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Research Article

Determination and Analysis of Residual Stresses Induced by High Speed Milling Using a Micro-Indent Method

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Abstract: The purpose of this work is to determine and analyze residual stress normal components and anisotropy degrees introduced by high-speed milling in specimens of AA 6082-T6 and AA 7075-T6 aluminum alloys. At each machined sample, the climb and conventional cutting zones were evaluated and compared. This paper includes a comprehensive study of thermal and mechanical effects associated with the residual stress introduction. For normal components determination, an optimized micro-indent method was used. Each measurement sequence from this approach was performed using a high accuracy measuring machine and classified according to thermal deviations measured. The residual displacements were determined with an absolute error down to ±300 nm. The normal components analysis allowed to infer the strong influence of the rolling process previous to high-speed milling and besides, the stress levels associated with thermal effects (higher in AA 7075-T6). Finally, the lower residual stress anisotropy degrees in both materials observed in the conventional cutting zone would indicate more homogenous local plastic stretching in this region for all planar directions.

Keywords: Aluminum alloys, anisotropy, high-speed milling, micro-indent method, residual stresses

INTRODUCTION

Residual stresses, which sometimes generate catastrophic failures, are always introduced before service loads and moments. These stresses develop when the solid undergoes non-uniform plastic deformation and/or is subjected to thermal gradients, which inevitably occurs in different manufacturing processes such as casting, rolling, welding, forging or machining (Rowlands, 1987; Lu, 1996).

At present, there is an incessant search for new machining procedures to reduce production costs. The design of new machine tools has allowed the increase of the primary process parameters such as feed rate and cutting speed. When this increment is significant, the cutting process is called high-speed machining (Schulz, 2003). It should be noted that this form of processing enables to increase considerably the volume of chip per unit of time.

However, slight variations in high-speed parameters can substantially modify the level and sign of the residual stresses introduced (Brinksmeier *et al*., 1982; Rao and Shin, 2001). Therefore, it is imperative to determine these levels and signs to know if a component has been strengthened or weakened in the surface during high-speed machining.

In the last years, different techniques have been developed to determine residual stresses from the introduction and measurement of micro or nanoindents. Most of these approaches compare the contact depth or load-displacement curve generated in stressed and unstressed samples, from which normal and tangential components of residual stress can be estimated (Suresh and Giannakopoulos, 1998; Swadener *et al*., 2001; Zhao *et al*., 2006). Recently, Wyatt and Berry (2006, 2009) developed a technique based on the measurement of the changes in the spacing of the micro-indents, which occur when the machined component is subjected to a distension treatment. More recently this method has been optimized, which allowed to carry out different studies in order to analyze the behavior of the normal and tangential components of residual stress in all directions, for the case of different aluminum alloys milled at high speed (Díaz *et al*., 2010; Díaz and Mammana, 2012; Vottero *et al*., 2017). It is important to note that this optimized approach proposes the use of

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a universal measuring machine, which leads to a very low measurement error (±0.9 MPa) when it is compared to that associated with the most used techniques such as X-ray diffraction (Noyan and Cohen, 1987; Prevéy, 1987) and the hole-drilling method (Rendler and Vigness, 1966; Gupta, 1973; Díaz *et al*., 2001), which is approximately ±25 MPa.

This study aims to determine and analyze normal components of residual stress in particular directions and besides, the anisotropy degrees introduced via high-speed milling in 6082-T6 and 7075-T6 aluminum alloys using a micro-indent method. It is important to note that in the literature there are very few works in which the residual stress anisotropy is studied. In order to optimize the implementation of this approach, each sequence of micro-indent measurement, which was carried out using a high precision measuring machine, was classified according to thermal deviations measured. Then, the associated residual displacements were determined with an absolute error down to ±300 nm. The residual stresses were calculated from these displacements using a model for the plane stress state. The high-speed tests were carried out using a numerically controlled vertical milling machine. The feed rate was varied to evaluate the differences in the behavior of the normal components, either between different zones of the machined surfaces as well as between both alloys. These differences allowed to analyze the mechanical and thermal effects associated with the residual stress introduction. Finally, the diameters of Mohr's circles, which were determined for each residual stress state, enabled to evaluate the homogeneity grade of the local plastic stretching generated by high speed milling for all planar directions.

MATERIALS AND METHODS

This study was completely performed in the year 2017 at the Departamento Ingeniería Electromecánica, Facultad Regional Rafaela, Universidad Tecnológica Nacional of Argentina.

