RESIDUAL STRESS IN COLD STRETCHING METAL PARTS

Diogo Antonio de Sousa, diogo.sousa@fiat.com.br
Frederico Ozanan Neves, fred@ufsj.edu.br
Durval Uchoas Braga, durva@ufsj.edu.br
Alex Sander Chaves da Silva, achaves@ufsj.edu.br
Universidade Federal de São João del-Rei

Abstract. *The cold metalforming is widely used in manufacture for several ferrous and non ferrous metals. Then, knowing its mechanical behavior when submitted to cold forming is very important, since it can be predict its performance in service. The deformed body is under cold hardening and residual stresses are generated. However the nature and intensity of residual stresses depend on the geometry of the deformed region, the type of loading it was imposed and mechanical properties of the material associated with elastic recovery. In this study, the goal is to correlate increments of plastic strain obtained by tensile stress on residual stress, measures by instrumented indentation tests. Tensile tests on aluminum, copper, bronze, brass and steel ABNT 1020 and ABNT 1045 specimens was done. The tests were stopped at 20%, 50% and 90% of its plastic field. Then instrumented indentation tests were done. Measures of residual stress by x-ray diffraction were also done. The results compared with non deformed specimens indicate that the hardness of the material present correlation to true strain and, associated to mechanical properties of the material, it is possible to predict the residual stress on material from its true strain history. Moreover, the results suggest that the residual stresses in the specimens are compressive and are function of coefficient of strain hardening, modulus of elasticity and Poisson rate.*

Keywords: *Residual stress, Cold forming, stretching, indentation test, x ray diffraction*

1. INTRODUCTION

The mechanical reliability of bulk (fatigue, fracture, corrosion and wear) is strongly affected by their residual stress, commonly introduced by thermal mismatch, or mechanical and thermal processing. In cold forming the material is deformed plastically between two or more dies so as to give it the desired shape and size. During forming, the friction at the die–test specimen interface makes the deformation as well as the stress distribution non-uniform. This inhomogeneity of the deformation gets manifested in the bulging of the test specimen. Another significant consequence of the inhomogeneity is the generation of residual stresses (Mungi, Rasanee and Dixit, 2003). Residual stresses are those that exist in a body when it is free from external forces. They are the consequences of all kind of interventions on the part, like heat treatment (Camurri, Carrasco and Dille, 2008 and Lados at all, 2010), deformation processes (Martins at all, 2006), machining (Tang at all, 2009), welding/joining (Gannon, at all, 2010) or combinations of above that transform the shape and/or change the properties of materials.

It is generally believed that the poor shape or bad surface finish are caused by the residual stresses. Residual stress can be of different nature: compressive or tensile one. In general, the nature (sign) of the residual stress are of opposite sign to sign of the plastic strain applied on the part. If a body is formed under compressive stress, residual stress generated will be of tensile nature and vice-versa. E.g., in the case of a rolled sheet, the residual stress pattern consists of a high compressive stress at the surface which was elongated in the longitudinal direction by rolling. After removing the external force, there is compressive stress at the surface and tensile stress at the center of the sheet.
Residual stress can improve mechanical strength or reduce it. Compressive residual stress acts to prevent the nucleation and propagation of crack. Further, a tensile residual stress near the surface can cause rapid propagation of a micro-crack.

In a wider view, two tests are used to measure the residual stress, destructive tests and non-destructive tests.

The most common non-destructive test is based on the relation between physical parameters measured by X-ray or ultra-sound. The concept to the stress state determination pass through the analyses of the monochromatic beam that interact with the polycrystalline material, doing the incident photons diffract under a known direction, determined by the Bragg equation (Bragg's law) (Neves and Button, 2005). When a part made with a polycrystalline material is plastically deformed, there is an uniform strain within certain long distances among the crystalline lattice plans where the crystallites (grains) are contained changing its free state to another state representative of the applied stress intensity. This new spacing among the grains (to any group of plans equally oriented towards the applied stress) is measured by X-ray diffraction. When an x-ray beam is directed onto the surface of a body, a part of these rays is absorbed by atoms while another part is reffracted in all directions of radiated area. In the case of x-rays on a crystalline body, unlike the bodies of amorphous substances, the dispersal or spreading because each atom is reinforced in certain specific directions with very small angular variation. This is the phenomenon called diffraction. The angle formed by the direction of the incident x-rays and the angle of the diffracted ray (2□ □ □ □ □ being half angle the angle of BRAGG (□ □ (Prevéy, 1986).

