INFLUENCE OF HEAT TREATMENT ON RESIDUAL STRESS IN COLD FORGING PARTS

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Summary *Residual stresses are those that remain in the body when there are no more external loads applied on it. Numerous factors can induce residual stresses in the material, among which the cold forming. Thermal treatments in steels are widely used nowadays, because it enables improvement of several mechanical properties of steels such as toughness, tenacity, resistance, among others. By, the thermal treatments are another source of residual stresses. This work investigates the effect of different heat treatment on residual stresses in cold forgings. This effect is obtained by the superimposition of residual stresses in the final product, which may reduce or increase its intensity and change its nature (sign) of compressive or tensile ones. Half cylindrical workpieces of AISI 1045 Steel were submitted to cold forging printing a wedge tool on one of its surfaces, causing the deformation gradient along its axis of symmetry. Then they were heat treated to annealing, normalizing, quenching and quenching and tempering. A group of workpieces was not forged and neither heat treated, providing a comparative effect before and after forging and forging followed by heat treatment. The numerical simulation of forging was done to determine the most probable region of high intensity of residual stress. Residual stresses have been measured at the points indicated by numerical simulation using Vickers indentation test technique. The results show that residual stresses after heat treatment depend on the type of treatment used and the intensity and nature of previously existing residual stress in the body.*

Keywords*: residual stress, cold forging, heat treatment*

1. INTRODUCTION

In forging, metal is deformed plastically between two or more dies so as to give it the desired shape and size. In the case of forging, the friction at the die–workpiece interface makes the deformation as well as the stress distribution non-uniform. This inhomogeneity of the deformation gets manifested in the bulging of the workpiece. Another significant consequence of the inhomogeneity is the generation of residual stresses on unloading. (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 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.

In general, the sign of residual stress will be opposite to the sign of the plastic strain which produced the residual stress, 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. Compressive residual stress is desirable when the part will be submitted to cyclical loads since it prevents the nucleation and the propagation of cracks, reducing the fail possibility by fatigue.

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

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. 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).

In this work we used another technique to evaluate the residual stress through an indentation test (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.

Heat treatments are widely employed in steels parts , due to its ability to improve its mechanical properties. Often cold formed parts are submitted to treatments heat treatment to implement any mechanical aspect that could not be induced during the forming process or to delete undesirable ones (Tawfik, Mutton and Chiu, 2008).

There are various heat treatments to steels carbon, among them the most common are the quenching, tempering, normalizing and annealing. The quenching is used to increase the hardness of the material. The tempering acts to relieve tensions marked as effect of quenching. Annealing is a technique used to recover cold work and relax stresses within a metal to improve formability, while normalizing is generally applied to ferrous materials to enhance the mechanical properties of the material by refining the microstructure. This treatment will in some instances improve mach inability and machine finish. An example of research involving residual stress and heat treatment is the Tanner and Robinson (2008) work. They studied closed die forgings manufactured from 2014 aluminium alloys subjected to both standard and non-standard heat treatments in order to reduce the as-quenched residual stress magnitudes and cocluded that quenching leads to very low residual stress but unsatisfactory mechanical properties.

In a different way, Koç and Altan (2006) studied the possibility to reduce residual stresses resulting from the treatment of quenching through cold forming. In his work concluded that the level of stress can be reduced by up to 90% through compression or stretch the body.

This study aims to know the mechanical strength of a cold forged part after heat treatment, analyzing residual stress presents. The assumption is that there will be a superposition of residual stresses in the final product, from the various stages of manufacturing. It is expected that facilitate the work of designers to choice both the process of manufacture and heat treatment, with a view to increasing the mechanical strength of the product relating to fatigue.

2. MATERIALS AND METHODS

A wedge-shaped tool was manufactured in Steel AISI H13 and after subsequently quenched and tempered to 52 RC. The wedge angle is 75º and the wedge basis length is 5 mm. A support to the samples was done with then material and submitted to the same heat treatment. The schematic representation of the experiment is shown in Fig. 1.

Sample of Steel AISI 1045 was. They were turned into half cylinder with a radius of 12.5 mm and a thickness of 10 mm, as shown in Fig (1). This material was chosen because it has a large range of heat treatments.