As mentioned above, an optimized micro-indent method was used to determine normal components of residual stress in different directions. This technique includes a universal measuring machine (GSIP MU-314), from which it is possible to measure the coordinates of a series of micro-indents previously introduced into the machined surface. First, these coordinates (x, y, z) are measured before and after a distension treatment (573 K during 80 min). Then, by processing the coordinates, the components of residual deformation and stress generated by high-speed milling are obtained. In this study, the values of these components correspond to a reference frame fixed to the surface evaluated.

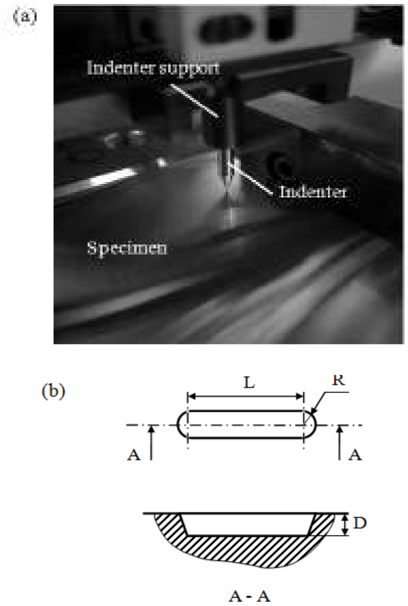


Fig. 1: (a): Picture of indenter-specimen interaction and (b): cross-section view of an elongated indent: (L) indent length; (R) end radius; (D) indent depth

For introducing the micro-indents, a particular design indenter was used, which is coupled to the main head of the universal measuring machine. Figure 1a shows the indenter making contact with the milled surface of the specimen. It is noteworthy that the body of the device is made up of a system of thin elastic strips that enables to regulate the indentation load. Moreover, an electronic sensor allows calibrating the depth of the indent with high accuracy. It is of great importance to note that this device allows introducing elongated micro-indents. This form reduces the uncertainty when the specimen is repositioned after the thermal distension (Díaz *et al*., 2010). In addition, from this type of indent, it was possible to increase the accuracy both in the introduction and in the specific localization. Figure 1b shows a cross-section view of an elongated micro-indent.

The samples were cut from two rolling products which can be considered to have middle and high mechanical resistance (yield and ultimate tensile strength). The 6082-T6 and 7075-T6 aluminum alloys were selected because they have good machinability (curled or easily broken chips and good to excellent finish). It must be noted that alloy 6082-T6 is a comparatively new alloy that is utilized in structures in transportation industries and also for milling precision components in the automotive industry. Moreover, alloy 7075-T6 is widely used in aircraft and aerospace structures due to its very high mechanical strength/weight ratio.

The dimensions of the samples are shown in Fig. 2. An annealing treatment was performed to remove the residual stresses generated in the pre-processing (hot

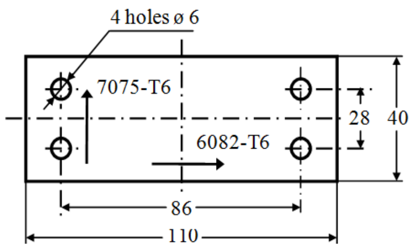


Fig. 2: Test specimen. The units are in mm, and the thickness is 4 mm

rolling). The annealing temperature and time were 573 K and 80 min, respectively. Figure 2 also shows the rolling directions corresponding to each alloy. It is noteworthy that these are orthogonal.

These samples were milled at high speed using a numerically controlled vertical milling machine (Clever CMM-100). The tool, a face mill of 63 mm in diameter, includes five inserts (Palbit SEHT 1204 AFFN-AL SM10) of tungsten carbide. The values of cutting speed and depth of cut were $V = 1000$ m/min and $d = 1.5$ mm, respectively. Furthermore, the feed rate was varied from $f = 0.1$ mm/rev to $f = 0.2$ mm/rev in order to evaluate the behavior of the residual stresses in the cutting zones. Figure 3a shows a superior view of the relative position of the specimen regarding the cutting tool. This figure also shows two regions in the machined surface called climb and conventional cutting zones (Trent, 1991).

For evaluating normal components of residual stress in different directions, two points were selected, which are located in the barycenters of the climb and conventional cutting zones. Figure 3b shows these points (A and B) and also 6 pairs of elongated micro-indents, which are located at the corners of two adjacent squares. Measuring the coordinates of each corner before and after the distension treatment, it is possible to obtain the residual displacements, strains and stresses introduced by high-speed milling at the points A and B.