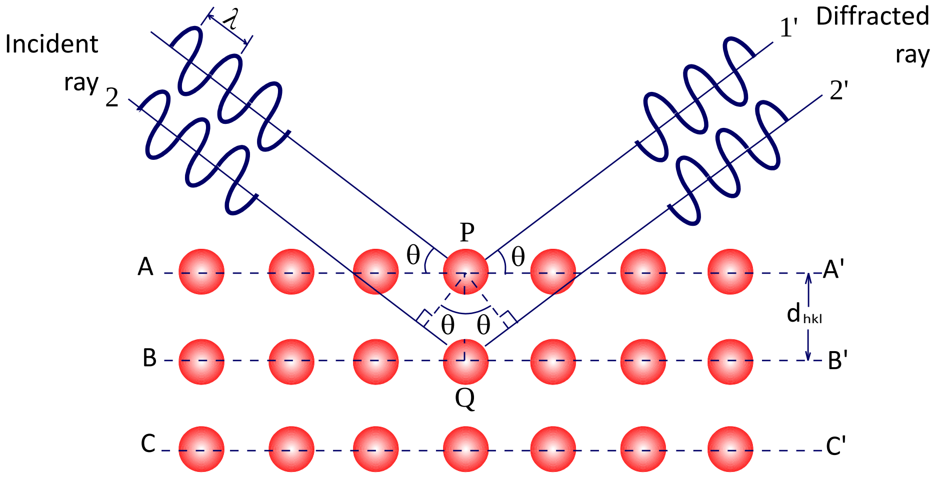

Figure 1. Illustration of the Bragg's theory.

More precisely, the conditions of diffraction are expressed by Bragg equation:

$$n\lambda = 2d.\ \mathrm{sen}\ (2\theta) \quad (1)$$

where n = 1,2, 3 ... and denotes the order of diffraction, □ is the wavelength of the ~~x~~-ray and d is the planar distance of the crystal. Therefore, any change in distance Planar implies changing the angle of diffraction. Then, reading the angle of diffraction can estimate the value of deformation of crystal and, in consequence, the existing value of the residual stress in the region of the body.

Recently the indentation test method has been employed to measure residual stress (Suresh and Giannakopoulos, 1998). If a surface is on compressive residual stress it is expected that indentation will be difficult and hardness will be bigger than a surface without residual stress. In the case of tensile residual stress present in the surface, the hardness will be lesser than a surface without residual stress. Otherwise, being tensile ones the penetration is more difficult and the result of the test will be of lesser values (Bocciarelli and Mayer, 2006). In this case, a map of the level and distribution of residual stress can easily be obtained without the need for sophisticated equipments and low cost. Figure 2 shows this behavior of the hardness in a instrumented indentation test. In the Fig.2, P is the indentation load, h is indentation height.

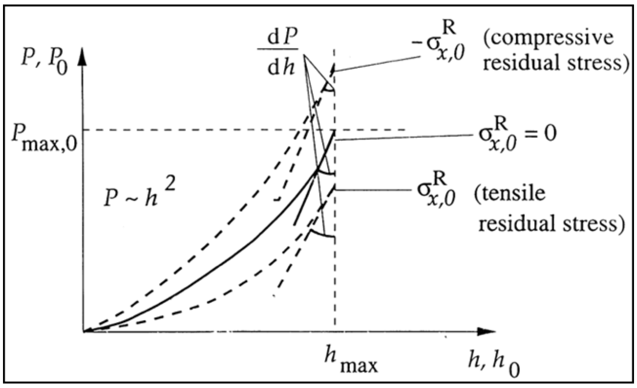

Figure 2. Hardness behavior on presence of residual stress

Others non-destructive test include ultrasonic velocity and Barkhausen noise analysis.

A very used semi-destructive technique is the hole-drilling strain gage method. In this case, a strain gage rosette is attached to the area of interest and a measurement hole with appropriate depth and diameters then drilled in the center of the gage circle in order to release the residual stress. The strain values detected by the strain gage are used into the strain–stress equation provided within the standard in order to compute the residual stress within the component (Lee and Liu, 2009).

This research proposes a study of the residual stress in cold stretching, observing the nature (sign) intensity and intends to correlates it with the mechanical properties of the material.

