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Analyses of Residual Stresses on Stamped Valves by X-Ray diffraction and Finite Elements Method

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ABSTRACT

The continuous development of engineering materials, the new manufacturing processes, and the more complex mechanical parts have required constantly improvement of techniques and methods able to make analyses fast and easy. Metal forming with dimensional changes by plastic deformation results internal stresses, named residual stresses, which can significantly affect the mechanical performance of parts and systems. The main objective of this work is to develop a method to analyze the residual stresses in stamped dynamical valves by X-ray diffraction and by the Finite Element Method (FEM). In this context it was developed a $\sin^2\psi$ alternative method based on the method commonly applied to the determination of residual stresses in metallic thin films. The results obtained from the X-ray diffraction are coherent to those obtained in the simulation by the Finite Element Method. These results were also compared to results from fatigue tests carried out with a laboratory bench (cantilever alternate reversed bending) with dynamic valves in the conditions: a) as blanked, b) blanked and plastically deformed on the regions subjected to high loads, and c) blanked, plastically deformed and grinded to eliminate potential dangerous regions as revealed in the simulation. The results obtained in the fatigue tests confirmed the validity of the methods applied in this work to analyze the residual stresses.

1. INTRODUCTION

The systems and products have mechanical parts that are under dynamical loading, which has required constant increase of their technological development. In the manufacturing the analyses of the metallurgical behavior of the materials along the processes are of such importance, since the choice of a process capable to provide shape and metallurgical characteristics is relevant to adequate the product to the project requirements (Breitling, 1997). Moreover, processes of metalworking by stamping and finishing of metallic parts generate residual stresses that change significantly the parts lifetime (Martins, J A, 2004).

2. REVISION

2.1 – Stamping

Stamping is an economical process of metalworking able to generate different and several geometrical shapes, sizes and finished surfaces, resulting semi-finished and final products (Ko,D. *et al*, 1997). The process of cutting by blanking is characterized for the large localized deformation followed by a ductile fracture. In the cutting region, three or four zones stand out and can be distingued in the blanking process. They are the bending zone or ”roll-over zone”, the shearing zone and the fracture zone, (Figure 2.1) (Schey,J.A, 1982).

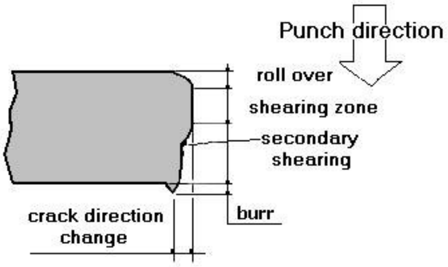

Figure 2.1 – Characteristic zones of the cutting by blanking process [2].

2.2 – Residual Stress

Generally, three types of residual stresses can be characterized according to their extensions. The first, called microscopic-stress extents for several grains of the material. The second, called structural micro-stress covers the distance of one grain or part of it, occurring for instance, between two material phases that have different physical characteristics, or even in regions where particles like inclusions are found. The third type covers several atomic distances within the grain limits in a small portion of the material (Lu and Retraint 1998).

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

The 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) (Lukin and Glenn, 2004).

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 (Cullity,B.D. 1978).

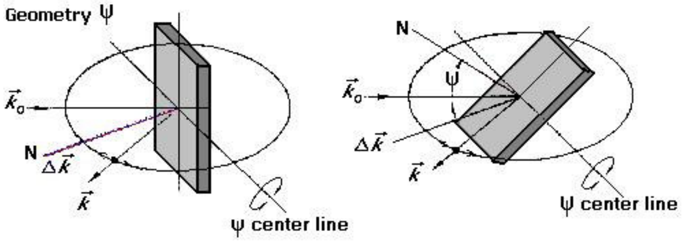

Figure 2.2- Schematic representation of the angle psi.

