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STUDY OF THE INFLUENCE OF ANISOTROPY ON THE RESIDUAL STRESSES GENERATED IN THE WIRE DRAWING PROCESS OF AN AISI 1045 STEEL[1]

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Abstract

The use of numerical simulation has increased in the industries of manufacturing process in the last years aiming to avoid errors that would be expensive to correct with long "try out" stages. In this study, this tool was used to show the effect of the anisotropic properties presents in the AISI 1045 rolled steel in the residual stresses generated in the wire drawing process, and compare this results with an isotropic material taken from the database of commercial software of numerical simulation. The anisotropic properties were obtained by compression tests on samples in different positions of the bars before drawing in order to obtain the yield stress in two directions. These yield stress were used to calculate the indices of anisotropy to use the Hill criterion for input data of the software. The simulations were validated by comparing simulated and calculated force by empirical equations found at the literature. The results of comparison between the residual stresses profiles obtained by simulation with two different descriptions of material, anisotropic and isotropic, expect to find differences around 200 MPa and this study will serve as a basis for further assessment of distortion of the bars.

Key words: Numerical simulation; Plastic anisotropy; Residual stresses.

ESTUDO DA INFLUÊNCIA DA ANISOTROPIA NAS TENSÕES RESIDUAIS GERADAS NO PROCESSO DE TREFILAÇÃO DE BARRAS DE AÇO AISI 1045

Resumo

O uso da simulação numérica por elementos finitos aumentou nas indústrias de processos de fabricação nos últimos anos, a fim de evitar erros, diminuir custos e otimizar estágios de produção. Neste trabalho, esta ferramenta foi utilizada para mostrar o efeito de propriedades anisotrópicas nas tensões residuais geradas pelo processo de trefilação a frio do aço AISI 1045 laminado e comparar esse efeito com outra simulação utilizando um material isotrópico do banco de dados do *software* comercial utilizado. As propriedades anisotrópicas foram obtidas pelo ensaio de compressão em corpos de prova tirados de diferentes posições de barras ainda não trefiladas, afim de obter a tensão de escoamento em pelo menos duas direções, radial e axial, e assim, chegar aos índices de anisotropia que são um dado de entrada importante para a simulação. As simulações foram validadas pela comparação de força do processo calculadas por equações empíricas encontradas na literatura. Com a comparação entre os perfis de tensões residuais obtidos pela simulação com duas diferentes condições do material, anisotrópico e isotrópico, espera-se encontrar diferenças que giram em torno de 200 MPa entre as simulações sendo que este estudo servirá como base para posteriores avaliações de distorção nas barras.

Palavras-chave: Trefilação a frio; Tensões residuais; Simulação numérica.

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1 INTRODUCTION

The use of drawn products has increased in last year's.[1] Drawn bars with different diameters are used in the manufacturing of automotive parts, reducing subsequent machining steps, costs and energy consumption. The wire drawing can be defined as a manufacturing process by plastic deformation in which the raw material (wire rod) is pulled through a die, thus causing a reduction in cross sectional area and an increase in the length. Some of the main features of the wire drawing process are the achievement of an excellent surface finishing and good dimensional accuracies, increase in mechanical strength and high processing speeds.[2] The main raw material used in the drawing of bars is the wire rod, i.e., rolled steel of continuous section, usually cylindrical, supplied as coils.
Residual stresses are the stresses present in the material without external forces or temperature gradients. In the cold drawing process the appearance of these stresses is the heterogeneous plastic deformation in the material and it can affect mechanical properties and the behavior of the material in distortion (dimensional and shape changes after heat treatment), sometimes they can lead to catastrophic failure of a component in service.[3]
Anisotropy is not be considered a phenomenon of rather rare occurrence. It is difficult to avoid in metal working and is invariably developed by any severe strain. It is present the theories of plastic flow for isotropic metals are only valid to a first approximation.[4]
The work material in metal working operations always shows some kind of anisotropy,[5] as the wire drawing process undergoes plastic deformation, the anisotropy occurs in the material whose characteristic yield stresses are different for each direction.[6] The resistance of deformation is higher along the longitudinal axis, and it decreases in the transverse direction of the flow direction.
This work simulates by finite elements the residual stresses generated in the cold drawing process in two situations: considering anisotropic and isotropic material. These results will be important to understand the contribution of the residual stresses as a potential of distortion that appear in the parts after processing.
The anisotropic properties were obtained by the compression test in specimens taken from AISI 1045 steel bars before drawing in order to obtain the yield stresses for different directions to apply the Hill´s Criterion. After the realization of the simulations were taken the profiles of residual stresses and a comparison was made between them.

