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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

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ABSTRACT

The use of numerical simulation has increased in the last years aiming to avoid errors before experimental tests that would be expensive to correct with long “try out” stages. In this study, simulation software was used to show the effect of the anisotropic properties presents in the AISI 1045 rolled steel in the residual stresses generated in a drawing process by comparison with an isotropic model. The isotropic and anisotropic simulation models of the process were created to compare the final residual stresses results. The isotropic behavior of the material was taken from the database of commercial software of numerical simulation Simufact.FormingGP®. The anisotropic material properties were obtained by compression tests on samples, as well as different positions of the bars were taken before drawing and measured in order to obtain the yield stress in two different directions (0º and 90º). These yield stresses were used to calculate the indices of anisotropy to use the Hill criterion as an input data to the software. The performed simulations were validated by comparing simulated and calculated forces by empirical equations found at the literature. Besides that, the results of comparison between the residual stresses profiles obtained by simulation in two different descriptions of material, anisotropic and isotropic, found differences around 200 MPa in the center of the bars and this study will be used as a basis for further simulations of distortion of the bars.

Keywords: *Numerical Simulation, Plastic Anisotropy, Residual Stresses*

RESUMEN

El uso de la simulación numérica se ha incrementado en los últimos años con el objetivo de evitar errores antes de realizar las pruebas experimentales que podrían ser costosos para corregir con largas etapas "try out". En este estudio, un software de simulación se utilizó para mostrar el efecto de las propiedades anisotrópicas que presenta en el AISI 1045 acero laminado y las tensiones residuales generadas en un proceso de trefilación por comparación con un modelo isotrópico. Los modelos de simulación isotrópico y anisotrópicos del proceso fueron creados para comparar los resultados de las tensiones residuales finales. El comportamiento isotrópico del material fue tomado de la base de datos de software comercial de simulación numérica Simufact.FormingGP ®. Las propiedades del material anisotrópico se obtuvieron mediante ensayos de compresión sobre muestras, así como también fueron tomadas las diferentes posiciones de las barras antes de trefilar y medir, con el objetivó de obtener el límite elástico en dos direcciones diferentes (0º y 90º). Estos esfuerzos de fluencia se utilizaron para calcular los índices de anisotropía para utilizar el criterio de Hill como un dato de entrada para el software. Las simulaciones realizadas fueron validadas mediante la comparación simulada y calculada de fuerzas mediante ecuaciones empíricas encontradas en la literatura. Además de eso, en los resultados de la comparación entre los perfiles de tensiones residuales obtenidos por simulación en las dos descripciones diferentes de material, anisotrópico e isotrópico, se encontraron diferencias alrededor de 200 MPa en el centro de las barras; de este modo este estudio se podrá utilizar como base para posteriores simulaciones de distorsión de las barras.

Palabras Clave: *Simulación, Tensiones residuales, Trefilación*

1 INTRODUCTION

Drawn bars with different diameters are used in the manufacturing of automotive parts, reducing subsequent machining steps, costs and energy consumption and the use of these products has increased in last year's [1]. 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.

One of the potential of distortions during the drawing process is the residual stresses generated by previous stages of manufacturing, which appear in the material without external forces or temperature gradients. Likewise, in cold drawing process, generally, the non-homogeneous plastic deformation in the material leads to heterogeneous residual stresses profiles, 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 considered a phenomenon of rather rare occurrence. It is difficult to avoid in metal working and is invariably developed by any severe strain. Theories of plastic flow for isotropic metals are only valid to a first approximation [4]. Materials in metalworking operations, as the wire drawing process, undergo plastic deformation which in turn leads to anisotropy in the material [5]. 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 flowing.

This work simulates by finite elements method the residual stresses generated in the cold-drawing process in two situations: considering anisotropic and isotropic behavior of the material. These results will be important to understand the contribution of the residual stresses as a potential of distortion that appears in mechanical 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 performing the simulations, residual stresses profiles were taken and a comparison was made between them.

2 INPUT DATA OF THE SOFTWARE

2.1 Isotropy and Anisotropy Criteria

A numerical model was generated in the Simufact.forming GP® software to study the state of residual stresses generated by the drawing of anisotropic AISI 1045 hot rolled steel.