The determination of the residual stress is done based on the strain present in the family of the planes *nkl* in some directions (ψ) (Figure 2.2) and pass through the determination of the stress tensor by the use of the constitutive equations (Genzel, C. *et al.*, 1996). These equations (2.2 and 2.3) assume the strain of the material as being within the elastic limit and in the meantime with an isotropic behavior (Scarminio J. 1989). The determination of the atomic inter-planar variation and the stress is given by:

$$\varepsilon = \frac{d_i - d_n}{d_i} \qquad (2.2)$$

$$\sigma_n = \frac{E}{(1+\nu)\mathrm{sen}^2\Psi}\left(\frac{d_i - d_n}{d_n}\right) \qquad (2.3)$$

The determination of the strain in a particular X-ray considered plan to an uniaxial stress comes from the definition of the sin of the diffracted angle θ, as follows:

$$\left(\frac{\mathrm{d_i}-\mathrm{d_n}}{\mathrm{d_n}}\right)=\frac{\operatorname{sen}\theta_n}{\operatorname{sen}\theta_i}-1 \tag{2.4}$$

$$\sigma_x=\sigma_y=\sigma=\frac{E}{(2\nu)}\varepsilon_z \tag{2.5}$$

with E being the Elasticity Modulus (Young), d_i or d_o the initial interplanar distance, d_n the interplanar distance in the n direction, ν the Poisson coefficient, ψ the angle psi and θ the beam incident angle (Bragg's angle).

In 1998, Scarminio (1989) studied the intensity of mechanical stresses in thin layers of Pb/Pd proposing a simple method to the measurement of the planes deformations by X-ray diffraction, allied to analytical calculus without the use of the squared psi method. According to him, the residual stress can be determined by Hooke's law to materials under linear and isotropic behavior, and assuming a planar and homogeneous stress state where $\sigma_x = \sigma_y = \sigma_z$ e $\sigma_{xy} = \sigma_{yx} = \sigma_z = 0$, according to the equations (2.4) e (2.5), as follows:

$$\sigma=\frac{E}{2\nu}\left(\frac{\operatorname{sen}\theta_n}{\operatorname{sen}\theta_i}-1\right) \tag{2.6}$$

3 – MATERIALS AND METHODS

3.1 – Material

Uddeholm Company supplied the material used on this work. Two materials were chosen to the analysis of the proposed processes, as presented in the Table 3.1. The first material designation UHB-20C normally used to manufacture valves with thickness less than 1.00 mm, and the material UHB 15N20, which has a higher thickness, between 1.00mm and 1.5mm.

Table 3.1- Chemical composition of the steels used to manufacture dynamic valves

Steel designation	Chemical composition (% in weight)							
	C	Si	Mn	P max.	S max.	Cr	Ni	Mo
UHB 20C	1.00	0.3	0.45	0.015	0.015	-	-	-
UHB15N20	0.75	0.3	0.4	0.020	0.015	-	2.00	-

The first steel UHB 20C was used to make the coining experiments on the blanked valves, beyond of the dynamical tests. The second, UHB 15N20, on the other hand, to make the blanking experiments, coining and measurement of the residual stress to compare the X-ray diffraction valve with the numerical simulation (FEM).

3.2 – Stamping

The measurement of small thickness parts by X-ray diffraction does not provide good signals due to the equipment limitations (poor signal intensity), therefore the stamping (blanking and coining) of the material to the residual stress determination was done with the higher thickness, 1,5mm, material UHB 15N20. The objective of the blanking was to verify the level of residual stress into the material in the same condition applied to the manufacturing process of the valves. This process was held in a mechanical guillotine type shear NEWTON model TM-8. There were more two additional samples made with this material thickness: the first, cut by wire EDM machine and then submitted to tumbling processes A and B to check the residual stress resulted from each one of these abrasive processes, considering that, as known, the wire EDM machine does not influence significantly the residual stress of the material. The second sample was blanked, and afterwards submitted to both additional tumbling processes A and B.

3.2.1 – Coining experiments

The coining operation was performed on the material UHB 15N20 thick 1,5mm cut by wire EDM machine as well as in the blanked valve (thinner material). The purpose of the coining to the thicker material was to determine the residual stress by X-ray diffraction and therefore to compare the obtained value with the results from the FEM.

