RESIDUAL STRESS EVALUATION IN COLD FORMING USING INDENTATION TEST

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Abstract. *Residual stress are present after cold forming. It can be of two different types: compressive or tensile stress. The most traditional method to evaluate the residual stress present in a part is the x-ray diffraction. However, there is limitation on it from geometric shape and its size. This work presents a alternative method to evaluate residual stress using indentation test. By hypothesis, when a compressive residual stress is present on metal surface, indentation test shows a greater value than the same test performed on a surface where residual stress is not present. I Other way, if tensile residual stress is present, indentation test shows a lesser value. Aluminum and copper samples were cold bending in five angles and indentation tests was performed on its lateral surface, from top to bottom in order to obtain the gradient of hardnes. Methodology includes a design of experiments using a analysis of variance. The results were compared to a tension gradient obtained from a FEM simulation. It can be demonstrate that there is a strong correlation between residual stress and hardness and it is also possible to determines the type of residual stress present. Thus, a simple method to evaluates residual stress was established using a indentation test.*

Keywords*: residual* stress; indentation test; cold forming

1. INTRODUCTION

In modern technology, the importance of metal is from the facility which it can be forming in useful shapes like tubes, bars and plates (Dieter, 1981).

Among several ways to work the metal, metalforming can be distinguished, where the material has its shape modified by forces applied on its surface, preserving its volume and mass. Parts cold metalformed presents good quality surface, closed and controlled dimensional tolerances and an increasing in mechanical strength because of the distribution of the fibers and hardening. (Monezi, 2005).

In metalforming process, material is submitted to a permanent strain and, then, residual stresses rises. Residual stresses are those that exists in the body when there is no more external forces applied on it.

On mechanical parts, residual stresses are present in worked surface and cab be of tensile or compressive nature. Tensile residual stress must be avoid to parts submitted to cyclical mechanic forces because, by its nature, to facilitate the nucleation and propagation of cracks, leading then to fail by fatigue (BIANCH, E. C. et all, 2000). Presence of tensile residual stress induces the designer to super to prevent premature fail on service. Another alternative is to submit the part a thermal treatment to reduce internal tensions. Both represent additional costs.

To determinate residual stress two types of tests are used destructive and non-destructive tests. Non-destructive tests are based on the relationship between physical parameters obtained by x-ray diffraction. A monochromatic x-ray interacts with the crystalline material leading incident photon diffracts in a previously known direction, in according to Braggs equation (1) (Martins, Cardoso, Frayman, Button, 2005).

$$\mathbf{n\,\lambda = 2\,d\,sin(2\theta)} \qquad (1)$$

In Equation (1), n=1,2,3… denotes the diffraction order, λ is the x-ray wave length, d is the interplanar distance e is the angle between the x-ray incident direction and the diffracted ray.

When the materials undergoes to a permanent strain, crystallographic plans are also deformed and the **θ** value is modified. Measuring the difference between angular positions of crystallographic plans, pointed by the peaks of the x-ray diffraction, it is possible to determine the stress present.

However, the determination of the residual stresses by conventional methods, as rays-x diffraction, demand specialized equipment of high cost, operators and installations special. Moreover, the rays-x diffraction is limited by the geometry of the part in examination. This method is present in the most of the materials characterization laboratories.

Indentation test allows to evaluate the penetration resistance of a material when a tool is forced against its surface. There are several standardized tests, among them the Vickers test. The advantage of this test is the small impression left on the surface by the tool used.

Residual stress can be analyzed by computational tool, based on Finite Element Method (FEM). This method is a mathematical analyses that consists to discrete continuous body using small elements that maintain the same properties of the original body (Lotti et all, 2006). Using FEM it is possible to determines global and residual stress in the begin of the design.

This works investigates if it is possible to determine the nature and intensity of the residual stress in cold forming parts using the indentation test.

2. METHODOLOGY

2.1 Workpiece

Two materials were choose to the study: aluminum and copper commercial. Both were used as received, in plates of 200x100x2,88 mm and 160x130x3 mm, respectively. Workpieces were cut in the dimension of 65x25 mm as shown in Fig. 1.