2. MATERIALS AND METHODS

To this five materials were chosen. They were the steel SAE 1020, commercial pure aluminum, commercial pure copper, bronze and brass. Material was brought in plates of 3 mm of thickness. Test specimens were done to be submitted to tensile test and prepared according to ABNT NBR 6136. The samples used were machined as standard specification.

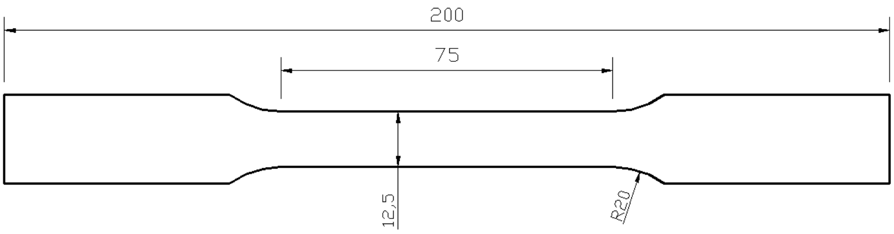

Figure 3. Dimensions of the samples. according to NBR 6152.

Three test specimens of each material was submitted to tensile test to obtain the mechanical properties of them. The properties obtained are yield tensile strength (σy), ultimate tensile strength(σu), modulus of elasticity (E), elongation at break (δ) and Poissons ratio (ν). From its stress-strain curve we determined the strain at ultimate tensile strength. This was taking as 100% of homogeneous plastic strains. We take the strain at yield tensile strength as 0% of homogeneous plastic strain. So, we divided this region in three parts: 20%, 50% e 90% of homogeneous plastic strain to study, as shown in Fig. 4.

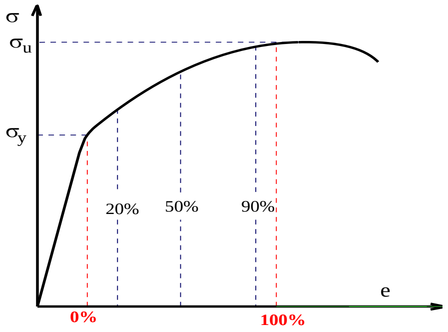

Figure 4. Homogeneous plastic strain - points of study

The tensile test was done and interrupted at this three points of percentage. To each point and from each material, three replicas were done.

The instrumented indentation test was done in one face of each sample. The other face of the sample was used to x-ray diffraction test. A group of test specimens not submitted to a tensile test, called "blank", was tested to hardness to form a group of comparison. The indentation test parameters used were: load of 500mN at maximum deep (hmax) and time of impression of 5s. Figure 5 exemplify an instrumented indentation test. In Fig. 5, maximum force (Lmax), maximum depth (hmax), depth of the indentation after the test (hp), tangent of the curve of return in relation to the depth axis (hr) and hardness measured after the test (DHV-2).

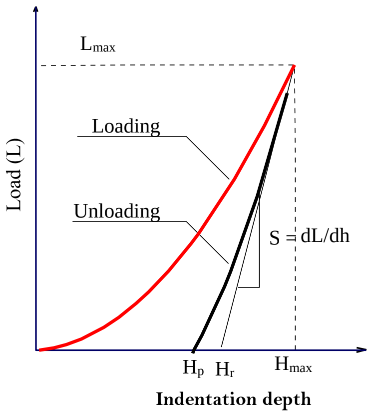

Figure 5 – Aspect of instrumented indentation test

X-ray diffraction tests were performed in a x-ray unit model Shimadzu XRD-6000 and the parameters were Cu x-ray tube, wavelength of 1,54Å, scanning speed of 0,2 degrees/min, voltage of 30 KV and electrical current of 30 mA.

Before the analysis it was carried out a survey to each material studied in order to find what were the scanning angles to the peaks of intensity. This was necessary to restrict the scanning area because a whole scan, from 0 to 180°, demands a very much time. The source for survey was the ICDD (International Center for Diffractor Date), a virtual library, in which it is cataloged all known materials. Figure 6 shows an example of the diffractions peaks to copper obtain from ICDD library.