Due to the present micro-indent method is based on a strict temperature control the measurement sequence of each corner was repeated, in each machined sample, a number of times until obtaining the best results. Figure 3b shows the measurement sequence carried out in this study (1-2-4-3-5-6). In each sequence, the coordinates were measured within a temperature range of 20±0.2°C, with a variation lower than 0.01°C/min. It is key to note that if the variation is higher than the specified value, the measurement error, which was estimated to be ±0.9 MPa, will increase significantly.

In this study, each sequence was classified according to the measured thermal deviations as very reliable, reliable and unreliable. Then, for each sample evaluated, two paths were taken. In the first, 9 random sequences were selected (5 after and 4 before the thermal distension). In the second path, 6 sequences were selected (3 after and 3 before the same procedure), considering only those very reliable. During the analysis of results, it was observed that, for the different components of residual strain and stress, the values obtained from both paths were similar. In this study, the results shown correspond to the second path. Then, from the 6 sequences mentioned, 9 values for each component of residual strain and stress were obtained. Finally, the values evaluated in this study correspond to the mean values.

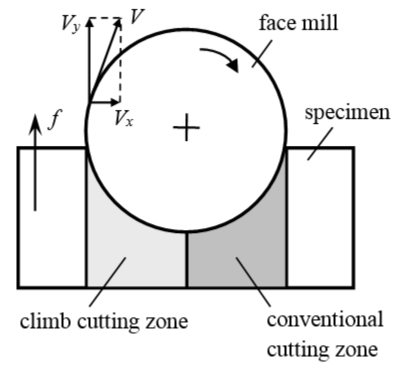
As above mentioned, for evaluating different normal components of residual stress, two significant points were selected, which are located in the barycenters of the climb and conventional cutting zones. For each barycenter, normal components of residual strain can be determined in three directions. Two of these are perpendicular (reference axes x and y) and the other one corresponds to the bisector ($\theta = 45°$ in Fig. 3b). In this study, these strain components were calculated from the square corner coordinates corresponding to 6 sequences of measurement following the procedure detailed in previous works (Díaz *et al*., 2010; Díaz and Mammana, 2012). Then, assuming that the milled surface is under a plane stress state and considering that the materials evaluated in this study are linear elastic, homogeneous and isotropic, the residual stress components σ_x, σ_y and τ_{xy} can be obtained from the strain components mentioned (Gere, 2004). Finally, the normal component associated with an arbitrary direction θ (Fig. 3b) can be obtained through:

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{xy} \cdot \sin 2\theta \qquad (1)$$

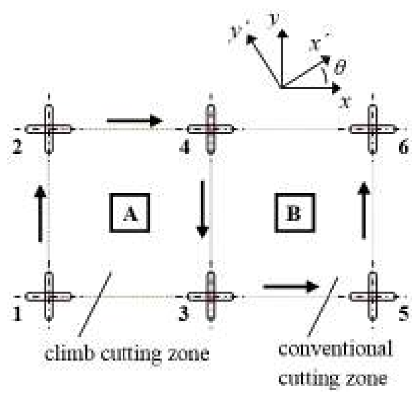
RESULTS AND DISCUSSION

The optimized micro-indent method allowed evaluating the states of residual stress introduced by high-speed milling at each significant point (A and B) of the machined surfaces. These states were analyzed according to different feed rates. As above mentioned, the points A and B correspond to the barycenters of the climb and conventional cutting zones, respectively.

Figure 4 and 5 show the normal components of residual stress σ_x, σ_y, σ_q and σ_p, which are represented as a function of the barycenters evaluated (A and B), for each material and feed rate. It should be noted that σ_q and σ_p are called principal components because they are associated with the principal directions (Gere, 2004). As can be seen in these figures, the stresses are compressive regardless of material, barycenter and combination of process parameters. In addition, the more compressive values correspond to the conventional cutting zone (Point B), which is more evident for the normal components σ_x and σ_q. This fact, which is independent of the type of alloy and feed rate, would be due to a higher local plastic deformation produced in the conventional cutting zone because the

