Original Article

Evaluation of experimentally observed asymmetric distributions of hardness, strain and residual stress in cold drawn bars by FEM-simulation

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ABSTRACT

The purpose of this paper is to investigate the correlation of strain and hardness parameters in a drawing process chain of an SAE 1045 steel bar. The present work discusses the application of the experimental and numerical method of analysis, based on hardness measurements, which allows evaluation of the strain distribution and mechanical properties in drawn products. The influence on the strain, hardness and residual stress distributions of cold drawing parameter variations were investigated by numerical simulation. A misalignment between bar and drawing tool was evaluated in the models, as well as variation of friction at different regions of the bar. Compression tests were carried out at different reductions to determine the flow curve and analyze the material behavior during a cold hardening process. The microstructural analysis has shown a potential influence of material segregation in the characteristics of the final products. Simulation results validate the assumption of die misalignment and inhomogeneous lubrication influences on residual stresses profiles after wire drawing. Taking into account effects of misalignment and friction at the same time, in a so-called combination model, a better agreement between numerical simulation and experimental results for cold drawing process was achieved.

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1. Introduction

In cold drawing process the generated plastic strains increase materials strength and improve surface quality, therefore this process is widely used in the manufacturing of components as shafts, wires and tubes with optimized mechanical properties. In metal forming, it is well known that good results can only be achieved with a deep knowledge about materials properties. Consequently, several factors must be considered, such as geometry and initial material properties, lubrication conditions, drawing angle and the interaction of all these factors [1].

Wire drawing process can be performed as shown in Fig. 1(a). First, the wire-rod is uncoiled and pre-straightened using two sets of rolls. After that, a shot blasting process is
applied in order to remove the contaminants from bar surface preparing it to pass through the drawing die. Then the bar is drawn (tool detailed in Fig. 1(b)), cut in 6 m length and finally polished. In addition, the automotive parts face heat treatment by induction hardening as a final step.

Materials metallurgical and mechanical history are influenced by each step or process of the chain. Thus, previous operations can generate a number of residual stresses in the final product [3]. These produced residual stresses may lead to undesired distortion in the next process: heat treatment.

Material properties and process parameters influences need to be investigated in order to identify possible sources of residual stress during the manufacturing chain. Dias et al. [4] has analyzed the cut process influences on final residual stress profile as well as the simulation of the wire-drawing process considering some uncontrollable variables such as segregation and the bar misalignment before the drawing step. Rocha [5] has investigated the redistribution of residual stresses resulting from the wire drawing process chain. Dias et al. [6] performed simulations of the residual stresses considering the anisotropy of the raw material. Hence, those previous works have shown advances in the study of the wire drawing process chain. Complementary to that, the strain and hardness analysis are important parameters that can be compared to a computational numerical approach.

On the other hand, investigations of different die working part profiles contribute to the technological improvement of the drawing process [7]. The strain field determines the properties distribution in the deformed material, as hardness distribution, mechanical strength and wear resistance. The finished products quality depends strongly on those properties. Likewise, hardness profiles are related to the forgeability of the material undergoing a cold forming process [8].

The wire drawing process is characterized by a great amount of inhomogeneous plastic deformation [9]. Therefore, researchers are often focused on finding a relation between these standard hardness criteria and effective strain. It is well known that high values of tensile internal stresses can be the cause of failures in the production of steel wires as internal bursts or chevron cracks, which are internal fractures, caused by high hydrostatic tension. These severe stresses that build up internally cause transverse subsurface cracks. Some of the factors that can contribute to the chevrons formation are incorrect die angles; either too great or too small in combination with an excessive reduction of cross-sectional area; excessive work hardenability of the material; inclusions or imperfections; segregation; and insufficient die lubrication [10–13].

A forecast of drawn wire mechanical properties can be obtained through the Finite Element Method (FEM). The main advantage of this method is the capability to obtain detailed knowledge about deformation mechanisms such as velocity, geometry, strains, stresses, and temperatures. A careful analysis also is not possible without a detailed setup of boundary conditions [14]. Kim et al. [15] have found a relation between Vickers hardness and effective strain by correlating the measured hardness and the numerically found strains.