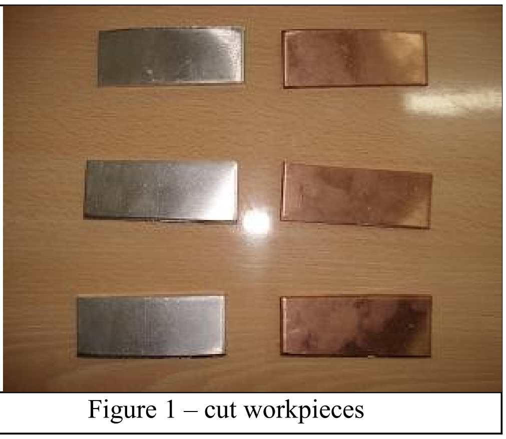

Figure 1 – cut workpieces

Workpieces were bend to introduces residual stress. Bending was choose because it is an easy forming process and to presents well defined residual stress. Workpieces were bend in four angles: 135º, 90º, 60º and 30º. One workpiece was not bend and corresponds to a piece without residual stress. Fig. 2 shows schematic draft of the bending tool and bend workpiece example.

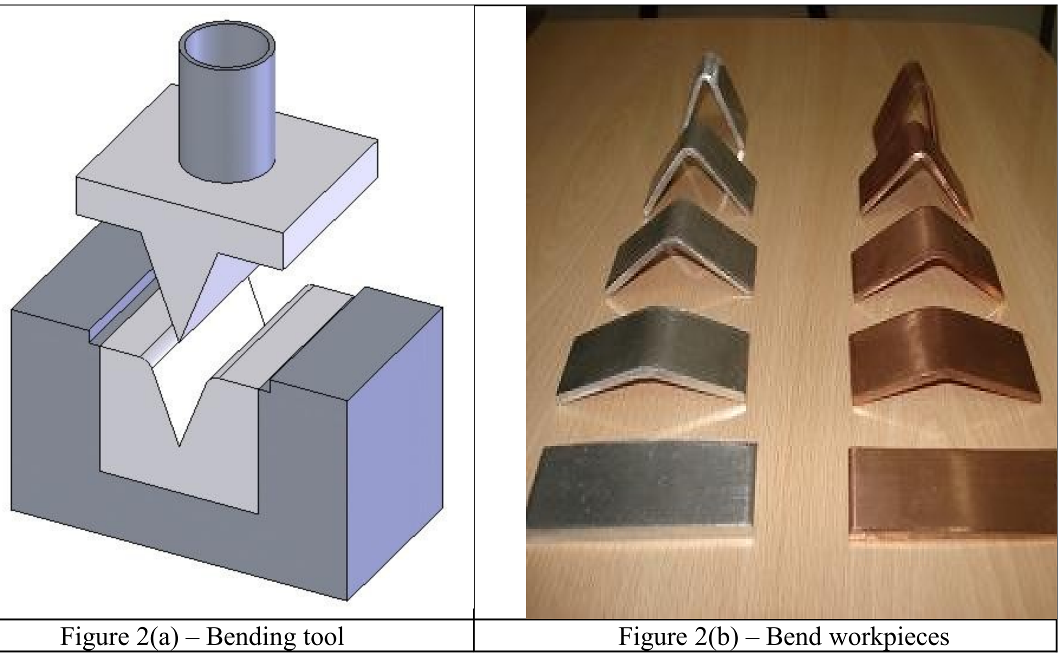

Figure 2(a) – Bending tool

Figure 2(b) – Bend workpieces

2.2 – Indentation test

Indentation test was done in the lateral surface of workpiece on the bending region, in three position: superior, middle and inferior, as shown in Fig. 3. To the tests it was used a load of 500 g during 10 s.