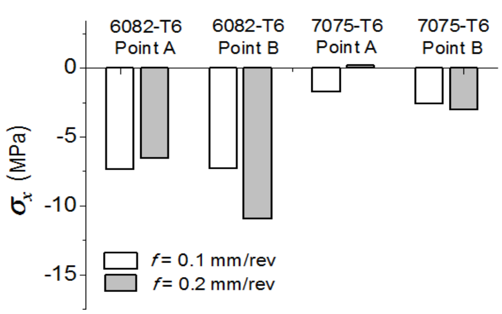


(a)

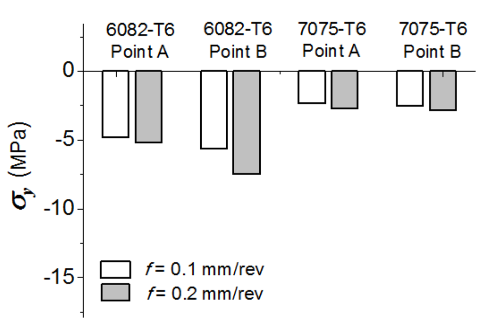


(b)

Fig. 3: (a): Diagram of the milling operation and (b): barycenters in cutting regions

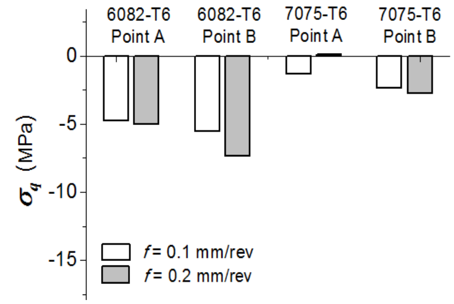


(a)

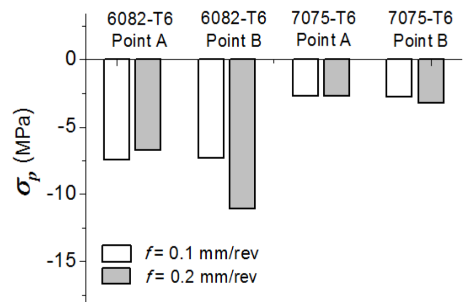


(b)

Fig. 4: Components; (a): σ_x and (b): σ_y of the residual stress (cutting speed: V = 1000 m/min, depth of cut: d = 1.5 mm)



(a)



(b)

Fig. 5: Components; (a): σ_q and (b): σ_p of the residual stress (cutting speed: V = 1000 m/min, depth of cut: d = 1.5 mm)

milling runs counter to feed direction in this region (Trent, 1991).

Regarding the influence of the material, the normal components introduced in the 6082-T6 alloy proved to be more compressive. These results confirm what was reported in previous works (Díaz *et al*., 2010; Vottero *et al*., 2017), in which other combinations of process parameters were evaluated.

The possible causes that generate these compressive stresses in both barycenters are analyzed in Fig. 6. The pattern of stress levels obtained in the different high-speed tests is shown in Fig. 6a. Although both levels are compressive, the one corresponding to the alloy 6082-T6 (σ_{6082}) is slightly larger than that associated with 7075-T6(σ_{7075}). On the other hand, the levels that are shown in Fig. 6b represent the relative roles of the thermal and mechanical effects in the residual stress introduction. It is known that compressive stresses are, in essence, introduced by mechanical effects (Jacobus *et al*., 2001). In contrast, thermal effects are responsible for tensile stresses. Because the cutting forces are greater in 7075-T6 (higher hardness), the local plastic deformation generated by milling should be higher in this alloy. The compressive levels generated by the local plastic deformation ($\sigma_{M_{7075}}$ and $\sigma_{M_{6082}}$) are shown in Fig. 6b. This figure also shows the stress levels whose origin is thermal ($\sigma_{T_{7075}}$ and $\sigma_{T_{6082}}$). In this case, the stress levels must be lower (in absolute value) than the compressive equivalent. Moreover, the following expressions should be valid:

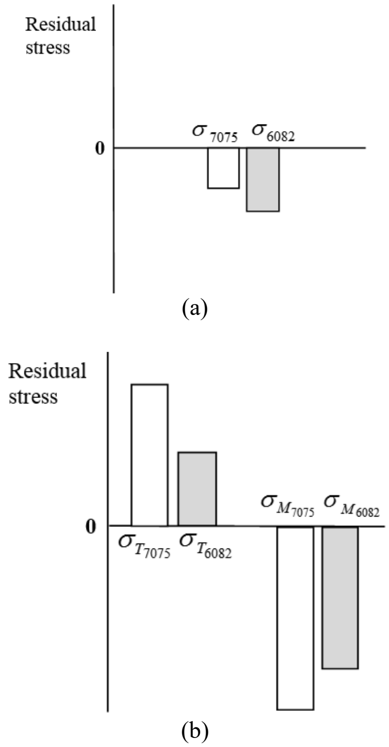


Fig. 6: (a): Global and (b): thermal and mechanical levels corresponding to normal components of residual stress

