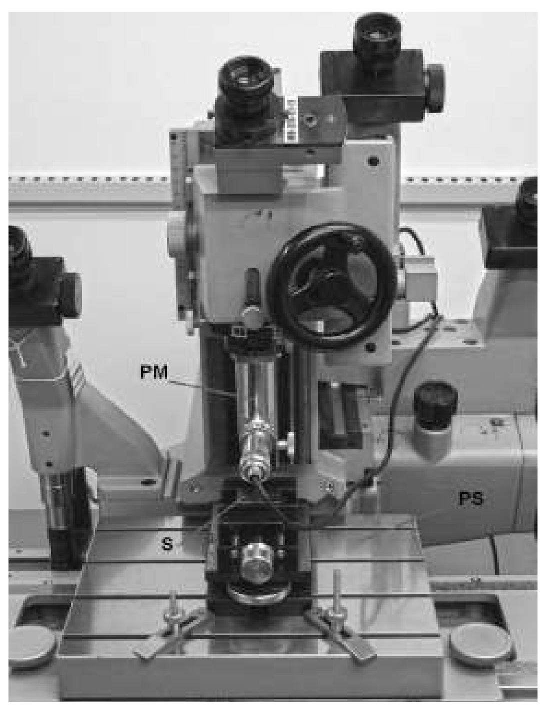


Fig. 1: Picture of the used measuring machine: (PM) precision microscope, (S) specimen, (PS) precision stage

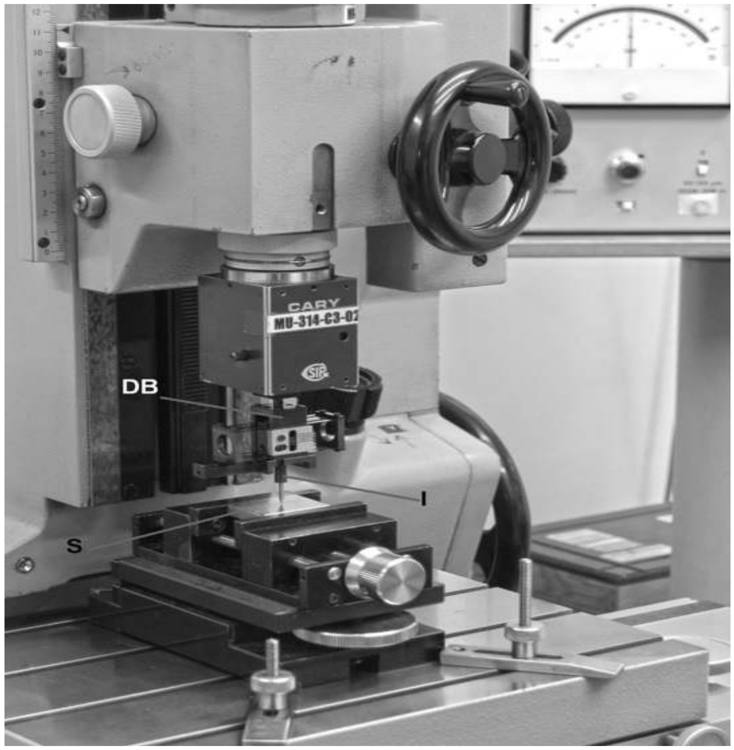


Fig. 2: Picture of indentator-specimen interaction; (DB): Device Body; (I): Indentator; (S): Specimen

flow activated by temperature is highly localized and it can be reduced to the annihilation of vacancies and dislocations of opposite sign and to rearrangement of dislocations into lower-energy configurations). In addition, if the specimen geometry is simple, the thickness is small and the cooling rate is slow, it is possible to avoid the development of thermal residual stresses.

In this study, a distribution of elongated micro-indents was introduced using the indentation device showing Fig. 2, which is assembled in the universal measuring machine (Díaz *et al*., 2010). By means of this device it is possible to achieve high precision both in the generation and in the subsequent optical location of the distribution (Díaz and Mammana, 2012). Figure 3 shows such a distribution, which consisted in the introduction of elongated micro-indents in the corners of an imaginary square centred on one side of the sample. The nominal dimension of each side of the square is 21 mm.