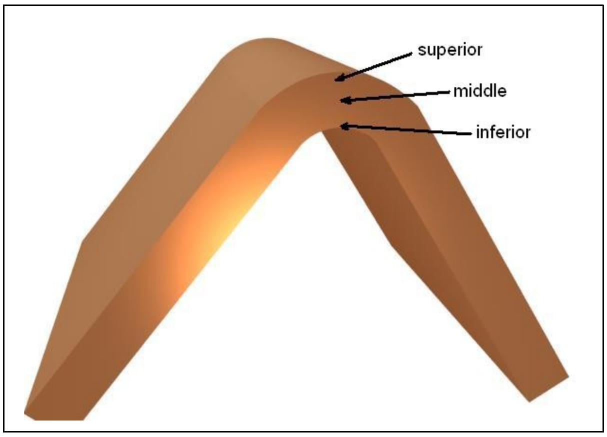

Figure 3 – Position of the measures

2.3 Design of experiments

A design of experiments with a factorial planning – fixed model was used. The treatment was bending angle (A) with five levels: 30º, 60º, 90º, 135º and 180º, and position of measure (B) with three levels: superior, middle and inferior.

2.4. Numerical simulation.

Bending was simulated using sithe ANSYS 5.6 software. The geometric models are shown in Fig. 4. It was used 206 bidimensional elements type viscoplastic 106, with four nodes to model the plate. To model the bending dies we used elements type solid 45 with 4 four nodes.

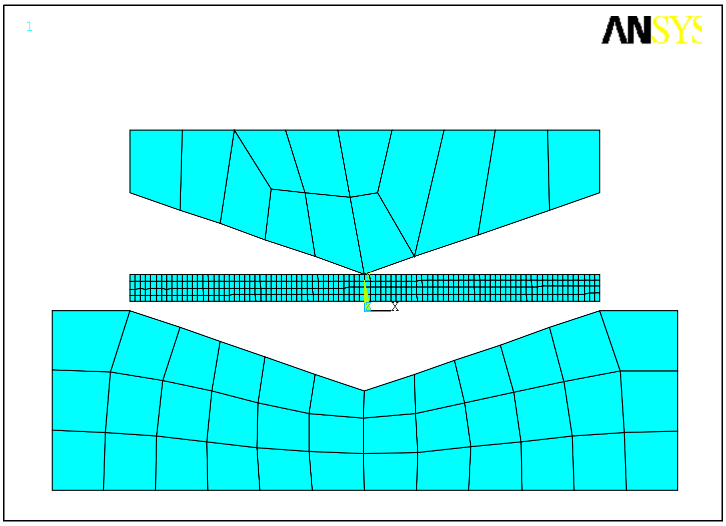

Figure 4– geometric model to numerical simulation

3. RESULTS AND DISCUSSION

Tab. 2 presents results from indention tests to Aluminum samples.

Table 2 - Vickers Hardness to aluminum samples

	Aluminum								
	Superior			**Middle**			**Inferior**		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
45°	27.3	27.2	27.4	26.2	25.9	25.8	23.9	23.8	23.7
90°	26.7	27.1	26.9	25.4	25.7	25.7	23.8	23.5	23
120°	25.2	25.9	25.8	23.4	23.1	23.3	21.7	22.4	22.6
150°	25.6	25.4	24.5	22.4	22.0	23.1	20.1	18.5	19.7
180°	22.4	22.0	22.9	22.4	22	22.9	22.4	22.0	22.9

Fig. 5 shows the graphic obtained from average of the samples in Tab. 2. As we can see, The hardness decrease from external region of bending (superior) to internal region (inferior), for all bending angles. The hardness to 180º angle is equal for all position of measure, as we can expected, since it will not submitted to a bending process. As the external bending region is under tensile stress that results in compressive residual stress, the hardness in this position is higher than in the internal region, where the opposite occurs. It also can be seen that hardness decreases to lower bending angles. This occurs because as more severe is the bending, higher is the bending stress resulting in higher residual stress.