Table 1: Diameters of Mohr's circles (MPa)

Alloy	*f*(mm/rev)	Point A	Point B
6082-T6	0.1	2.7	1.8
	0.2	1.7	3.7
7075-T6	0.1	1.4	0.4
	0.2	2.6	0.4

$$\sigma_{T_{7075}} > \sigma_{T_{6082}} \tag{2}$$

$$\Delta\sigma^{T} > \Delta\sigma^{M} \tag{3}$$

where, $\Delta\sigma^{T}$ and $\Delta\sigma^{M}$ are the differences between stress levels, which are generated by thermal and mechanical effects, respectively. Expression (2) would be linked to the amount of heat retained in the machined surface, which would be higher in 7075-T6 due to its lower thermal conductivity.

Figures 4 and 5 also show that, in the conventional cutting zone (point B), the increase in feed rate introduces more compressive stresses in all cases (the differences are more significant in alloy 6082-T6). It should be noted that, in this region, the direction of the feed rate is opposite to that associated with the V_y component of the cutting speed (Díaz *et al*., 2010). In the climb cutting zone (point A), the values generated by the higher feed rate are less compressive for σ_x and more compressive for σ_y. It is noteworthy that feed direction corresponds to the axis *y* in the orthogonal reference frame used in this study.

From Fig. 4 and 5 it is possible to advert that the behavior of the more compressive principal component σ_p approaches to σ_x for the case of 6082-T6 and is similar to σ_y for 7075-T6. Therefore, the opposite should occur in the case of the less compressive principal component σ_q, which can be seen in the same figures. This implies that, for the alloys 6082-T6 and 7075-T6, the principal directions are near the reference axes *x* and *y*, respectively, which would be due to the strong influence of the directions of the rolling process prior to milling, as were reported in previous works (Díaz *et al*., 2012, 2015). In the samples tested in this study, the rolling directions are perpendicular, as shown in Fig. 2.

On the other hand, Table 1 shows the diameters of Mohr's circles, which were obtained from the subtraction of the principal components. It should be noted that these circles contain information about the normal and tangential components of residual stress in all directions. In this table, it can be seen that, in 3 of 4 cases, the diameters at point B are smaller than in A. This fact means that in the conventional cutting zone the residual stress anisotropy degree is lower than in the climb cutting zone. It is essential to note that this type of anisotropy, for the state evaluated, is directly proportional to the diameters mentioned (Timoshenko and Goodier, 1970). For this case, the concept of anisotropy refers to the values of all components (normal and tangential) in the different planar axes. These results would indicate that in the conventional cutting zone, where the directions of the feed rate and the V_y component of the cutting speed are opposite (Fig. 3a), the local plastic stretching is more homogenous for all directions. This fact would be more evident for alloy 7075-T6 because it shows smaller circles in the cutting region mentioned. Finally, the values obtained for these diameters (0.4 MPa), which are shown in Table 1, would indicate that the stress states associated with alloy 7075-T6 in that cutting zone are quasi-isotropic.

CONCLUSION

Different normal components of residual stress induced by high-speed milling in aluminum alloys were exhaustively analyzed in particular directions from an optimized micro-indent method. Each sequence of measurement was performed using a high accuracy universal measuring machine and classified according to the measured thermal deviations. In all cases, the components were compressive and low. Through an analysis carried out modifying the feed rate, it was detected that the normal components are slightly greater in the conventional cutting zone. This fact would be related to the larger local plastic deformation generated when the directions of the V_y component of cutting speed and feed rate are opposite. The analysis of these components also allowed to infer that the stress levels associated with thermal effects are higher in 7075-T6, probably due to lower thermal conductivity and besides, the principal directions in 6082-T6 and 7075-T6 are near the reference axes *x* and *y*, respectively, which would be related to the influence of the hot rolling process prior to high-speed milling. Finally, it was observed that the residual stress anisotropy degree in the conventional cutting zone is lower, which would mean more homogenous local plastic stretching in this region for all planar directions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Brinksmeier, E., J.T. Cammett, W. Konig, P. Leskovar, J. Peters and H.K. Tonshoff, 1982. Residual stresses-measurement and causes in machining processes. CIRP Ann., 31(2): 491-510.