Thus, this paper aims to correlate strain and hardness parameters of the combined drawing process of SAE 1045 steel bar. The present work discusses the application of the experimental and numerical method of analysis, based on hardness measurements, which allows evaluation of the distribution of strain and mechanical properties in drawn products. Therewith, numerical simulations were used to investigate process parameters evaluating the influences of die misalignment and friction differences between bar regions on residual stress profiles.

### 2. Material and methods

#### 2.1. Material

The material used to perform the simulations and experimental analysis was SAE 1045 steel in hot-rolled condition. This material is classified as medium carbon steel with good mechanical properties and toughness and its applications include shafts, gears, crankshaft and common structural components and machines [16].

The standard chemical composition was compared with the chemical results of experiments carried out by Dias [2], which are presented in Table 1.

The flow curve was taken by compression tests of steel samples from the raw material at room temperature and in the rolling direction (Fig. 2(a)). In addition, microstructure along the transverse direction was evaluated before drawing process to identify the raw material behavior as received – after hot rolling, without subsequent mechanical processes. The images were obtained by following standard metallographic preparation procedures, samples were etched with Nital (3%}

![Fig. 1 – Schematic of (a) cold drawing process chain and (b) of the drawing die (adapted from [2]).](image-url)
vol. HNO₃ in methanol). Fig. 2(a) shows the average flow curve obtained from the evaluated material and Fig. 2(b) presents the microstructure where the white phase is Ferrite and the dark phase is Perlite.

### 2.2. Experimental

The experimental methodology is represented in Fig. 3, where a schematic procedure of experiments is demonstrated in (a) and the distribution of hardness measurements positions are shown in (b) and (c).

#### 2.2.1. Compression tests

Compression tests with different reductions were carried out in order to correlate the material hardness and strain profile. Cylindrical samples were taken (15 x Ø10 mm each), and subjected to a series of upsetting (compression) experiments.

The reductions were determined considering the drawing process parameter, which is 11% deformation ($\varphi = \ln A/A_0$). Based on that, the first chosen reduction was 10% and additionally 20, 30, 50 and 60% in order to construct a hardness x strain profile. The reductions were set in the compression machine by the final height of each sample and for each compression test were used four samples to minimize the error. The real reduction obtained after compression test were determined relating the initial with the final height.

The experiments followed the ASTM E9-89a Standard test methods of compression testing of metallic materials at room temperature. The equipment used was a universal testing machine, EMIC®, with a maximum capacity of 600 kN, using graphite based lubricant and a press velocity of 5 mm/s.

Then, effective strains of the compressed samples for each reduction were calculated. Additionally, after the compression test, the surfaces of compressed samples were prepared with sanding and polishing to perform the Vickers hardness with low force according to the ASTM E92-16 Standard test methods for Vickers and Knoop hardness of metallic materials. Finally, all the samples were cut and the cross section was then prepared in order to measure the core hardness.

Microhardness measurements provide a convenient, non-destructive means to evaluate the strength of materials, as well as to characterize plastic deformation effects. Likewise, it is a general microprobe technique to assess the bond strength, apart from being a measure of bulk strength [17,18]. Thus, the
hardness behavior was analyzed measuring 18 points on the sample surface (Fig. 3(c)) for each reduction, as well as on a standard sample – raw material as received. The samples were cut and hardness measurements on 14 points were carried out at different positions on the cross section (Fig. 3(b)).

2.2.2. Analytical model
The schematic presented in Fig. 3(a) describes the followed procedure to verify the analytical models. Parametrical variations of a drawing process were analyzed by Finite Element Method (FEM) to obtain effective strain and residual stresses distributions with subsequent experimental verification of the obtained values.

Firstly, a flow curve of the selected material was determined through upsetting (compression) experiments. Effective strain at the central line of the drawn bars away from the edges was already known analytically. Besides, FEM analysis of the drawn process was carried out to find the effective strain distribution. Thus, it was possible to verify the region where analytically calculated strains were valid. Then, the hardness corresponding to the effective strain was predicted through analytical models. After that, the results were compared with the measured hardness of a drawn bar.