To the valve (Figure 3.1), it aimed the introduction of the compressive residual stresses that might result in the increase of its endurance. To this particular coining operation was developed a special tool and the operation was done in a mechanical eccentric press [9].

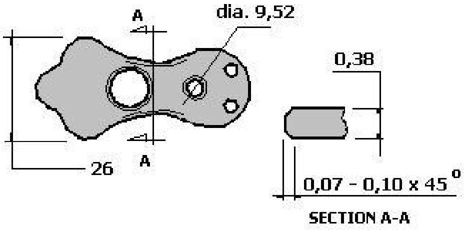

Figure 3.1 – Blanked and coined valve by stamping.

3.3 – Tumbling

The tumbling operation was done to evaluate its influence in the residual stress of the material UHB 15N20, cut by wire EDM machine and stamped (blanked and coined). This operation was performed under different process parameters, called A and B. The process time was kept the same to both tumbling processes. The tumbling processes are not detailed in this work due to the fact as being private company technology. These processes were also applied on the valves in the conditions just blanked, and blanked and coined.

The measurement of the resultant chamfers from the coining operation was done with equipment Mitutoyo Contracer model CBH-400.

3.4 – Finite element analyses (FEA)

The analyses with the finite element method were done with the software MSC.Superform version 2004. The simulation took into account the parameters, E=210000 MPa and $\nu = 0.30$ to elastic behavior and $\nu = 0.5$ to plastic behavior. The Coulomb friction coefficient was assumed to equal to 0.3, similar to metal drawing under poor lubrification. The flow curve, Holloman curve ($\sigma = K.\varepsilon^n$), was utilized to both materials. The coefficients to both materials were determined by tensile test, being to UHB 20C K=2300 MPa and the strain-hardening coefficient n=0.0487, and to the material UHB15N , K=1900 MPa and n=0.0487.

The coining process of the steel UHB 15N20 with 1.5mm material thick simulated by FEM considered axis-symmetric quadratic elements with third eight nodes in the material thickness direction.

As known the particular stamping process treated in this work is symmetric, then only one side of the material was simulated with a bi-dimensional model, moreover it was not used any automatic remeshing procedure available in the software due to the low difference between the residual stresses values. The yielding criterion utilized in the simulation was the von Mises to isotropic materials. The von Mises equivalent stress, soon after release the punch loading is considered the remaining stress to be compared with the results from the X-ray diffraction. After the blanking, the average strain from this operation, 0.26, was used on the forward coining numerical simulation [9].

3.5 – X-ray diffraction

The samples were analyzed along 90° (Figure 3.2) of its thickness to the coined sample, and along 180° to the strip cut by wire EDM machine and by blanking. The samples analyzed by X-ray follow, just blanked, cut by wire EDM machine, cut by wire EDM machine and afterwards tumbled and the blanked plus coined sample (stamped). It should be clarified that the samples measured by X-ray diffraction have the same thicker thickness due to avoid poor signals due to the equipment limitation. The equipment used to measure the material interplanar strain was a diffractometer Philips 1710 radiation $Cu_{K\alpha,}$ (1,5405 Å) and a monochromator of graphite to diffracted beam.

As known from the literature [4], the plans (310) are the most common used to measure the residual stress due to its higher Bragg's angle. In this particular case, due to the poor signal the plan (110) was chosen. The result of these measurements verified by the change of the angle 2θ (44.456°), determined the interplanar variation due to the applied strain.

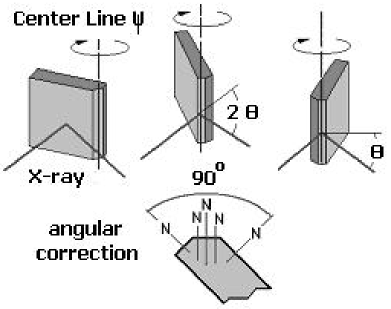

Figure 3.2 – Positioning of the sample for X-ray diffraction analyses.