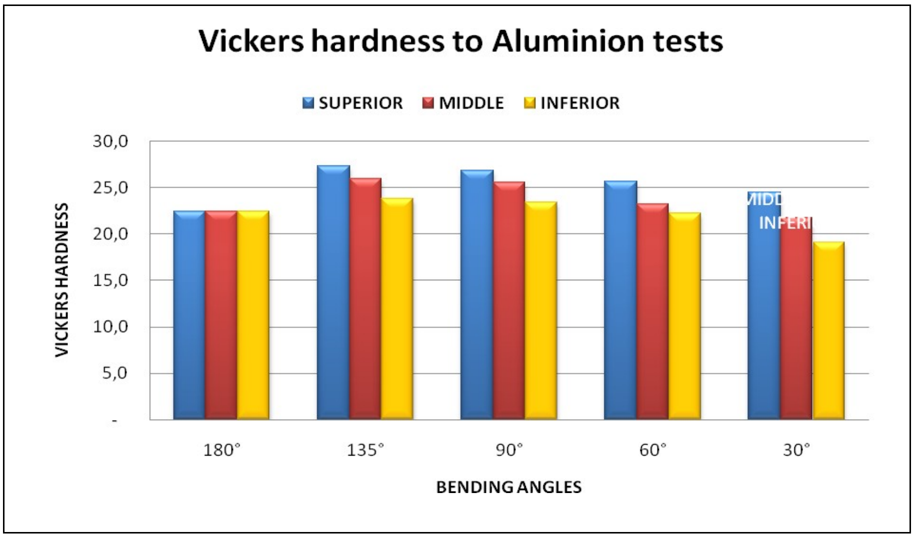

Figure 5 - Vickers harness (HV) x bending angles

Analysis of variance (ANOVA) shows that there is difference of the medias with □ = 0.05, between bending angles and between position of measure. A contrast test shows the highest harness occurs in the external region to 135º bending angle.

Tab. 3 shows the hardness tests results to copper.

Table 3 - Vickers Hardness to copper samples

COBRE									
	Superior			**Meio**			**Inferior**		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
45°	67,3	69,3	68,5	66,2	66,1	66,1	62,7	59,7	61,2
90°	66,7	67,5	66,9	63,4	63,2	64,4	60,9	58,9	59,5
120°	65,5	65,3	65,4	62,1	62,3	62,2	58,6	58,8	58,6
150°	64,8	64,7	64,8	61,3	61,2	61,6	58,3	56,8	56,3
180°	47,5	48,4	47,5	47,5	48,4	47,5	47,5	48,4	47,5

Fig.6 shows the graphic obtained from average of the samples in Tab. 3. The same behavior can be seen as that obtained to Aluminum. The hardness decrease from external region of bending (superior) to internal region (inferior), for all bending angles. The hardness to 180º angle is equal for all position of measure too. The hardness is higher in the external than in the internal region. It also can be seen that hardness decreases to lower bending angles because the same mechanism explained to aluminum.

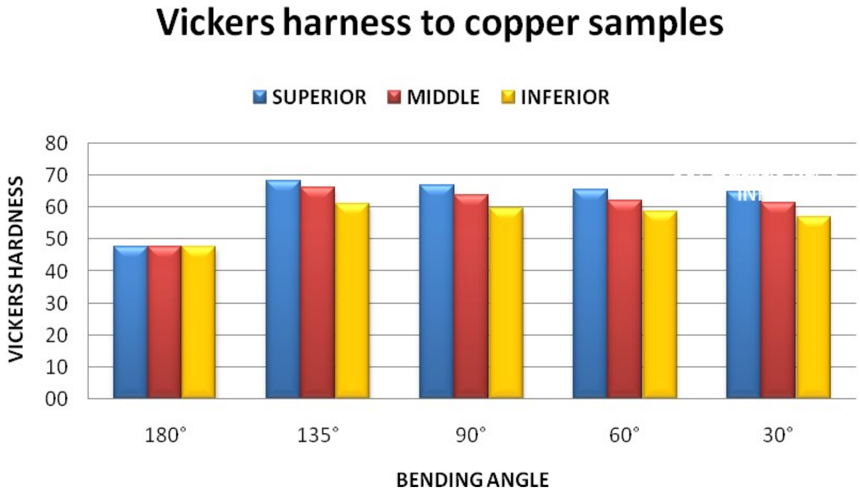

Figure 6 - Vickers harness (HV) x bending angles

Analysis of variance shows that there is difference of the medias with □ = 0.05, between bending angles and between position of measure to copper. A contrast test shows the highest harness occurs in the external region to 135º bending angle, , in the same way that we see to aluminum.