The analytical models were also verified by checking how well they predict the FEM and experimental results obtained by compression tests. Therefore, microhardness measurements along the cross section of the bar were performed as shown in Fig. 3(b). The hardness was measured, according to the ASTM E92-19 mentioned in Section 2.2.1, at points that were regularly distributed between the surface and the center.

Vickers hardness (HV) test uses a pyramidal indentor and can be defined as the load divided by the surface area of the permanent impression. The angle between the opposite faces of the pyramid is 136° such that the base of the pyramid has an area equal to 0.9272 times its lateral area [19,20]. Thus, Vickers hardness is given by Eq. (1) where \( P_m \) is the mean pressure (force divided by the projected area). Once the diagonal of the indentation is measured or predicted through a model, Vickers hardness can be calculated. It is important to assume that the deformation behavior of the material fits a simple power law such that if the material is under uniaxial loading, then true stress–true strain curve can be described by Eq. (2), where \( k \) and \( n \) are material constants. The author [20] assumed that there is again a representative flow stress (\( \sigma_c \)) which is linearly related to mean pressure (Eq. (3)). Based on the hardness measurements obtained from a material that had been compressed by various amounts, Tabor concluded that the initial uniaxial strain (\( \varepsilon_0 \)) is additive to the representative strain (\( \varepsilon_c = 0.08 \)) using a constant \( c \) of 2.9, then HV may be expressed by Eq. (4).

\[
HV = 0.9272(P_m) \quad (1)
\]

\[
\sigma = k \cdot \varepsilon^n \quad (2)
\]

\[
P_m = c \cdot (\sigma_c) \quad (3)
\]

\[
HV = c(k \varepsilon_0 + \varepsilon_c)^n \quad (4)
\]

2.2.3. Residual stress measurements
Residual stresses were evaluated by neutron diffraction in order to compare with the simulation. The neutron diffraction residual stress measurements were performed at the Helmholtz Center Berlin, in Berlin, Germany on beam line E3 of the BER II reactor. The primary beam path was composed by a segmented elastically bent Silicon monochromator with a mask of 2 by 2 mm close to the surface of the sample. The diffracted beam with an aperture of accordingly 2 mm in width and no height limitations was recorded with a 3He Position Sensitive Detector of 300 × 300 mm size, using 256 × 256 channels. A diffractometer with automatic XYZ-translation table was used. The standard deviation of measurements was typically around ±25 MPa. More details about the experiment can be found in Souza et al. [21].

2.3. Simulation models
Simulation models using the Deform™-3D software were created with the die dimensions, bar and mesh as can be seen in Fig. 4. Based on the real drawing process chain investigated, the standard model was constructed using the simulation parameters described in Table 2. This numerical analysis was carried out to reproduce an ideal drawing process for further comparison with the simulation cases of misalignment between bar and tool, and friction differences.
Table 2 – Simulation model input parameters for the standard case.

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial diameter (D₀)</td>
<td>21.46 mm</td>
</tr>
<tr>
<td>Final diameter (D₁)</td>
<td>20.25 mm</td>
</tr>
<tr>
<td>Reduction</td>
<td>11%</td>
</tr>
<tr>
<td>Die angle (α)</td>
<td>20°</td>
</tr>
<tr>
<td>Coulomb friction (μ)</td>
<td>0.1</td>
</tr>
<tr>
<td>Drawing process velocity</td>
<td>1250 mm/s</td>
</tr>
<tr>
<td>Yield function type</td>
<td>Von Mises</td>
</tr>
<tr>
<td>Hardening rule</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Model type</td>
<td>Lagrangian Incremental</td>
</tr>
<tr>
<td>Solver</td>
<td>Sparse</td>
</tr>
<tr>
<td>Iteration method</td>
<td>Newton-Raphson</td>
</tr>
<tr>
<td>Flow curve equation of the drawn material</td>
<td>(1292.8 \times \phi^{0.2018})</td>
</tr>
<tr>
<td>Die misalignment</td>
<td>(\beta = 0) (zero)</td>
</tr>
</tbody>
</table>

The Coulomb friction coefficient (\(\mu\)) used in the simulation of drawing was 0.1. This value was obtained by ring compression tests and a comparison with calibration curves obtained by simulation. The details of this comparison can be seen in Rocha et al. [22]. The simulation results were compared with the experimental measured residual stress distributions determined by neutron diffraction.