Experiments was done following a Factorial Planning randomized by level. The influence factor was the material condition (A) in six levels - A1: forged and quenched, A2: forged, quenched and tempered, , A3: as received and forged, A4: forged and normalized, A5: material as received and not forged and A6: forged and annealed. The response variable was Vickers hardness measured in three positions (P), in three levels - P1: left edge of the wedge tool impression; P2: center of the wedge tool impression and P3: right edge of the wedge tool impression, as shown in Fig. 2. It was done three replicas to each one condition.

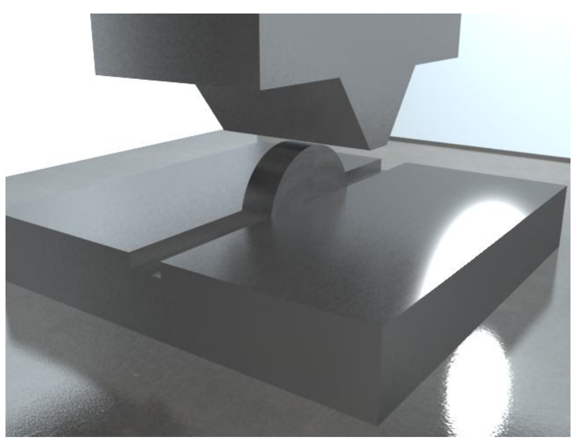

Figure 1- Schema of the experiments

Indentation tests was the Vickers hardness, because its scale permits evaluate the hardness since the condition as received up to the quenched. The Vickers hardness test is based on the strength of the material the penetration of basic diamond Indenter square, under a load set. The load used in tests to quenched, quenched and tempered, normalized and as received and forged workpieces was 588N or 60Kp. The load used to annealed and as received workpiece was 294N or 30Kp. This variation in load is required to obtain more precision in the results.

The heat treatments carried out as following. In quenching the material was heated to 800 ° C, maintained at this temperature during 25 minutes and cooled in water with circular movements. In annealing, the material was heated to 800 ° C, maintained at this temperature during 25 minutes and cooled in the furnace. Normalization was performed by raising the temperature at 910 ° C, maintained at this temperature during 25 minutes and cooled at a calm air. In tempering temperature was raised to 400 ºc maintained at this temperature during half-hour and cooled at a calm air.

Table 1 resumes the Design of the Experiments.

Table 1 – Planning the factorial One Way.

Design of Experiments										
		Hardness in P1			Hardness in P2			Hardness in P3		
Conditions		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rép3	Rep. 1	Rep. 2	Rep. 3
	A1	X	X	X	X	X	X	X	X	X
	A2	X	X	X	X	X	X	X	X	X
	A3	X	X	X	X	X	X	X	X	X
	A4	X	X	X	X	X	X	X	X	X
	A5	X	X	X	X	X	X	X	X	X
	A6	X	X	X	X	X	X	X	X	X

An Analysis of Variance was used interpret the results at a significance level of 5%.

In this work an Finite Element analysis was used to help and indicate the locations at which the piece would be more sensitive to residual stresses due to forging. To perform finite element analysis we used the Abaqus software™. It was 3000 solid parametric elements of 8 nodes.

3. RESULTS AND DISCUSSIONS

Through the results obtained from numerical analysis by Abaqus software, it was possible to set the locations in which the parts would be more subject to residual stresses due to forging. As shown in Fig. (2), the biggest deformation occurs exactly in the region of the lateral edges of the wedge. The figure shows the von Mises equivalent strain, where we can distinguish that the strain in the central region has a significantly lower intensity. So we assume that the residual stress will be the same distribution. Based on these numerical results we have determined the positions P1, P2 and P3, which we refer previously.

In Figure (3), taking as reference the hardness of the workpiece on condition "as received and not forged" (condition A5), it is clear that the heat treatments increased the hardness in all cases, except to condition A6. If the reference is the hardness of the workpiece on condition "as received and forged" (condition A3), heat treatments of quenching and quenching and tempering increased hardness of the workpiece, while the annealing and normalizing reduced the hardness. The Figure also indicates that there is not significant difference of the hardness between the positions of measure for each treatment.

Knowing that the increase of hardness indicates the presence of compressive residual stresses while residual stresses are indicated by reduction of hardness, we can affirm that the cold forging introduced compressive residual stress. This means a benefit for parts that are subject to cyclical efforts.