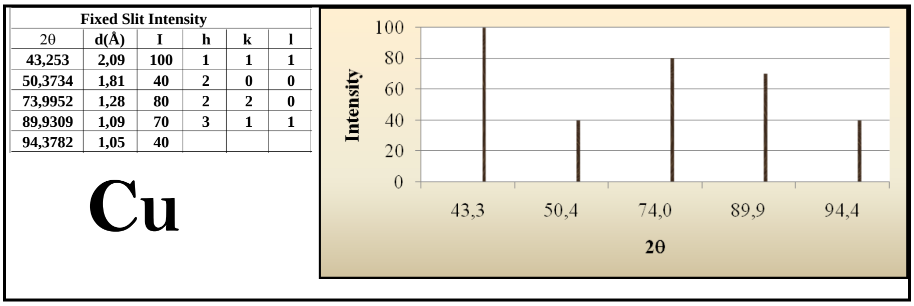

Figure 6 – X-ray diffractions peaks to copper (from ICDD)

In this example, it is observed that the material present characteristic peaks at certain angles of diffraction wich correspond to a crystallographic plane. We can identify which plan is most sensitive to deformation and, in this example, the plan chosen was the (1 1 1), because it refers to higher residual stress.

A statistical analysis was done using an Analysis of Variance with significance level of 5%. The influence variable is the material and the percentage of homogeneous strain. The first, in five levels and, the second, in three levels. The response variable was the hardness.

3. RESULTS AND DISCUSSION

Table 1 presents the mechanical properties obtained from the tensile tests.

Table 1 – Mechanical properties obtained from tensile test

Material	Modulus of Elasticity [GPa]	Yield tensile strength [MPa]	Ultimate tensile strength [MPa]
Steel SAE 1020	170,2	556,2	778,8
Aluminum	67,8	90,3	125,7
Copper	143,7	257,9	277,7
Bronze	92,4	381,7	452,0
Brass	117,1	463,7	706,6

Table 2 illustrates the results obtained from instrumented indentation test. The results refer to a test of the steel SAE 1020. results . There are two results to Vickers hardness: DHV1 and DHV2. The first refers to the harness at the maximus depth (hmax) and the second refers to the hardness after elastic recovery (hp). The second is the hardness used in this work.

Table 2 - Illustration of the result from an indentation test to steel SAE 1020.

SEQ	Fmax [mN]	hmax [mm]	hp [mm]	hr [mm]	DHV-1	DHV-2
1	507,04	3,1776	2,8361	2,09322	193,748	243,219
2	507,66	3,241	2,9252	2,9997	186,46	228,895
3	507,87	3,1449	2,7833	2,8956	198,116	252,936
Average	507,52	3,1878	2,8482	2,9425	192,775	241,683
Std. Dev.	0,43	0,049	0,072	0,053	5,889	12,093
CV	0,085	1,533	2,518	1,795	3,055	5,004

In the Tab. 3 we present the results of the indentation test.

Table 3. Results from indentation tests – Vickers hardness

	Blank	20%			50%			90%		
Aluminum	54,2	50,7	48,5	55,3	51,1	48,2	61,1	59,6	67,5	54,4
	60,9	51,9	71,3	55,3	51,1	48,3	46,5	50,8	55,2	50,0
	54,3	60,0	52,9	48,8	57,0	61,2	52,6	62,8	57,2	52,6
Brass	190,5	199,5	208,1	216,8	219,7	219,7	203,5	234,5	230,5	226,1
	180,6	193,8	202,4	206,7	207,9	220,4	210,6	234,6	236,8	239,7
	199,0	213,5	214,0	213,9	226,4	229,4	221,7	251,2	235,5	229,5
Copper	124,0	126,7	113,3	114,0	122,7	130,8	128,9	128,4	128,6	121,0
	134,3	134,8	128,4	121,6	133,2	127,6	126,1	133,8	134,3	124,7
	142,9	122,9	127,9	123,2	129,6	127,6	130,6	135,9	138,5	126,5
Bronze	252,3	241,6	252,3	268,8	232,8	270,3	252,3	235,9	265,0	253,6
	247,7	245,4	238,3	234,0	266,4	264,4	267,1	264,5	222,0	246,3
	230,2	263,3	294,5	253,4	236,6	235,1	274,9	293,2	254,7	234,9
Steel SAE 1020	243,2	270,9	250,3	248,7	280,9	259,4	272,3	293,1	273,0	293,3
	228,9	254,2	268,8	263,5	263,8	252,9	270,8	281,9	283,7	282,7
	252,9	266,9	254,9	251,6	264,3	256,6	263,0	265,0	272,8	277,6

Figure 8 shows Vickers hardness average from each material at each intensity of plastic strain accumulated. Its is possible to see that there is a significant difference of hardness between the materials. Blank is the material not worked and it can be seen that there is an increasing of hardness as the material is strain hardening. Since the increase of hardness denotes an introduction of compressive residual stress, we can say that cold stretching is an metalforming process responsible for this.