2 INPUT DATA OF THE SOFTWARE

2.1 Anisotropy Indices

Hill proposed the criterion of the anisotropic flow through the simplification of the criteria originally proposed by von Mises. Hill´s criterion assumes that the material has anisotropy in three orthogonal planes.[4,5]
The initial yield stress (σ_o) depends on six components (σ_1, σ_2, σ_3, τ_{12}, τ_{13} and τ_{23}). The Hill´s criterion can be expressed in Cartesian components by de Equation 1.

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2.L.(\sigma_{23})^2+2.M.(\sigma_{31})^2+2.N.(\sigma_{12})^2=1 \quad (1)$$

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F, G, H, L, M and N are constants characteristic of the current state of anisotropy. F, G and H can been determined by compression tests and L, M and N for shear tests or empirical equations.
The constants in the Hill criterion can be expressed as function of the yield stresses x, y and z directions, which results in ratio between yield stress in each direction with the initial yield stress and this is shown in Equations 2 to 7.

$$2F = \frac{1}{(\sigma_{o22})^2} + \frac{1}{(\sigma_{o33})^2} - \frac{1}{(\sigma_{o11})^2} \quad (2)$$

$$2L = \frac{1}{(\tau_{o23})^2} \quad (3)$$

$$2G = \frac{1}{(\sigma_{o11})^2} + \frac{1}{(\sigma_{o33})^2} - \frac{1}{(\sigma_{o22})^2} \quad (4)$$

$$2M = \frac{1}{(\tau_{o13})^2} \quad (5)$$

$$2H = \frac{1}{(\sigma_{o11})^2} + \frac{1}{(\sigma_{o22})^2} - \frac{1}{(\sigma_{o33})^2} \quad (6)$$

$$2N = \frac{1}{(\tau_{o12})^2} \quad (7)$$

Where σ_{oii} and τ_{oij} are taken from the Equations 8, 9, 10.

$$\sigma_{oii} = \frac{\sigma_{ii}}{\sigma_o} \quad (8)$$

$$\tau_{oij} = \frac{\tau_{ij}}{\tau_o} \quad (9)$$

$$\tau_o = \frac{\sigma_o}{\sqrt{3}} \quad (10)$$

2.2 Compression Test

A compression test of the steel under study was carried out to get the flow curve of the material.[7]
The specimens were taken from a bar before drawing and they were machined to obtain the dimensions of 10 mm in the diameter and 15 mm in the height (Figure 1).

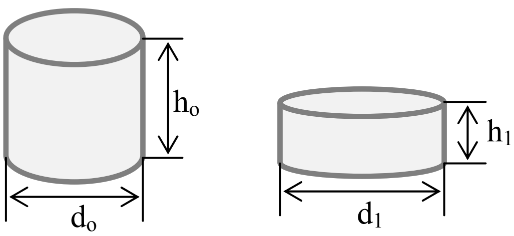

Figure 1. Compression test geometry.

Six cylinder samples were machined from the AISI 1045 steel rolled and used for compressive tests for the 0º direction of the bar and six cylinder samples were machined for the 90º direction of the bar. The specific locations of the samples are illustrates in Figure 2.

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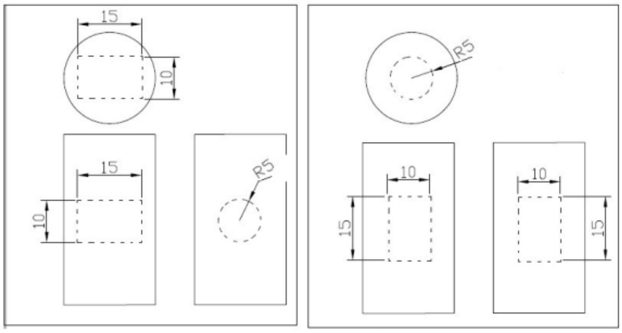

Figure 2. Specific locations of the samples.

The experiments were carried out with a *Eka*® machine, controlled with hydraulic press. The tests were carried out at room temperature and loading speed of 6 mm/s.

2.3 Ring Test to Estimate the Friction Coefficient

In the drawing process, friction is one of more important variables. Friction is the resistance to surfaces motion of two bodies in contact during the sliding of one over the other.[8]
The friction influences material flow,[9-11] changing the values of forces and tool wear in life. The ring compression test is one of typical methods for the quantitative evaluation of friction coefficients. The coefficient of friction can be estimated through the change in the internal diameter of the deformed ring.
The knowledge of the friction coefficient value of the process is necessary as an input data to the simulation software. Computer simulations of the ring test were carried out in order to get a calibration curve and compare with experimental tests. More information about this test can be found in Soares, Rocha and Souza.[12-14]
The value of the Coulomb of friction coefficient used in the simulation was 0.1. It is important to remember that the in the ring test, the coefficient of friction can be overestimated under the presence of anisotropy and the calibration curve carried out in this his work considerate an isotropic material for this simulated test.