3.6 – Fatigue

The fatigue test was performed on dynamical valves in order to validate the valve endurances under the conditions just blanked, coined, and coined and tumbled. The type of loading applied was the alternate reverse bending (Figure 3.3).

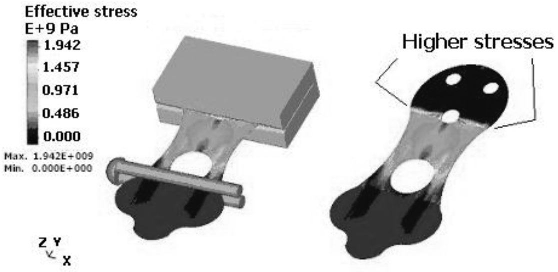

Figure 3.3 –Sketch detailing of the fatigue test set up.

4- RESULTS

4.1 – Verified stresses in the coined material under simulation (UHB-15N20)

It is assumed that the residual stress is the remained stress in the material after the forming process, and since it can be represented by the equivalent stress. This is perfectly justified because this stress is determined by a complex stress state that considers the interaction of all stresses that the material undergoes, therefore being the most representative of the residual stress.

The maximum value observed is 1356MPa normal to the chamfer in the FEM, close to the superior extreme of the chamfer and 45° far from one of the faces, as verified in Figure 4.1.

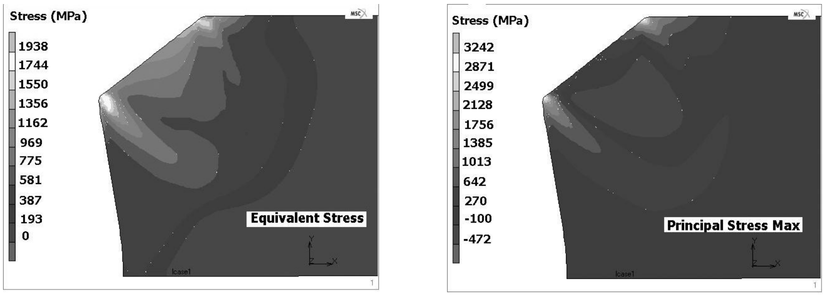

Figure 4.1 – Equivalent stress of the thicker material deformed by coining

It can be verified that despite of a higher residual stress (equivalent stress 1700MPa) in the chamfer extremes, these are regions that contain the higher tensile stress states, $\sigma_1 = +2800$MPa.

4.2 – Verified stresses in the valves under simulation (UHB-20C)

The coined valve presents a compressive residual stress state almost in all chamfer extension, Figure 4.2. The tensile stress state is seen on the chamfer surface, with σ_1 equal to +1100 MPa in a very restricted portion, as verified on the simulation of coining previously done, shown in the Figure 4.1, for the thicker material.

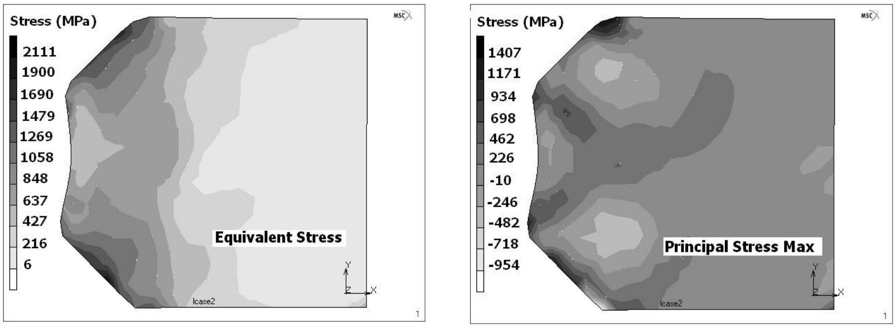

Figure 4.2 – Equivalent stress of the dynamic valve deformed by coining

4.3 – Stresses determined by diffraction (UHB-15N20)

The determination of the residual stresses proceeded as described in the item 2.2 of this work. The Figure 4.3 presents the results of residual stress obtained by FEM and X-ray diffraction. It can be seen the evolution of the residual stress measured by X-ray as well as those obtained by FEM on the blanked samples. The FEM has a different tendency when compared with the values measured.