Sequence of Fig. 7 to Fig. 14 shows results of numerical simulation of the copper and aluminum bending process. We see the S_{xx} tensor component in bending region. This is the component responsible to residual stress. Note that in the internal region the S_{xx} component is negative and positive in the external region.

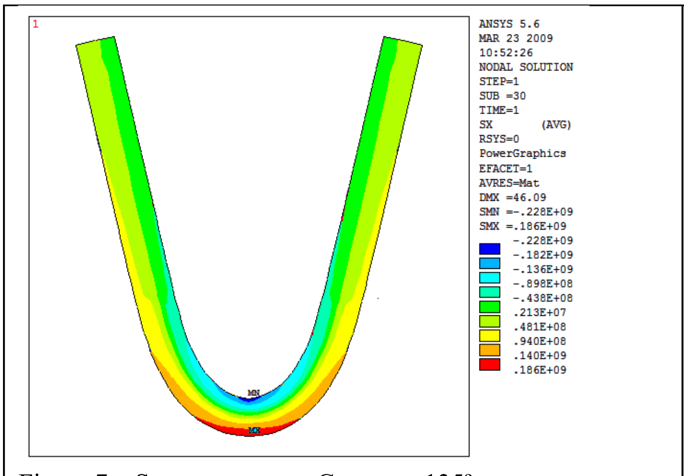

Figure 7 – S_{xx} component – Copper - 135º

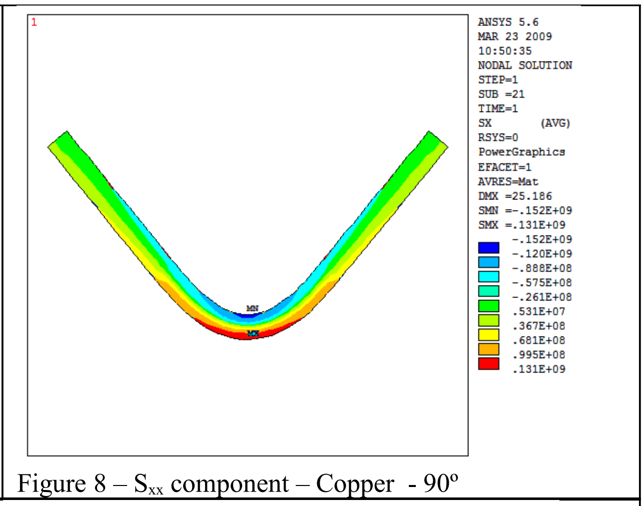

Figure 8 – S_{xx} component – Copper - 90º

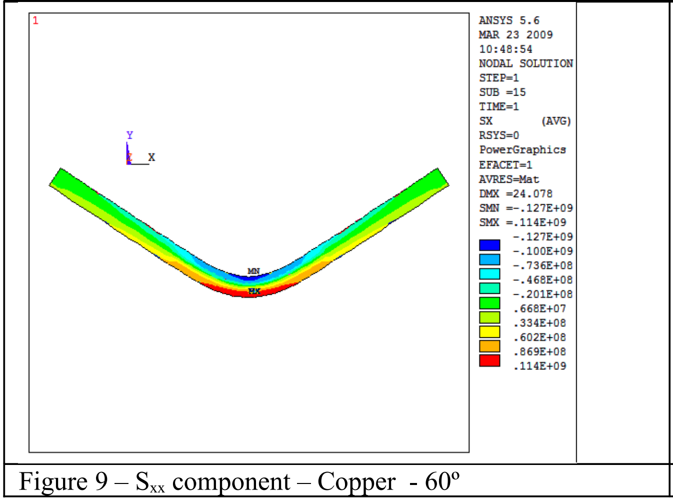

Figure 9 – S_{xx} component – Copper - 60º

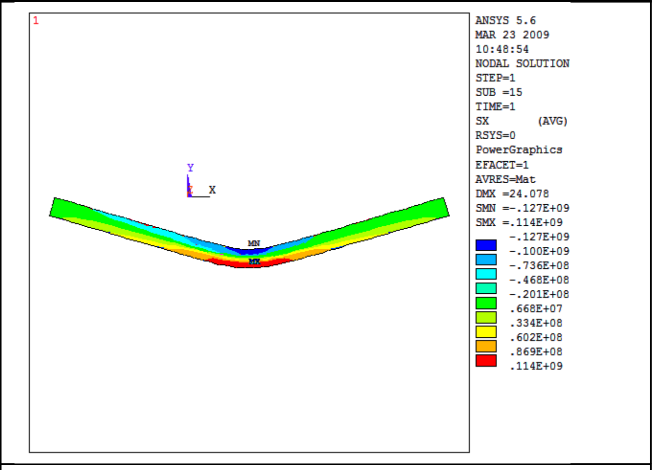

Figure 10 – S_{xx} component – Copper - 30º

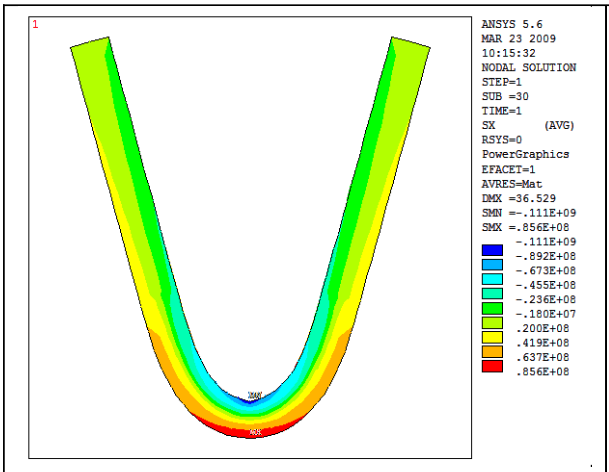

Figure 11 – S_{xx} component– Aluminum – 135º

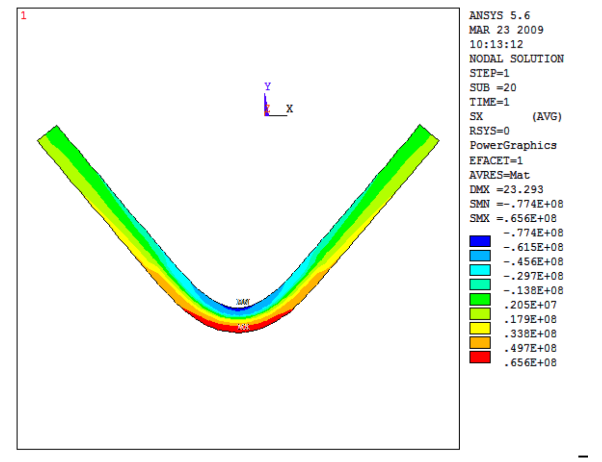

Figure 12 – S_{xx} component– Aluminum –90º

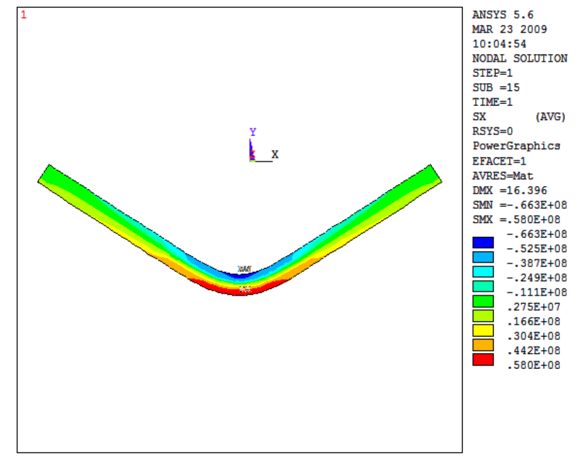

Figure 13 – S_{xx} component– Aluminum – 60º

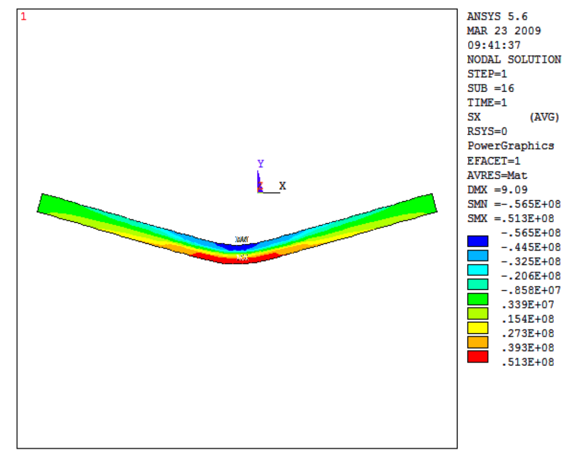

Figure 14 – S_{xx} component– Aluminum – 30º

Figures 7 to 14 shows that in the internal region of the bending there are compressive stress, while, in the external region there are tensile stress. This stress will become tensile and compressive residual stress, respectively. In the central region, the stress are reduced. Table 11 shows the correlation between stress obtained from the numerical simulation and hardness measured in the external and