3 NUMERICAL SIMULATION OF THE DRAWING PROCESS

The parameters used in the numerical simulation for the isotropic material are shown in Table 1. The drawing speed of 1,250 mm/s for both simulations was estimated from real industrial applications.

Table 1. Parameters of the wire drawing simulation for isotropic material

Analysis	**3D mechanical**
Elements	64,000
Material	AISI 1045 (data base Simufact Forming)
Coulomb friction coefficient (μ)	0.1
Drawing speed	1,250 mm/s
Initial and final diameter	21.463 and 20.25 mm
Initial Temperature	20°C
Die angles (2 α)	15°
Young Modulus	210 GPa
Poisson coefficient	0.3

In Table 2, it is possible to see the simulation parameters for anisotropic material. The value of the initial yield stress in the 0º direction is 390 MPa and for the 90º is 349 MPa, which means 10% higher in the 0º direction.
The compression tests showed in the end of the experiment a barrel shaped in the samples. This effect indicates anisotropy in the material.(15)

Table 2. Parameters of the wire drawing simulation for the anisotropic material

Analysis	3D mechanical
Elements	64,000
Material	AISI 1045
Coulomb friction coefficient (μ)	0.1
Drawing speed	1,250 mm/s
Initial and final diameter	21.463 and 20.25 mm
Initial Temperature	20°C
Die angles (2 α)	15°
Young Modulus (E_1, E_2, E_3)	195 GPa, 175 GPa, 175 GPa
Poisson coefficient (v_1, v_2, v_3)	0.3; 0.269; 0.269
Shear Modulus* (G_1, G_2, G_3)	75 GPa; 69 GPa; 69 GPa
Anisotropy indices normal direction (F, G, H)	0.747; 0.5; 0.5
Anisotropy indices normal direction (L, M, N)	0,5; 0,692; 0,692

The indices of anisotropy were obtained with the application of the equation shown at the 2.1 section. With the results obtained by the compression tests was possible to calculate the Young and Shear modulus by specific equations shown in Equations 11 and 12.

$$E = \frac{\sigma}{\varphi} \qquad (11)$$

$$G = \frac{E}{2.(1+v)} \qquad (12)$$

To apply the drawing speed (V) a device called "puller" attached in the end of the bar was used, which simulates the effect of the mechanical device that pulls the workpiece during the real process of wire drawing. The model is shown in Figure 3.

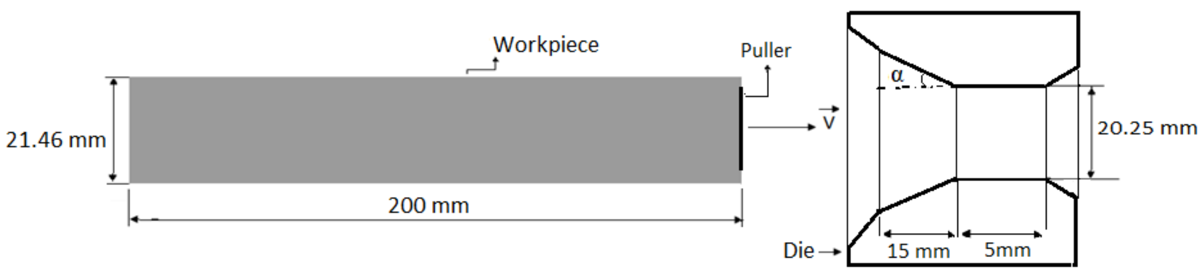

Figure 3. Tridimensional model created.

4 RESULTS AND DISCUSSION

The ability of numerical simulation predicts the drawing force was verified by comparison between numerical results and the empirical equations of Sachs(2) given in Equation 13 and of Avitzur(9) given in Equation 14.
The Sachs equation, take into account the friction coefficient and the die angle in its formulation.