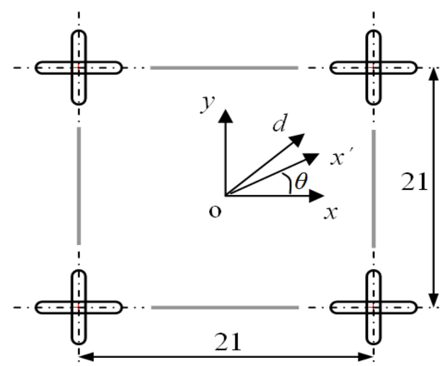


Fig. 3: Elongated micro-indent distribution

## RESIDUAL STRESS DETERMINATION

Through the above-mentioned distribution of elongated micro-indents it is possible to determine all components of the in-plane residual stress. It must be noted that to measure the through-thickness residual stress distribution, progressive removal of uniform layers from the specimen surface by chemical etching should be implemented. However, in out-of-plane direction, residual stresses are usually difficult to measure in thin layers of deposited or affected material, even by volumetric techniques like neutron diffraction (Withers and Bhadeshia, 2001).

For determining all components of the in-plane residual strain, in first place normal components in three directions are determined. Two of these (associated to $\varepsilon_x$ and $\varepsilon_y$) are perpendicular. The other direction (associated to $\varepsilon_d$) is the bisector of the perpendicular directions (Fig. 3). These components can be expressed as:

$$\varepsilon_x = \frac{l_x - l'_x}{l'_x} \qquad \varepsilon_y = \frac{l_y - l'_y}{l'_y} \qquad \varepsilon_d = \frac{l_d - l'_d}{l'_d}$$

(1)

where, $l_x$ and $l'_x$ are the mean values of the horizontal sides of the square (Fig. 3) and, $l_y$ and $l'_y$ are the mean values of the vertical sides, in both cases before and after the thermal distension, respectively. In turn, $l_d$ and $l'_d$ are the positive gradient diagonal of the square, also before and after the distension, respectively. Then, the angular component of residual strain can be obtained using the normal components:

$$\gamma_{xy} = 2 \cdot \varepsilon_d - \varepsilon_x - \varepsilon_y \tag{2}$$

Finally, if the measured surface is considered under plane stress conditions (Timoshenko and Goodier, 1970), the normal and tangential components of residual stress in the case of linear elastic, homogeneous and isotropic material can be expressed as:

$$\sigma_x = \left(\varepsilon_x + \nu \cdot \varepsilon_y\right) \cdot k \quad \sigma_y = \left(\varepsilon_y + \nu \cdot \varepsilon_x\right) \cdot k$$
$$\tau_{xy} = G \cdot \gamma_{xy} \tag{3}$$

where, $k = E/(1-\nu^2)$, $\nu$ is the Poisson's ratio and $E$ and $G$ are the longitudinal and shear elastic modulus, respectively.

## RESULTS AND DISCUSSION

In this study, a series of three measurements of distances between elongated micro-indents, before the distension treatment, was carried out. Then, three subsequent measurements were performed after the relaxation of the sample. Using Eq. (1), (2) and (3) the components of the residual strain and stress associated to the original reference system (axes $x$ and $y$) were obtained. The combination of three measurements before and after the distension treatment allowed obtaining nine values for each component of residual strain and stress. These values and the corresponding averages are shown in Table 3 and 4.

With respect to the components of residual stress, the absolute error of the present method of micro-indents is ±0.9 MPa. On the one hand, this error can be considered very small considering the values obtained for normal components (less than 3%). On the other hand, it can be considered high for the case of tangential components (around 40%). However, it should be noted that the tangential components obtained in this study are extremely small.