On the coined sample, compressive stress state is present due to the decrease of the interplanar distance to the planes (110). The maximum value found is 1500MPa, compatible to the material mechanical properties and also to the mechanical deformation applied. It was not detected by the X-ray diffraction measurement any tensile stress state as verified on the simulation FEM, Figure 4.4 (a).

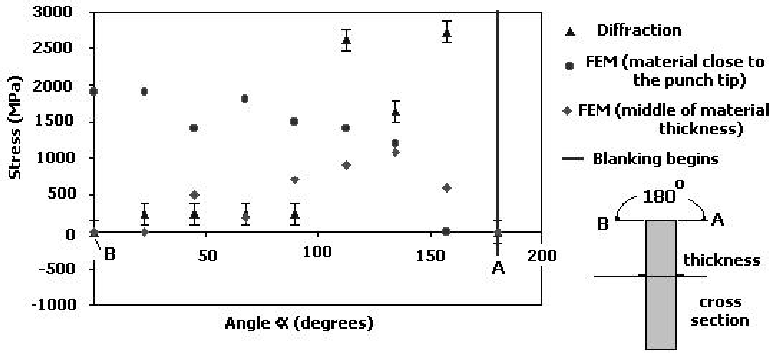

Figure 4.3-Variation of the calculated residual stress obtained on the diffraction and simulated by FEM to the material UHB 15BN20 just blanked

The samples cut by wire EDM machine plus the tumbling process A [Figure 4(a)], beyond of presenting the lower tensile stress state, has the lower results variability which are of such importance to improve the part endurance. Analyzing Figures 4.4 and 4.5 below it can be seen that the higher effectiveness on the elimination of tensile stress state is found when the tumbling process A is adopted on the blanked parts. Therefore, the combination of the processes blanking plus tumbling, brings benefits to the dynamical parts due to the fact of reducing the tensile stress state and in some cases even introducing compressive stresses.

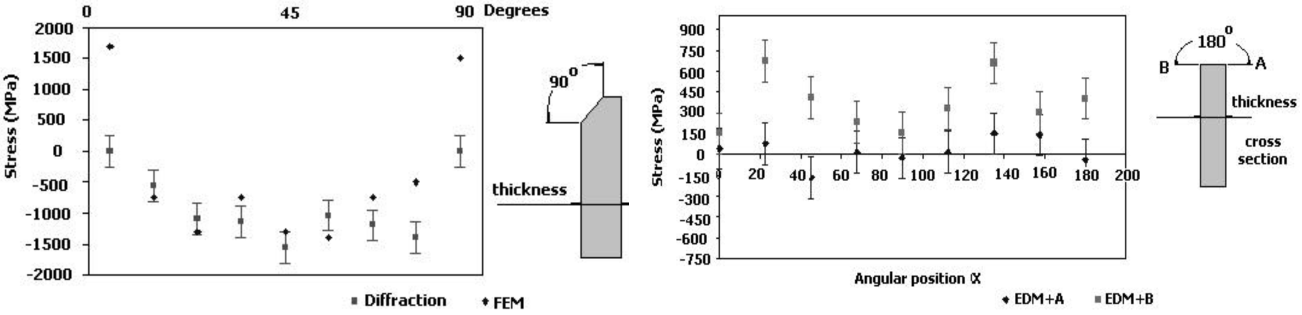

Figure 4.4 – (a) Measured and determined residual stress by simulation (equivalent stress) to the material UHB 15N20 coined, (b) residual stress obtained by the X-ray diffraction along the sample cross section under the two tumbling processes.