The studied case, shown in Fig. 5(a), represents a misalignment of the drawing tool and it was constructed considering \(\beta = 1°\) between raw material and die. The second case was the influence of different friction coefficients between the bar sides, as shown in Fig. 5(b). To obtain a valid model, the analysis has to take the inputs and outputs measurements of the real system, and the attributes of intermediate variables [13]. The results were acquired from a stable region of the drawn bar and different position as shown in Fig. 5(c).

The hexahedral mesh used [14,23] had a radial number of 8 elements and the geometry of the bar was built starting from a 2D model, which was rotated in turns of Z axis using 26 repetitions with a total number of 18,750 elements. A three-dimensional (3D) Lagrangian formulation was used in the simulation with an elastic-plastic and isotropic behavior of the material. This procedure proved to give an excellent convergence of the model without remeshing.

The strain is a measurement of the degree of deformation in an object. Through various mathematical techniques, which are beyond the scope of this discussion, it is possible to define the so-called “principal axes” on which all components of shear strain are zero. The strains measured along these axes are termed principal strains. It is frequently useful to have a single characteristic strain value to describe the degree of deformation. DEFORM™ software uses a value common to metal forming analysis known as the effective or Von Mises strain. For elastoplastic materials, the strain values stored are only the inelastic parts of the total strain [23].

3. Results and discussion

Samples were compressed with different reductions to determine the flow curve and analyze the material behavior during a cold hardening process. Hardness variation was evaluated on the sample surface and cross section of each reduction, as well as on a standard sample – raw material as received. The average results are presented in Fig. 6(a) where, as expected, an increase in hardness can be verified. Considering that, the standard deviation between measured points was around 11HV0.5, the differences between surface and cross section hardness measurements were less than 5%.

In order to ensure reliable use of the part, it is necessary to characterize and determine the material strength. A practical way of characterizing strength is to perform centerline hardness measurements of each cylinder in order to avoid problems of inhomogeneity. Therefore, the effective strain values of the samples with different reductions were calculated and compared with hardness measurements as shown in Fig. 6(b).

Combining the material flow curve (Fig. 2) with the hardness relation proposed by Tabor [19,20], it was possible to assume that the analyzed SAE 1045 raw material follows the hardness behavior as shown in Eq. (5) when submitted to a simple upsetting test.

\[
HV = 302.9(t_0 + 0.08)^{0.1079}
\] (5)

Fig. 6(b) shows an important deviation between measured points when looking for each reduction. For example, in the case of 20% reduction, the measurements presented a maximum value of 292.5HV0.5 and a minimum value of 252.5HV0.5, that represents around 9% differences, already considering the deviation.

The experiments were carried out with samples from the raw material without previous forming process, the compression parameters and lubrication were constant for all reductions, and the measurements were an average of each sample to minimize the error. Taken into account that, and observing the microstructure shown in Fig. 7, it is possible to connect the hardness differences with the carbon segregation in the material, as well as to an anisotropic material behavior [6].

According to Sonmez and Demir [8], in a cold forging process, plastic strains are induced, and consequently hardness of the workpiece increases due to strain hardening. The authors further affirm that any inhomogeneity may cause different readings especially for Vickers hardness, which has a smaller impression. Besides, the specimens were cut to take the hardness in the cross section, which leads to additional plastic deformations and consequently increases in hardness values.

Fig. 8(a) presents the hardness profile obtained from a drawn bar using 20° die angle and 11% reduction. Hardening effect can be seen on both sides of the measured drawn sample with values between 243 and 293HV1. This result shows an inhomogeneous hardness distribution which is related to the manufacturing steps influences and to drawing process parameters. Fig. 8(b) shows the strain–hardness correlation calculated by Eq. (5), where an effective strain maximum of 0.65 can be observed at the left (0°) side of the measured bar.