For describing the isotropic flow in materials was used von Mises criteria, in 1913, in the form of a quadratic function, Equation 1 [2].

$$\bar{\sigma}_M = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \quad (1)$$

Where: σ_1, σ_2 and σ_3 are the main stresses (MPa) and $\bar{\sigma}_M$ is the effective stress or equivalent stress (MPa). Hill proposed a criterion to 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 2:

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

Where: F, G, H, L, M and N are characteristic constants of the current state of anisotropy. F, G and H can be 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 yields stress in each direction with the initial yield stress.

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 samples were taken from a bar before drawing and they were machined to obtain the diameter of 10 mm and the height of 15 mm. Six cylinder samples were machined from an 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 experiments were carried out with an *Eka®* machine, controlled with a hydraulic press and the tests were carried out at room temperature and loading speed of 6 mm/s.

2.3 Ring test to estimate the friction coefficient

Friction is the resistance to the surfaces movement of two bodies in contact during the sliding of one over the other [8] and it is one of the more important variables in the drawing process. The friction influences material flow [9], changing the values of forces and wear of the tool. The knowledge of the friction coefficient value of the process is necessary as an input data to the simulation software. Because of that, 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 [10, 11, 12]. The value of the Coulomb friction coefficient used in the simulation was 0.1.

3 NUMERICAL SIMULATION OF THE DRAWING PROCESS

In order to characterize the material in the numerical model, the isotropic and anisotropic material (AISI 1045) were used and the parameters are shown in Table 1. The drawing speed of 1250 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	64000
Coulomb friction coefficient (μ)	0.1
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
Shear Modulus	80,769 GPa
Anisotropy indices normal direction (F, G, H)	0.634; 0.424; 0.424
Anisotropy indices normal direction (L, M, N)	0,5; 0,692; 0,692

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 [13]. The indices of anisotropy were obtained with the application of the equation shown at the 2.1 section. The shear and Young modulus were by literature [2]. 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 1.

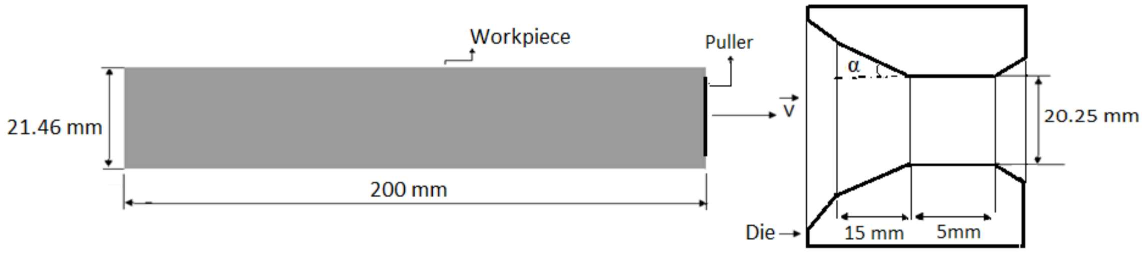

Figure 1. Tridimensional model created.

4 RESULTS AND DISCUSSION

The numerical validation, Figure 2 (a), was performed by comparison between the analysis of the theoric strain ($\varphi = \ln\frac{A_0}{A_1}$) and simulated strain [14].

Also in Figure 2 (a), it is possible to observe the results of strains obtained with the isotropic and anisotropic simulations in comparison with the analytical strain. The found differences to the theoretical equation are around 6.1% when the isotropic simulation is evaluated and 4.6% in evaluation of anisotropic simulation.