Regarding the residual strain component values showed in Table 3, these will change when the orientation of their directions is modified. Then, it is possible to express strain components associated to an arbitrary direction, which will depend on the components corresponding to the reference orthogonal axes $x$ and $y$ (Gere, 2001):

$$\varepsilon_{x'} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta + \frac{\gamma_{xy}}{2}\sin 2\theta$$
$$\gamma_{x'y'} = (\varepsilon_y - \varepsilon_x)\cdot \sin 2\theta + \gamma_{xy} \cdot \cos 2\theta \tag{4}$$

where, $\theta$ is the angle of the arbitrary direction with respect to reference axis $x$ (Fig. 3). Then, the shear component can be expressed as:

$$\varepsilon_{x'y'} = \gamma_{x'y'} / 2 \tag{5}$$

For the same angle $\theta$, the normal and tangential components of residual stress will be:

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy} \cdot \sin 2\theta$$
$$\tau_{x'y'} = -\frac{\sigma_x - \sigma_y}{2}\sin 2\theta + \tau_{xy} \cdot \cos 2\theta \tag{6}$$

The residual strain and stress components, which vary continuously with the angle $\theta$, can be represented by means of a graphical tool known as Mohr's circle (Timoshenko and Goodier, 1970). This representation is very useful because it allows visualizing the relationships between normal and tangential components corresponding to different directions. In addition, this representation also enables to observe clearly the variation ranges of both components of residual deformation and stress.

Figure 4 shows Mohr's circles obtained for the measured surface using the mean values of Table 3 and 4. It is important to note that orthogonal coordinates at each point represent the values of components corresponding to an infinitesimal element whose axes were rotated an angle $\theta$ with respect to the reference

Table 3: Components of residual strain (%)

| Combination number | $\varepsilon_x$ | $\varepsilon_y$ | $\gamma_{xy}$ |
|---|---|---|---|
| 1 | - 0.04682 | - 0.02233 | 0.00475 |
| 2 | - 0.04368 | - 0.02868 | 0.00215 |
| 3 | - 0.04947 | - 0.02139 | 0.00180 |
| 4 | - 0.04657 | - 0.02610 | 0.01010 |
| 5 | - 0.04344 | - 0.03244 | 0.00750 |
| 6 | - 0.04923 | - 0.02516 | 0.00715 |
| 7 | - 0.04657 | - 0.02586 | 0.01412 |
| 8 | - 0.04344 | - 0.03221 | 0.01152 |
| 9 | - 0.04923 | - 0.02492 | 0.01117 |
| Average | - 0.04649 | - 0.02655 | 0.00781 |

Table 4: Components of residual stress (MPa)

| Combination number | $\sigma_x$ | $\sigma_y$ | $\tau_{xy}$ |
|---|---|---|---|
| 1 | - 42.6 | - 29.7 | 1.3 |
| 2 | - 41.8 | - 33.9 | 0.6 |
| 3 | - 44.4 | - 29.6 | 0.5 |
| 4 | - 43.4 | - 32.6 | 2.7 |
| 5 | - 42.6 | - 36.8 | 2.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | - 45.2 | - 32.5 | 1.9 | 9 | - 45.2 | - 32.4 | 2.9 |
| 7 | - 43.3 | - 32.4 | 3.7 | Average | - 43.4 | - 32.9 | 2.1 |
| 8 | - 42.5 | - 36.6 | 3.0 | | | | |