The process parameters were investigated by numerical simulations to evaluate the influences of die misalignment and bar friction differences between sides on residual stress profiles. In order to test the suitability of the models, a
comparison between the measured hardness of materials with known flow properties and the hardness predicted by these analytical models was performed.

Firstly, the simulation of standard or reference model with homogeneous friction distribution and straight wire-rod is shown in Fig. 9. As expected, the residual stress profile presents tensile values (670 MPa) at bar surface and compressive behavior in the center bar (−861 MPa). Puller effects were avoided by taking results from a zone where a stationary state has been reached [24]. Thus, displayed results were taken from 40 mm of the bar ends for all simulations, in addition, the residual stress distributions were taken from a cross section in the middle of the bar (B–B).

The residual stress profile from simulation shown in Fig. 10(a) for the standard model can be compared with the residual stresses profile measured by neutron diffraction performed by Rocha et al. [5]. These authors have performed measurements of residual stresses in samples of the same material and with the same parameters used in this paper as material and drawing tool.
According to those authors, the highest effect on the distortion of drawn bars after induction hardening resulted from the drawing process itself together with small deviations during this process. Real drawing conditions and their experimental verification clearly showed a deviation from ideal drawing, what can be explained by the inhomogeneity of the drawing process. Even though, a typical residual stress distribution occurred after the simulation with ideal process parameters.

The simulation of drawn bar presented compressive residual stresses in the core near the center, achieving a minimum around −800 MPa and a maximum tensile residual stress at the surface of 503 MPa. The profile also features an almost homogeneous distribution and can be used for comparison with the other studied cases: misaligned die, friction differences and the combination of misaligned die and friction differences. Fig. 10(b) shows the effective strain in the abscissas axis the left (negative distance x) and right (positive distance x) sides. The effective strain profile, shown in Fig. 10(b), presents a homogeneous distribution in the bar center (0.1203) and around 6.5% difference between the right and left side for the simulation of standard or reference model. Besides that, the vertical measured point’s orientation shows 0.0166 difference in the effective strain value at right side and 0.01496 at the left.

The differences between simulations and experimental measurement are considerable. Nunes [25] and Dias et al. [6] showed that residual stresses are around 400 MPa on the surface and −500 MPa in the bar center. The neutron measured values are also affected by errors coming from the \( d_0 \) (lattice spacing's without stresses) determination, and interactions between the different phases in the material, as the measured values with neutrons correspond to residual stresses in α-iron phase.

The FEM simulation did not consider material microstructure. Besides that, anisotropic materials behavior, Bauschinger effect, and consequent changes in the kinematic hardening materials behavior were not considered. According to Dias...
et al. [6], results using an isotropic model of the material overestimates 10% the residual stresses in the center but presents 17% less residual stresses in the surface than the anisotropic simulation model results.

Additionally, as presented by Diehl et al. [26], the residual stresses remained from previous process steps as from pre-straightening can also contribute to the observed differences between experimental and simulation results. The authors further stated that the strains generated in the horizontal pre-straightening step are larger than those generated in the vertical step due to the original curvature of the coil, which is curved in the horizontal direction. This leads to higher residual stresses in the contact lines with the rolls. Such influence remains after the vertical step.

According to Nakagiri and Inakazu [27], for the drawing process, the wire rod must be straightened, because an increase of the curvature increases the drawing force. Then, damage or even fracture into the die, as well as reduction of the fatigue life of the final products may occur. Influences of the misaligned die and inhomogeneous friction (μ = 0.1 and μ = 0.15) were evaluated and compared with standard model as well as experimental results.

Fig. 11(a) shows the effective strain from the simulation and respective calculated hardness profile for the misaligned die case. An increase in deviation from bar surfaces can be seen, around 24% and an effective strain similar to the standard model in the center (0.1291). Furthermore, a curvature behavior change is observed, that means the effective strain presents differences according to the measured orientation. Considering the vertical measurements, it is possible to observe the values of the left side picture are 19% higher than those of the right side. On the other hand, for the 45° measurements, the values decrease 11.5%, and for the 135°, the values are 14.4% lower. These effective strain variations between left and right sides of the graphic lead to a non-homogeneity distribution of hardness values, as well as, residual stress along the drawn bar. Thus, the applied β angle has a considerable influence on the bar behavior after the drawing process.