The heat treatment of annealing produced an undesirable effect to fatigue strength because it reduced the hardness to a value less than the hardness measured in material "as received and not forged" including material received. Once the material used is a rolled steel and, therefore, there were a portion of residual stresses introduced by rolling. Annealing would have destroyed such stresses. So, we can consider that residual stress in the workpiece is a tensile ones taking as reference the material "as received and not forged".

The heat treatment of normalization also reduced residual stresses in the workpiece forged, but these remained higher than residual stress of the material "as received and not forged". We can say that the compressive residual stresses introduced by forging just were relieved, since remained higher than the material "as received and not forged". So, annealing and normalizing, are not recommended treatment post forged as done in this work.

Treatments of quenching and quenching and tempering increased the level of residual stresses and these are of compressive nature in relation to "as received and forged". Therefore we can be recommended this heat treatment to increase the fatigue strength to cold forged products, as done in this work.

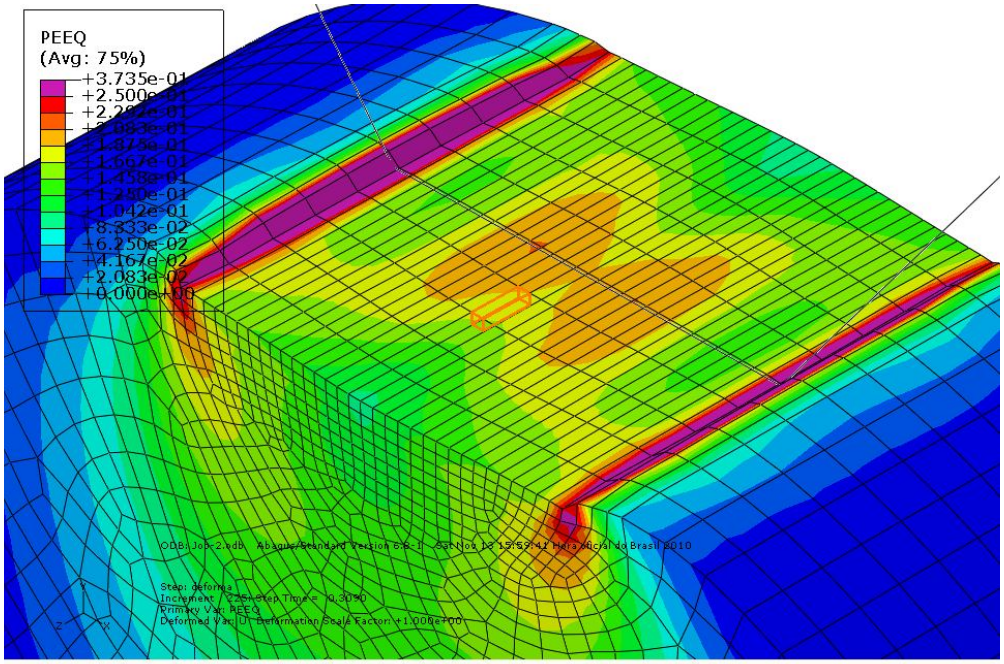

Figure 2 – Numerical simulation – von Mises equivalent strain

The results of the experiments are shown in Tab. (2) and the graph of average hardness for each position is shown in Fig. (3).

Table 2 – results of Vickers hardness to the positions P1, P2 and P3

Conditions		Position		
		P1	P2	P3
A1: Forged and quenched	Rep. 1	724	699	662
	Rep. 2	678	672	672
	Rep. 3	678	682	695
A2: Forged, quenched and tempered	Rep. 1	460	452	477
	Rep. 2	475	471	485
	Rep. 3	481	487	471
A3: as received and forged	Rep. 1	247	253	262
	Rep. 2	264	269	272
	Rep. 3	268	262	263
A4: Forged and normalized	Rep. 1	206	206	206
	Rep. 2	206	205	206
	Rep. 3	198	200	204
A5: as received and not forged	Rep. 1	184	180	180
	Rep. 2	177	179	178
	Rep. 3	176	180	185
A6: Forged and annealead	Rep. 1	158	156	160
	Rep. 2	161	156	156
	Rep. 3	165	161	161