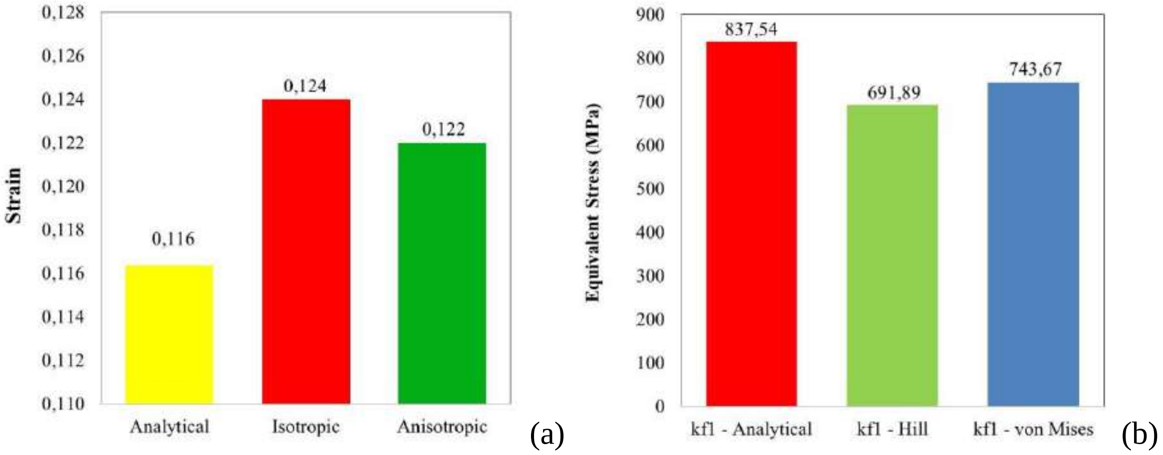

Figure 2. Numerical validations by comparison between (a) theoretical and simulated strains and (b) equivalent stresses.

After that, the simulations were verified by von Mises equivalent stress in the case of the isotropic simulation, and the equivalent stress proposed by Hill to the anisotropic case (Figure 2). The Hill equivalent stress obtained a value of 691.89 MPa and for the von Mises equivalent stress the value was 743.67 MPa. These equivalent stresses of the simulations (by Hill and von Mises) must be less than the end yield stress of the bar (kf1), which has a value of 837.54 MPa for a strain in the area of 0.116.

The found differences in the evaluation between the calculated and the simulated strains are considered minimal. The equivalent stresses considering the equations of von Mises and Hill, showed lower values than the end yield stress of the drawn material. Thus, these simulations can be considered valid for this model.

Figure 3 shows the simulated profiles of residual stresses for the 15º drawing angle. Where is shown the comparison between the isotropic and anisotropic simulations for axial (a), radial (b) and hoop (c) directions. The profile of axial residual stresses (Figure 3 (a)) shows a tensile value at surface and compressive at the center of the bar. For the isotropic simulation the profile of simulated residual stresses has a maximum value of 730 MPa at the surface, and a minimum at the center of the bar of -1034 MPa. For the anisotropic simulation, the profile of simulated residual stresses has a maximum value of 815 MPa at the surface and a minimum at the center of the bar of -877 MPa.

Figures 3 (b) and (c) represents 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, only with lower values. For the isotropic simulation in the radial direction, it is clear from Figure 3 (b) that the residual stresses have a minimum value at the center of the bar of -312 MPa and, for the anisotropic simulation a minimum value at the center of -296 MPa. At the surface of the bar, the radial component is approximately zero in all simulations.