Besides the die misalignment, the lubrication is an important factor in all manufacturing processes; its application can help to control the forces and metal flow in the drawing case. Lubrication will also extend the life of the die, reduce temperature and improve surface finish. Friction acts in the interface between the wire and the die and disrupts the relative motion of the wire. The difference in the drawing force depends on the magnitude of the friction [28].

Due to this friction, the material experiences inhomogeneous deformation, the actual stress is larger than provided and clearly indicate that friction has significant effects on the drawing force which decrease with area reduction.

Therefore, the results of the analyzed friction case can be seen in Fig. 11(b), where the effective strain in the center, sides (horizontal 0.1172; others 0.14068) and curvature present considerable differences between each measured orientation. As well as the respective hardness profile indicates an increase of the values. When calculating, around 36.4% difference between the left (−12 mm) and the right (12 mm) sides can be observed. Besides, a large deviation from each curve was noticed, where 135° shows the higher (0.5413) value from the right side and vertical (0.5461) for the left side.

The analyzed models showed a significant inhomogeneity in the values of effective strain and hardness. Those differences can lead to high residual stresses and characterize as a potential of distortion in the final drawn product.

In order to verify the influences of friction and die misalignment in the residual stresses, the results of performed simulations were compared with the experimental measurements. In addition, as presented in Fig. 12, it was verified the need to combine a die misalignment with friction differences in order to achieve an agreement of simulation and measured residual stress. It is possible to observe that the simulation results in the surface region of the bar (12 mm or right side and −12 mm or left side) were compared with the experimental measurement and presented similar values.

As shown in Fig. 12(a), the effective strain presented high differences between the sides and measured orientations, in which can be seen 35% difference from vertical left and horizontal right sides. In addition, the center presented lower value of effective strain for the horizontal measured orientation (0.1095) compared to the others (around 0.1314).

Considering the simulation results, as shown in Fig. 12(b), the assumption of mixed influence of die misalignment and inhomogeneous lubrication affecting residual stress distribution in the drawn bars was validated by numerical simulation.

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**Fig. 11** – Effective strain from the simulation and hardness profile of (a) misaligned die and (b) friction differences according to the models shown in Fig. 5.
The combination model results in a similar residual stress profile as that measured from a drawn bar by neutron diffraction. Experimental hardness profile of a cross section drawn bar (Fig. 8) and its effective strain correlation showed 50 HV1 difference between left (0°) and right (180°) measured sides. That effect can also be seen in the simulation models of friction inhomogeneities and process variation as a misaligned die, as presented in Figs. 11 and 12.

4. Conclusions

In this paper, metallurgical and mechanical properties of a combined wire drawing process for the production of SAE 1045 steel bars were analyzed. The presented work discussed the application of the experimental and numerical methods of analysis, based on hardness measurements, which allows evaluation of the distribution of strain and mechanical properties in drawn products. Besides that, influences of misalignment of die and friction heterogeneities were taken into account in FEM simulations in order to identify influences in strain, hardness and residual stress distributions after drawing.

The applied methodology to obtain the correlations curves between measured hardness data in upsetting and strains simulation results in the same process showed excellent validity. By using available equations from the literature, also a possibility of hardness prediction from effective plastic strain was explored, once the flow stress is determined.

Both methods were applied to calculate hardness distribution from strain simulation values in cold drawing. The calculated hardness values showed then good correlation with experimentally measured microhardness values from cold drawn bars. Therefore, the opposite direction can be explored, i.e., measurement of hardness distributions from cold drawn material to calculate strain distributions and then correlating with numerical simulation results.

A model including die-bar misalignment and friction variations was carried out to explain observed non-symmetric strain and residual stress distributions. The comparison of experimental and simulation results proved the validity of the assumption that both effects (misalignment and friction differences) were the main responsible for the asymmetric distributions.

Conflicts of interest

The authors declare no conflicts of interest.

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