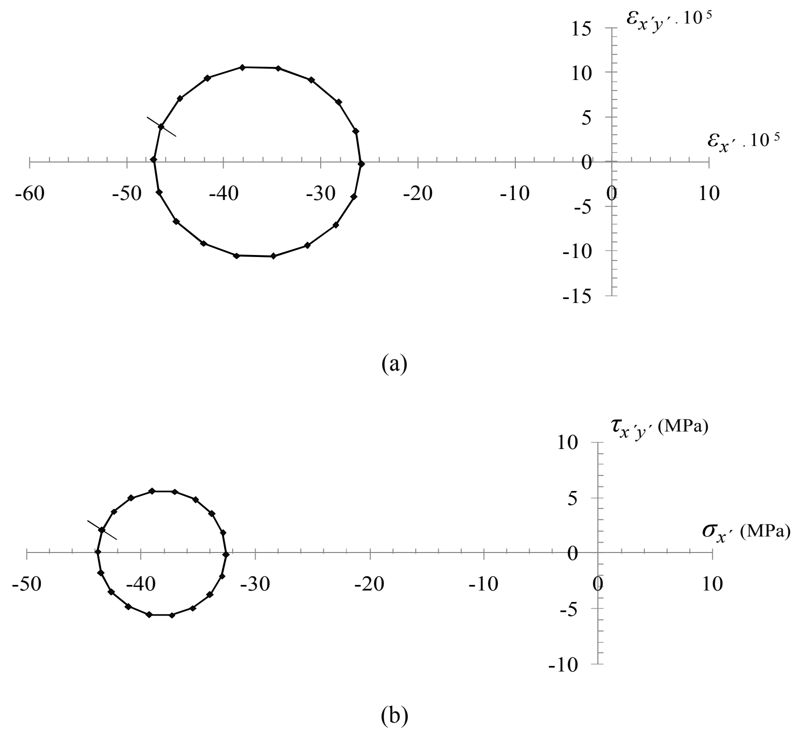


Fig. 4: (a) Strain and (b) stress Mohr's circles

axes (Gere, 2001). Furthermore, the small segment of each circle defines the point corresponding to the reference direction ($\theta = 0$ in Fig. 3). Regarding the stress circle showing Fig. 4b, a great difference between normal and tangential components is observed (quasi-isotropic state). In this circle, the maximum tangential component value is 5.9 MPa, which reduces the relative measurement error with respect to that obtained for the original reference system (axes $x$ and $y$). In turn, the values corresponding to the maximum and minimum compressive normal components are -43.6 and -32.3 MPa, respectively. These values correspond to orthogonal directions which are rotated an angle of approximately 10° counter clockwise with respect to the reference axes $x$ and $y$, respectively. It is very important to note that in the case of homologous circles of strain and stress, the angles corresponding to the principal directions must agree (Timoshenko and Goodier, 1970). In our case, given that the strain and stress tensors were obtained by averaging nine tensors in each case (Table 3 and 4) the principal angles are slightly different. The obtained values were 10.7° and 10.2° for the strain and stress circles, respectively. The small difference between both angles, less than 5%, indicates that the analysis based on mean values is appropriate.

Figure 5 shows the real importance of the above-mentioned rotation of approximately 10° counter clockwise with respect to the original reference system. This rotation indicates that the direction associated to the more compressive principal component is very close to the axis $x$, direction in which the rolling

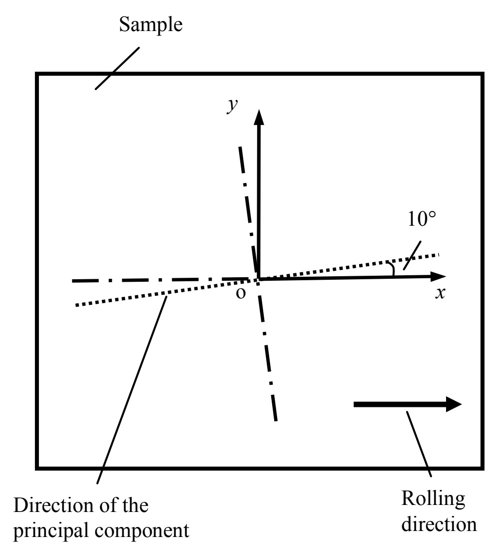


Fig. 5: Direction corresponding to the more compressive principal component of residual stress

process of the material was carried out. This fact would indicate that the plastic deformation generated by the rolling process is the most important cause of the residual stresses introduced in the present material, even though it was later hardened by means of a thermal process. This thermal process would help to transform the original residual stress state in a quasi-isotropic state because the normal component value in the rolling direction was only 32% greater than that obtained for the perpendicular direction. In another study performed in a normal spring steel 55 Cr 3 rolled with assistance of a ball -without subsequent hardening- the component of residual stress measured in the rolling direction was 200% higher than the component measured in the perpendicular direction (Müller, 2005).