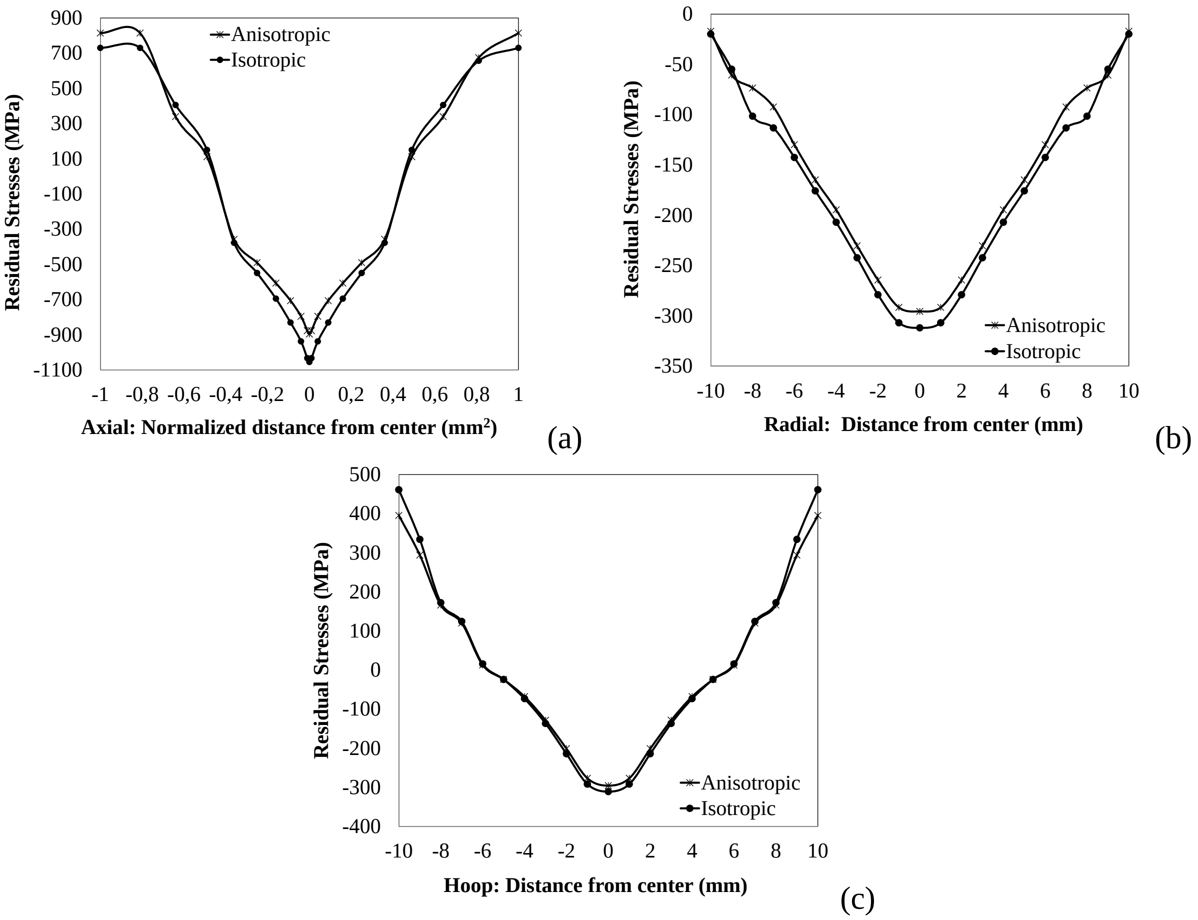

Figure 3. Comparison of profiles of residual stresses for (a) axial direction, (b) radial direction and (c) hoop direction between isotropic and anisotropic model.

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 3(c)) the profile of simulated residual stresses has a maximum value of 461 MPa at the surface and a minimum at the center of the bar of -311 MPa. For the anisotropic simulation, the profile of simulated residual stresses has a maximum value of 395 MPa at the surface and a minimum at 1 mm close to the center of the bar of -296 MPa.

The comparison between the simulations shows differences for the axial direction of 85 MPa (10%) in the surface and 158 MPa (17%) for center of the bar (Figure 3 (a)). For the radial direction (Figure 3 (b)) the differences are around 50 MPa in the center of the bar between both simulations and on the surface, the residual stresses must be zero and in the center, these tensions must be equal to the hoop direction [11, 13, 14]. For the hoop direction (Figure 3 (c)), the observed differences between the isotropic and anisotropic simulations are 15 MPa for the center of the bar, and 66 MPa for the surface.

5 CONCLUSIONS AND OUTLOOK

In this study, simulations were performed in order to analyze the effect of anisotropic properties presents in the AISI 1045 rolled steel on the residual stresses generated in a wire drawing process by comparison with an isotropic model.

According to the measurements done through compression tests in two directions of the bar following Hill's criteria, the stress value in the 0º direction is 10% higher than in the 90º direction.

The values of axial and hoop residual stresses after wire drawing should be close to each other when near to the surface, which agrees with the simulated results [9, 14, 15]. 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.

The observed differences between simulations are in according to the literature[9, 14], 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 comparison between isotropic and anisotropic simulations shows the maximum difference for the axial direction of 85 MPa in the surface and 158 MPa for center of the bar. It is less than expected in the beginning of this job, when the expected differences between isotropic and anisotropic simulations were 200 MPa. The isotropic model of the behavior of the material overestimates the residual stresses in the center but presents less residual stresses in the surface than the anisotropic simulation this study will be used as a basis for further simulations of distortion of the bars.

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