The results also show that there is an increasing of compressive residual stress as the homogeneous strain accumulated is higher, since the Vickers hardness increases too.

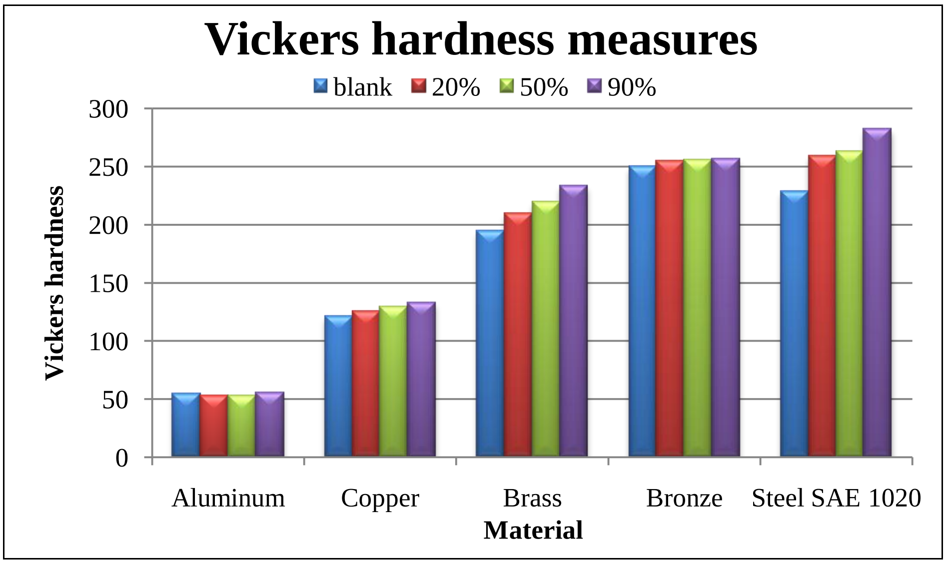

Figure 8. Vickers hardness measures as function of material an homogeneous strain accumulated

Table 4 presents the Analysis of Variance. In this Table, SST is the square sum of all measures, SSA is the square sum of the measures for each material (variable A), SSB is the square sum of the measures for each intensity of homogeneous strain accumulated (Variable B), SSAB is the square sum of the interactions AB and SSerr is the square sum of the random errs of all measure. DF is degrees of freedom to each variable, MSS Average square sum, Fcalc is the Fisher statistic the evaluated the variance of the variable and Ftab is the Fisher's statistic. If Fcalc is lesser than Ftab, we accept the null hypothesis that the medias are equal. The results confirm the conclusions obtained from Fig. 8. There is significant difference between the residual stress introduced in each material and there is significant difference from residual stress introduced by each intensity of homogeneous strain accumulated. There is no interaction between the influence variables.

Table 4 – Analysis of Variance of hardness

		DF	MSS	Fcalc	Ftab	Result
SST	992.987,00	149,00				
SSA	972.370,17	4,00	243.092,54	2.174,53	2,44	Influence
SSB	4.709,15	3,00	1.569,72	14,04	2,67	Influence
SSAB	1.374,85	12,00	114,57	1,02	1,83	no Influence
SSerr	14.532,83	130,00	111,79	1,00		

The results to residual stress measured by x-ray diffraction are presented in Tab. 5. Residual stress is evaluated using a Eq. 1, where d is interplanar distance, d_o is interplanar distance measured in the blank, E is the modulus of elasticity and ν is the Poisson's coefficient. See again Fig. 6.

$$S = \left(\frac{E}{\nu}\right)\left(\frac{d - d_o}{d_o}\right) \qquad \text{(Eq. 1)}$$

Table 5 – Residual stress from x-ray diffraction analysis - MPa

	Material				
ε^p acumullated	Brass	Copper	Bronze	Aluminum	Steel SAE 1020
20%	-508,98	-560,15	-287,05	-51,23	-206,73
50%	-628,36	-682,29	-352,08	-68,31	-382,35
90%	-639,08	-731,30	-442,73	-138,00	-584,64

In all cases, the residual stress was compressive which is evidenced by the minus signal in the results. This was observed to indentation tests and shown in Fig. 8. And, as the stretching process is a forming under uniaxial tensile stress, the residual stress nature (compressive stress) is in according to the expected.