internal bending regions. There is a higher correlation to copper, for both region, internal and external. To aluminum, as shown in Table 4 there is higher correlation to internal region and very good correlation to external surface.

Table 4 – Correlation Analysis - copper

angle	external		internal	
	Stress (FEM)	Hardness media	Stress (FEM)	Hardness media
45°	186	68,36667	-228	61,2
90°	131	67,03333	-152	59,76667
120°	114	65,4	-127	58,66667
150°	97,7	64,76667	-106	57,13333
correlation		0,959186		0,94756

Table 5,1 – Correlation Analysis - Aluminum

angle	external		internal	
	Stress (FEM)	Hardness media	Stress (FEM)	Hardness media
45°	86	27,3	-111	111
90°	65	26,9	-77	77
120°	58	25,63333	-66	66

150°	51	25,16667	-56	56
correlation		0,90		0,987

4. CONCLUSIONS

For the results, we can conclude that:

1. According to numerical simulation, as more severe is the bending higher is the residual stress in the deformation zone;
2. The external surface of the bending is under compressive residual stress and the internal surface is under tensile residual stress. In the middle of the deformation zone the material is under no residual stress;
3. As result of indentation test, as more severe is the bending higher is the hardness in the deformation zone;
4. For angles that results on less severe bending, as we can observed with the 150º angle, the hardness shows no changes compared to the material no deformed. This is more pronounced to aluminum than to copper;