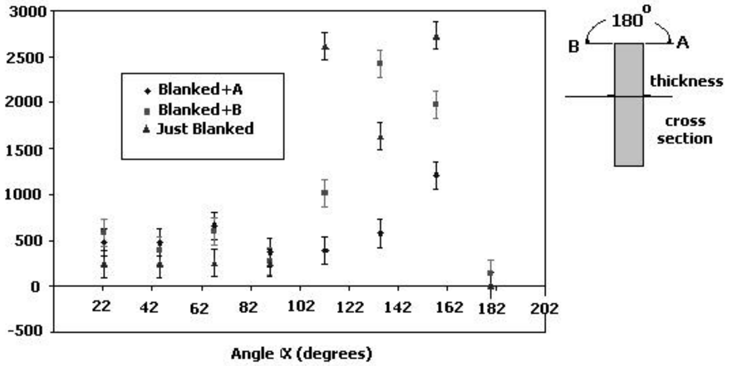

Figure 4.5 – Variation of the residual stress along the cross section under different process conditions.

4.4 – Fracture analyses

The analyses under scanning electron microscopy (SEM) showed the potential regions verified by FEM to the crack initiation, being the chamfer extremes that have the higher tensile stresses as shown in the Figure 4.6.

Striations are found on a region very close to the chamfer end and it is verified that the propagation of the crack moves from the chamfer extreme to nearby the middle of the material thickness, Figures 4.6.

Beach marks are not present on the fracture surface, although the presence of striation is a particular constituent useful to characterize the fatigue phenomena. As expected, the better condition blanked plus tumbling A also showed the same fatigue fracture surface characteristic.

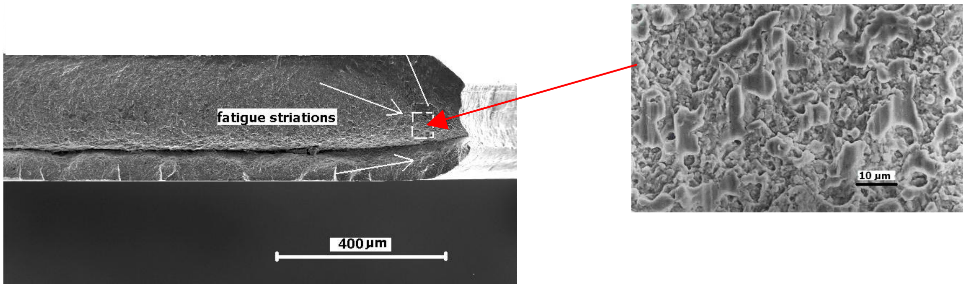

Figure 4.6 – Fracture surface microscopy of the blanked valve.

4.5 – Endurance lifetime

The results are well compatible with the theory developed ever since, it means that coined condition increases the compressive stress state, and as consequence, a considerable increase on the part endurance, as presented on the Table 4.1 when compared to the condition just blanked. The additional tumbling was imposed to the coined condition in order to eliminate or minimize the tensile stress in the material as revealed on the simulation. This benefit characteristic can be checked up by the increase of the valve endurance.

Table 4.1 – Results verified on the fatigue tests of valves under several conditions.

Condition	**Cycles to fracture**	**Std deviation**
Just blanked	50,200	7,700
Coined	158,200	53,300
Coined plus tumbled A	390,800	69,450

5 - CONCLUSIONS

- The residual stress in the material UHB 15N20 thick 1.5mm observed in the FEM simulation of the blanking process is close to the values measured by X-ray diffraction.
- The process of coining brings benefits to the parts due to the increase of endurance, even if according to FEM some regions present tensile stresses.
- The equivalent stress and the principal stresses are reliable to the residual stress determination of materials that present plastic deformation caused by metalworking processes.
- The method proposed in this work is user-friendly because it does not require high operational costs.
- The results met by X-ray diffraction and by finite elements are very close, evidencing the method effectiveness, to the blanking as well as to the coining operation.
- The fracture surfaces in all the studied conditions are characteristic of the fatigue phenomena.
- Even the considered better condition showed the crack initiation very close to the chamfer extreme surface, what means that despite of the abrasive additional operation the tensile regions were not eliminated as a whole.
- The best fatigue endurance is attributed to the condition of interaction between the processes of coining plus tumbling A.

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