Finally, in the Tab. 6 it is presented the statistic correlation between the Vickers hardness and residual stress measured by x-ray diffraction to each material. As it can be seen, there is a very strong correlation for all materials, except to brass, for which there is a strong correlation. The reasons to this difference behavior of the brass in respect to the others materials could be explained to its work hardening characteristic. But this must be better investigated.

Table 6. Correlation between Vickers hardness and residual stress by x-ray diffraction

Brass	Copper	Bronze	Aluminum	Steel SAE 1020
-0,858	-0,975	-1,000	-0,987	-0,948

4. CONCLUSIONS

This work is a study of residual stress introduced in metal parts by cold stretching. Residual stress were measured using the technique of instrumented indentation test and x-ray diffraction. The conclusions can be resumed as following:

1. Residual stress measured by x-ray diffraction are of compressive nature in all cases and, since the stretching is a metalforming under tensile stress , the results are in according to the expected;
2. Residual stress increases with the increasing in accumulated plastic strain;
3. Vickers hardness increased with the increasing in accumulated plastic strain and, since the increasing in hardness is a indicative of compressive residual stress, the results are in according to the expected
4. Analysis of variance confirms that the differences indicates in Vickers hardness, between the materials and between accumulated plastic strain, ares significative at a confidence level of 95%;

5. There are very strong or strong correlation between the results from indentaion tests and results from x-ray diffraction. This indicates that there is possible to use Vickers hardness to estimate the residual stress introduced by the mechanical process.

5. ACKNOWLEDGEMENTS

The authors wish to thank FAPEMIG for financial support to this research.

6. REFERENCES

ABNT – Associação Brasileira de Normas Técnicas. "NBR 6152 - Materiais metálicos – Ensaio de tração à temperatura ambiente". Rio de Janeiro, RJ, 2002.

Bocciarelli, M., Maier, g. 2007, Indentation and imprint mapping method for indentification of residual stress , Computational Materials Science, v. 39, Issue 2, April 2007, pp. 381-392.

Carrasco, C.,and Dille J. C., 2008. Residual stress during heat treatment of steel grinding balls. Journal of Materials Processing Technology, Volume 208, Issues 1-3, 21, pp. 450-456.

Gannon, L. at all. 2010. Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates Marine Structures, Volume 23, Issue 3, pp. 385-404.

Harjo, s. at all. 1999, "Measurements of thermal residual elastic strains in ferrite ± austenite fe-cr-ni alloys by neutron and x-ray diffractions ". Acta mater. Vol. 47, no. 1, pp. 353-362.

Lados, D. A. at all. 2010. Minimization of residual stress in heat-treated Al–Si–Mg cast alloys using uphill quenching: Mechanisms and effects on static and dynamic properties. Materials Science and Engineering: A, Volume 527, Issues 13-14, pp. 3159-3165.

Martins, J. A. at all. 2006. Analyses of residual stresses on stamped valves by X-ray diffraction and finite elements method . Journal of Materials Processing Technology, Volume 179, Issues 1-3, pp. 30-35

Montgomery, D.C. 1991. Design and Analysis of Experiments, 3ª ed., John Wiley and Sons, 621 p.

Mungi, M. P.; Rasane, s. d. and Dixit, p. m. 2003, axisymmetric Residual stresses in cold forging , Journal of Materials Processing Technology, v. 142, Issue 1, november p. 256-266.

Neves, F. O.; Button, s. t. 2005, ' Residual Stress on A304 Stainless Steel tube drawn with fixed plug "Proceedings of the International Congress of Mechanical Engineering, Ouro Preto. v. CDROM.

Suresh, s. and Giannakopoulos, e. 1998, ' A new method for estimating residual stresses by instrumented sharp indentation ", Acta mater. Vol. 46, no. 4, pp. 264-5767

Tang, Z.T. at all. 2009. The influence of tool flank wear on residual stresses induced by milling aluminum alloy. Journal of Materials Processing Technology, Volume 209, Issue 9, pp. 4502-4508.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.