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$$F = A_1 . k_{fm} . \left(1 + \frac{1}{\mu . \cot\alpha}\right) . \left[1 - \left(\frac{A_1}{A_o}\right) . \mu . \cot\alpha\right] \qquad (13)$$

Where F is the drawing force, A_o and A_1 are the area before and after drawing (mm^2), k_{fm} is the average yield stress (MPa), μ is the Coulomb friction coefficient and α is the half of the drawing angle (rad)
The Avitzur equation takes into account the calibration region of the die.

$$F = A_1 . k_{fo} . \frac{\left\{2 . f(\alpha) . \ln\left(\frac{D_o}{D_1}\right) + \frac{2}{\sqrt{3}} . \left(\frac{\alpha}{(\sin^2\alpha)} - \cot\alpha\right) + 2 . \mu . \left(\cot\alpha . \left[1 - \ln\left(\frac{D_o}{D_1}\right)\right] \ln\left(\frac{D_o}{D_1}\right) + \frac{2 . H_c}{D_1}\right)\right\}}{1 + 4 . \mu . \frac{H_c}{D_1}} \qquad (14)$$

Where k_{fo} is the initial yield stress (MPA), D_o and D_1 are the initial and final diameter of the bar (mm), H_c is the length of the calibration region of the die (mm) and *f* is the function of the force carried out to generate the homogeneous deformation.
The results of the comparison between calculated and simulated drawing forces are shown in Table 3.

Table 3. Comparison between the simulated and calculated results of force

<table>
<tr><th>Type of simulation</th><th>Simulated force (N)</th><th>Avitzur force (N)</th><th>Sachs force (N)</th></tr>
<tr><td>Anisotropic Simulation</td><td>42,707</td><td rowspan="2">45,714</td><td rowspan="2">43,585</td></tr>
<tr><td>Isotropic Simulation</td><td>76,415</td></tr>
</table>

Table 3 presents the results of simulated and calculated forces. The maximum difference between the force of the isotropic simulation is 59.82%, when compared with the Avitzur force and 57.03% for Sachs force. The maximum difference between the force of anisotropic simulation is 6.58% for Avitzur equation and 2.01% for the Sachs equation.
The results of the comparison between calculated and simulated forces are very close for the anisotropic simulation. The found differences between the simulation and the theoretical equations for the isotropic simulation can be originated from several factors, including the limitations in the equations, for example, in the isotropic simulation, the software flow curves take into account the strain rates, but the used equations and experimental tests didn´t take it into account. The consideration of strain rates in the theoretical forces would change the result of forces, reducing this differences.
The simulated values of residual stresses (Figures 4, 5 and 6), were compared the isotropic and the anisotropic simulation for axial, radial and hoop directions.

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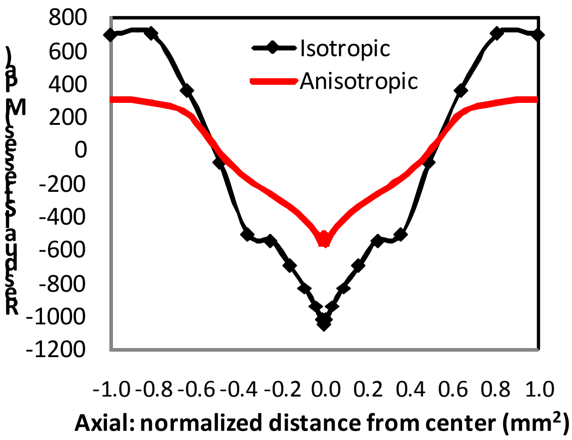

Figure 4. Comparison of profiles of residual stresses for axial direction between isotropic and anisotropic model.

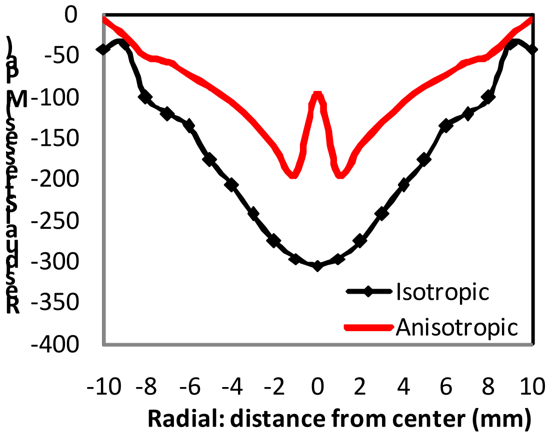

Figure 5. Comparison of profiles of residual stresses for radial direction between isotropic and anisotropic model.