Díaz, F.V., G.H. Kaufmann and O. Möller, 2001. Residual stress determination using blind-hole drilling and digital speckle pattern interferometry with automated data processing. Exp. Mech., 41(4): 319-323.

Díaz, F.V., R.E. Bolmaro, A.P.M. Guidobono and E.F. Girini, 2010. Determination of residual stresses in high speed milled aluminium alloys using a method of indent pairs. Exp. Mech., 50(2): 205-215.

Díaz, F.V. and C.A. Mammana, 2012. Study of residual stresses in conventional and high-speed milling. In: Filipovic, L.A. (Ed.), Milling: Operations, Applications and Industrial Effects. Nova Science Publishers, Inc., New York, pp: 127-155.

Díaz, F., C. Mammana and A. Guidobono, 2012. Evaluation of residual stresses induced by high speed milling using an indentation method. Modern Mech. Eng., 2(4): 143-150.

Díaz, F.V., C.A. Mammana and A.P.M. Guidobono, 2015. Evaluation of residual stresses in low, medium and high speed milling. Res. J. Appl. Sci. Eng. Technol., 11(3): 252-258.

Gere, J.M., 2004. Mechanics of Materials. 5th Edn., Brooks/Cole, Pacific Grove, CA.

Gupta, B.P., 1973. Hole-drilling technique: Modifications in the analysis of residual stresses. Exp. Mech., 13(1): 45-48.

Jacobus, K., S.G. Kapoor and R.E. DeVor, 2001. Experimentation on the residual stresses generated by endmilling. J. Manuf. Sci. Eng., 123(4): 748-753.

Lu, J., 1996. Handbook of Measurement of Residual Stresses. Fairmont Press, Lilburn, Géorgie: Upper Saddle River, N.J.

Noyan, I.C. and J.B. Cohen, 1987. Residual Stress Measurement by Diffraction and Interpretation. Springer Verlag, Berlin.

Prevéy, P.S., 1987. X-ray Diffraction Residual Stress Techniques. Metals Handbook, American Society for Metals, Metals Park, OH, pp: 380-392.

Rao, B. and Y.C. Shin, 2001. Analysis on high-speed face-milling of 7075-T6 aluminum using carbide and diamond cutters. Int. J. Mach. Tool. Manu., 41(12): 1763-1781.

Rendler, N.J. and I. Vigness, 1966. Hole-drilling strain-gage method of measuring residual stresses. Exp. Mech., 6(12): 577-586.

Rowlands, R.E., 1987. Residual Stresses. In: Kobayashi, A. (Ed.), Handbook on Experimental Mechanics. Prentice-Hall, New Jersey, pp: 768-813.

Schulz, H., 2003. High-speed Machining. In: Dashchenko A.I. (Ed.), Manufacturing Technologies for Machines of the Future. Springer, Berlin, pp: 197-214.

Suresh, S. and A.E. Giannakopoulos, 1998. A new method for estimating residual stresses by instrumented sharp indentation. Acta Mater., 46(16): 5755-5767.

Swadener, J.G., B. Taljat and G.M. Pharr, 2001. Measurement of residual stress by load and depth sensing indentation with spherical indenters. J. Mater. Res., 16(7): 2091-2102.

Timoshenko, S.P. and J.N. Goodier, 1970. Theory of Elasticity. McGraw-Hill, New York.

Trent, E.M., 1991. Metal Cutting. 3rd Edn., Butterworth/ Heinemann, London.

Vottero, S., F.V. Díaz, C.A. Mammana and A.P.M. Guidobono, 2017. Analysis of residual stresses in high speed milled aluminum alloys. Res. J. Appl. Sci. Eng. Technol., 14(3): 119-123.

Wyatt, J.E. and J. Berry, 2006. A new technique for the determination of superficial residual stresses associated with machining and other manufacturing processes. J. Mater. Proc. Tech., 171(1): 132-140.

Wyatt, J.E. and J. Berry, 2009. Mapping of superficial residual stresses in machined components. J. Ind. Technol., 25(1): 1-8.

Zhao, M., X. Chen, J. Yan and A.M. Karlsson, 2006. Determination of uniaxial residual stress and mechanical properties by instrumented indentation. Acta Mater., 54(10): 2823-2832.