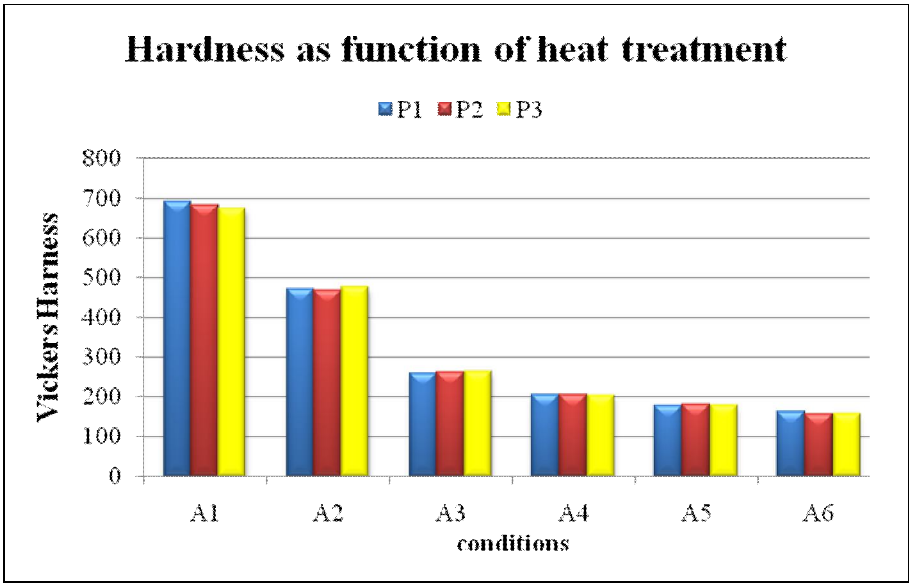

Figure 3-Vickers hardness depending on the position of measurement and processing

In Table (3) is presented the Analysis of Variance of the experiments, SST is the square sum of all measures; SS (A) is the square sum of all treatments (conditions); S (P) is the quadratic sum of all positions; SS (AxP) is the square sum of interactions and SSerro is the square sum of the errors for all measures. GL is the degree of freedom for each element. MSS is the average of square sums. F is the Fisher statistic that allows to evaluate the variance of the element. Fcalc is the observed statistic and Ftab expected for the 95% confidence level. If the expected variance (Fcalc) is less than the observed variance (Ftab) , then the treatment influences the result and the treatment averages are different.

Table 3 – analysis of Variance

	SS	GL	MSS	F calc	F tab	Analysis
SST	1969766	53				
SS(A)	1965219	5	393043,8	3002,881	2,533	influences
SS(P)	37,814	3	12,60	0,096	2,922	No influence
SS(AxP)	582,407	15	38,82	0,296	2,0148	No influence
SSerr	3926,667	30	130,88			

The analysis of Variance showed that treatments (thermal and mechanical) influenced the result because there is a statisticall significant difference. So, average hardness measures of the conditions (thermal and mechanical treatments) are different.

Positions have not influenced on the result. I.e. the hardness at P1, P2 and P3 are statistically equal.

Analysis of Variance also pointed that there is no interaction between treatments (thermal and mechanical) with the positions of measurement.

4. CONCLUSIONS

Considering the forging of a ASTM 1045 steel using a wedge-shaped toll as presented in this work, subsequently submitted to heat treatment, we can concluded that:

1.Cold forging introduces compressive residual stresses in the surface of the worked region;

2.The heat treatments of quenching and quenching and tempering residual increased the compressive residual stresses in the forged workpiece, the first treatment more than the second;

3 Heat treatment normalizing reduced the residual stresses in the forged workpiece but these were higher than those measured in the workpiece on conditions of “as received and not forged”;

4 .Thermal treatment of annealing reduced residual stresses and they are lesser than those measured in conditions of “as received and not forged”. In this case, they must considered of tensile nature;

5 .No significant differences was observed in residual stress measurement on the edge of the wedge towards the center of the tool, although the numerical simulation pointed a difference.

As general conclusion, we can say that focusing on the fatigue strength, it is not recommended use annealing or normalization treatment to a part forged as in this work. Already the quenching and quenching followed by tempering proved to be favorable to increase fatigue strength.

5. ACKNOWLEDGEMENTS

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