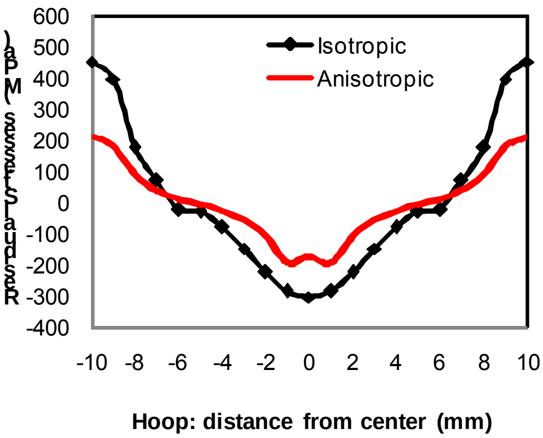

Figure 6. Comparison of profiles of residual stresses for hoop direction between isotropic and anisotropic model.

The Figure 4 shows the comparison of profiles of residual stresses for axial direction. Figure 5 shows the profiles of residual stresses for radial direction and Figure 6 shows the profiles of residual stresses for the hoop direction between isotropic and anisotropic simulation. Figures 4 shows the profiles of residual stresses for the axial direction as function of the cross-sectional area, where the points -1 and 1 represent

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the surfaces of the bar and the point 0 represents the center of the bar. The Figures 5 and 6 show the results of residual stresses for the radial and hoop directions, where the points -10 and 10 represent the surface and the point 0 is the center of the bar.

The profile of residual stresses for the studied cases in the axial direction shows a tensile value at surface and compressive at the center of the bar. For the isotropic simulation (Figure 4) the profile of simulated residual stresses has a maximum value of 695 MPa at the surface, and a minimum at the center of the bar of -1,052 MPa. For the anisotropic simulation, the profile of simuated residual stresses has a maximum value of 314 MPa at the surface and a minimum at the center of the bar of -493 MPa.

Figures 5 and 6 represent radial and hoop directions, a compressive behavior is observed through all area of the bar for the radial direction, and the hoop direction has a similar behaviour as the axial direction.

For the isotropic simulation in the radial direction, it is clear from Figure 5 that the residual stresses have a minimum value at the center of the bar of -296 MPa and a minimum value at 1 mm distant from the center of -194 MPa for the anisotropic simulation. Also the radial component is approaching zero close to the surface, for the both simulations, as also it should be, since the the radial component will be a normal to the surface.

The profile of residual stresses in the hoop direction shows a tensile value at surface and compressive at the center of the bar. For the isotropic simulation (Figure 6) the profile of simulated residual stresses has a maximum value of 450 MPa at the surface and a minimum at the center of the bar of -285 MPa. For the anisotropic simulation, the profile of simuated residual stresses has a maximum value of 212 MPa at the surface and a minimum at 1 mm close to the center of the bar of -177 MPa.

The comparison of simulation with the isotropic and anisotropic simulations shows differences for the axial direction of 382 MPa to the surface and 559 MPa for center of the bar (Figure 4). It means a difference of 55% to the surface and 53% to the center. The comparison for the radial direction (Figure 5) shows a difference of 37 MPa for the surface, and 208 MPa for the center of the bar. For the hoop direction (Figure 6), the found differences are 129 MPa for the center of the bar, and 238 MPa for the surface.

The found differences are in according to the literature,[11,16] when considering an isotropic material, there will be an overestimation of residual stresses at the center of the bar to the axial direction, to radial and tangential directions the same amount is underestimated.

The values of axial and hoop residual stresses after wire drawing should be close to each other close to the surface, which agrees with the simulated results.[11,16,17] The values of radial and hoop residual stresses are identical in the center of the bar for the isotropic simulation, because in that position these two stress components have the same direction.

5 CONCLUSIONS AND FUTURE IDEAS

Computer simulations were carried out to show the effect of the anisotropic properties presents in the AISI 1045 rolled steel in the residual stresses generated in the wire drawing process and compare this results with an isotropic material taken from the database of commercial software of numerical simulation.

A ring test simulation was carried out and compared with an experimental ring test to make a calibration curve. The found result of Coulomb friction coefficient was 0.1.
A compression test were carried out to take the initial yield stresses in two directions of the bar and the Hill´s criterion were used to take into account the anisotropy of the material. The value of the stress in the 0º direction is 10% higher then in the 90º direction.
The comparison between the force of the isotropic simulation presents differences of 59.82%, when compared with the Avitzur force and 57.03% for Sachs force. The maximum difference between the force of anisotropic simulation is 6.58% for Avitzur equation and 2.01% for the Sachs equation.
The comparison between isotropic and anisotropic simulations shows the maximum difference for the axial direction of 382 MPa in the surface and 559 MPa for center of the bar. It is more than expected in the beginning of this job, when the expected differences between isotropic and anisotropic simulations were 200 MPa.

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