Regarding the measured surface, which is considered under plane stress conditions, it cannot be predicted whether it will fail or not through comparison between the obtained residual stress values and those corresponding to a uniaxial testing. Therefore, some criterion about the mechanism of failure must be applied. This would allow comparing the values of both stress states. The most appropriated criterion for the material evaluated in this study is the von Mises yield criterion of maximum distortion energy (Budynas and Nisbett, 2008). This criterion establishes that yielding would occur when total distortion energy absorbed per unit volume, due to applied loads, exceeds the distortion energy absorbed per unit volume at the yield point. In terms of residual stresses, this requirement is equivalent to obtain the von Mises comparison stress:

$$\sigma_c = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \cdot \sigma_y + 3 \cdot \tau_{xy}^2} \tag{7}$$

and then to compare it with the tensile yield stress $\sigma_{y_{0.2}}$:

$$\sigma_c \leq \sigma_{y_{0.2}} \tag{8}$$

because for most engineering purposes it is customary to use the same yield stress for tensile work as for compressive. By using the mean values of the residual stress components corresponding to the original reference system (Table 4) the stress $\sigma_c$ was 40 MPa. It can be adverted that this comparison stress is sufficiently below the limit at which the material will fail (250 MPa). However, considering the residual origin, the comparison stress value is important. It is noteworthy that the worst case for the rolled sheet evaluated in this study is that in which the service stresses are compressive, which could lead to buckling failures. This is because the service stresses must be added to the residual stresses, which have the same sign. Therefore, to avoid risks, the comparison stress must be used to compute the work stress. Finally, the levels obtained for residual stress components would also generate dimensional and geometric distortion if the studied material is subjected to machining operations.

## CONCLUSION

The micro-indent method used in this study proved to be very practical and useful to determine, with great accuracy, normal and tangential components and consequently the residual deformation and stress tensors generated during the manufacture process of the evaluated alloy. The tangential component values of residual stress were very low and close to zero. Regarding the normal components, these were compressive and significantly higher than the tangential components. The principal direction, in which the maximum compressive component was obtained, nearly coincides with the direction of the *x* axis of the original reference system. This is due to the rolling of the alloy was performed in this direction. This observable fact shows the relevance of the rolling process previous to the T6 thermal hardening procedure in the final residual stress state. Then, this thermal procedure would tend to homogenize the normal component values in the different directions.

By applying the von Mises yield criterion it was possible to compare the final state of residual stress with the failure stress. Although the value of the von Mises comparison stress obtained through this approach was 40 MPa, due to the residual origin of this stress, it is suitable taking into account its value in the calculation of the work stress in order to avoid premature failures when the studied material is subjected to service loads. Finally, the obtained comparison stress value also suggests that a distension treatment is a suitable method to avoid dimensional and geometric distortion in case of performing machining operations.

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## NOMENCLATURE

A : Elongation (%)
$E$ : Longitudinal elastic modulus (GPa)
$G$ : Shear elastic modulus (GPa)
HV0.5: Vickers micro-hardness (test load: 500 gf)
$k$ : Elastic constant
$l_x$, $l'_x$ : Mean values of the distances between indents located at the *x* direction, before and after the stress-relieving, respectively (mm)
$l_y$, $l'_y$ : Mean values of the distances between indents located at the *y* direction, before and after the stress-relieving, respectively (mm)
$l_d$, $l'_d$ : Positive gradient diagonal of the indent distribution, before and after the stress-relieving, respectively (mm)
$\gamma_{xy}$ : Angular deformation component
$\gamma_{x'y'}$ : Angular deformation component associated to an angle $\theta$

$\varepsilon_d$ : Normal deformation component associated to an angle $\theta = 45°$
$\varepsilon_x$ : Deformation component at the $x$ direction
$\varepsilon_{x'}$ : Normal deformation component associated to an angle $\theta$
$\varepsilon_y$ : Deformation component at the $y$ direction
$\varepsilon_{x'y'}$ : Shear deformation component associated to an angle $\theta$
$\theta$ : Angle formed by an arbitrary direction and the axis $y = 0$
$\upsilon$ : Poisson's ratio
$\sigma_c$ : Von Mises comparison stress (MPa)
$\sigma_x$ : Residual stress component at the $x$ direction (MPa)
$\sigma_{x'}$ : Normal stress component associated to an angle $\theta$ (MPa)
$\sigma_y$ : Residual stress component at the $y$ direction (MPa)
$\sigma_u$ : Ultimate Tensile Strength (UTS) (MPa)
$\sigma_{y_{0.2}}$ : Yield strength (MPa)
$\tau_{xy}$ : Tangential stress component (MPa)
$\tau_{x'y'}$ : Tangential stress component associated to an angle $\theta$ (MPa)

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