5. Hardness i higher on the external bending surface and decreases toward the internal surface;

6. For both materials, there is a strong correlation between hardness and residual stress simulated on the bending region.

7. Since the this correlation was demonstrated, its possible to establish an alternative method to evaluate residual stress using indentation test.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

BIANCH, E. C., MONICI, R. D., SILVA, E. J., AGUIAR, P. R., VALARELLI, I. D. D. Análise do Comportamento da Microestrutura de Materiais Endurecidos Retificados com Rebolos de CBN. Revista Materials Research, v. 3 n. 4, p. 147-154, 2000.

CALLISTER Jr., W. D. **Ciência e Engenharia de Materiais: uma introdução**. 5.ed. Rio de Janeiro: LTC, 2002. p-94-95-96.

DIETER, G. E. Metalurgia Mecânica. 2. ed. Rio de Janeiro: Guanabara Dois, 1981. p. 452.

MARTINS, J. A., CARDOSO, L. P., FRAYMANN, J.A., BUTTON, S. T. Análise de Tensões Residuais em Válvulas Estampadas por meio da Difração de Raios-X e do Método de Elementos Finitos. Campinas, tese de Doutorado, 2003, 12 p.

MONEZI, C. Temas de Produção e Controle ll, seminários 1º semestre de 2005. São Paulo: Mackenzie. Disponível em http://meusite.mackenzie.com.br/carlosmonezi/ seminarios/ 1o_semestre/1_2005/forjamento.pdf. Acesso em: 31 de maio 2006.

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