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The effect of cyclic straining on the drawing stress of low carbon steel bars

E.C.S. Corrêa [a], L.D.R. Melo Filho [b], M.T.P. Aguilar [c], W.A. Monteiro [d], P.R. Cetlin [a,*]

[a] *Department of Metallurgical and Materials Engineering, Federal University of Minas Gerais, Rua Espírito Santo 35, Centro, 30160-030, Belo Horizonte, Minas Gerais, Brazil*
[b] *Department of Production Engineering, Federal University of Minas Gerais, Rua Espírito Santo 35, Centro, 30160-030, Belo Horizonte, Minas Gerais, Brazil*
[c] *Department of Materials Engineering and Civil Construction, Federal University of Minas Gerais, Rua Espírito Santo 35, Centro, 30160-030, Belo Horizonte, Minas Gerais, Brazil*
[d] *Center of Materials Science and Technology, Nuclear and Energetic Research Institute, Rua 400, Cidade Universitária Armando Salles, 0508-900 São Paulo, Brazil*

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Abstract

The investigations covering the work hardening behavior of metals under strain path changes have pointed out the possibility of employing the strain softening phenomenon in sequential forming operations, specially in the case of cyclic straining. In this paper, the effects of cyclic torsion on the drawing stress of low carbon steel bars have been investigated. The material was drawn up to five passes. Cyclic straining was carried out between the last two stages of drawing and between every drawing pass. The substructural aspects of the bars were also analyzed. Cyclic torsion led to a decrease in the drawing stress values, whose magnitude depended on the number of forming passes considered in the experiment. The results also showed the occurrence of non-cumulative strain softening effects. Dislocation restructuring was found to be the softening mechanism related to the results.

Keywords: Cold working; Microstructure; Strain softening

1. Introduction

The analysis of strain path change effects on the work hardening of metals has been the subject of several investigations, covering the evaluation of the mechanical behavior [1–8], microstructural evolution [9–16] and mathematical modeling [17–20].

The reported results, involving sequential deformation steps and/or cyclic straining experiments, have revealed the inadequacy of using simple monotonic tests to study the plastic behavior of metals under real forming conditions, in which the product may undergo complex deformation paths. On the other hand, the results have also brought out the possibility of employing variable straining/loading paths during mechanical processing, in order to improve multiple-stage forming operations.

In the case of cyclic straining, the development of saturation flow stresses at relatively low deformation levels [7,8,12,14–16] and the occurrence of strain softening of pre-strained samples [6–8] represent the main significant features attained in the investigations. Most of these studies, however, have been performed employing standard mechanical tests, such as multidirectional compression [7], cyclic torsion [8] and cyclic tension/compression [6,12]. Regarding forming processes, it seems that little or almost no work has been done, excepting a specially designed extrusion operation, the so-called CEC method [14–16], and the KOBO system [21], which comprises several conventional operations combined with cyclically reversible straining. The first one is based on an extrusion/compression technique, which

* Corresponding author. Tel.: +55 3132381849; fax: +55 3132381815.
E-mail address: pcetlin@demet.ufmg.br (P.R. Cetlin).

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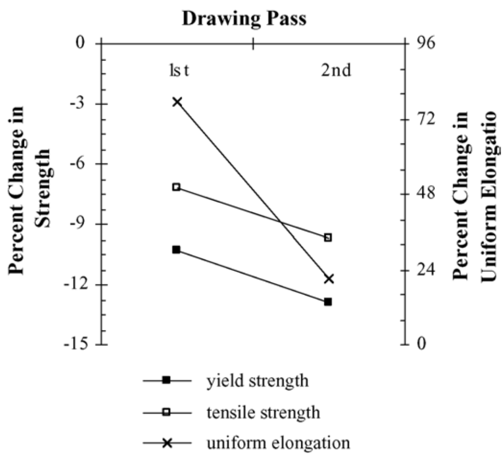

Fig. 1. Effect of cyclic torsion on the mechanical properties of low carbon steel bars [23].

allows the achievement of saturation state and severe plastic deformation. The KOBO method, successfully applied to forging and to extrusion, refers to any process where changes in the deformation mechanism from a homogeneous fine slip to heterogeneous shear banding are caused by the cyclic rotation of working tools in contact with the material.

Previous investigations have shown the effects of cyclic torsion on the mechanical properties of low carbon steel and 6063 aluminum alloy pre-drawn bars [22,23]. For both materials, a softening process was verified, indicated by a decrease in the yield and the tensile strength and by an increase in the uniform elongation. Fig. 1 displays some data obtained for steel samples. In this case, drawing was performed in one and two passes and torsion was conducted in a total of 10 cycles, with shear strain amplitude equal to 2.8%. The values exhibited in the graph represent the percent change in relation to the tensile properties of non-twisted samples.

The aim of the present research is the evaluation of the effects of cyclic torsion straining on the drawing stress of low carbon steel bars in multiple-pass drawing operations, reflecting experimental conditions closer to those found under industrial situations. The investigation covered up to five drawing passes as well as the corresponding substructural aspects.

2. Material and methods

The material used in this study was a low carbon steel, whose chemical composition is shown in Table 1. The specimens, bars with 6.40 mm of diameter and 390 mm of length, were annealed in vacuum at 850 °C for 2400 s. The final homogeneity of the samples was verified through hardness tests and metallography.

Table 1
Chemical composition of the material (wt.%)

C	0.12
Mn	0.47
Si	0.08
P	0.016
S	0.013

The main experimental procedure consisted in three groups of tests: (I) drawing up to five passes; (II) drawing up to five passes, carrying out cyclic torsion only between the last two passes considered in the analysis; (III) drawing up to five passes, performing cyclic torsion in between every pass. Two or three specimens were used for each situation.

Drawing was conducted in an Instron model 4482 machine, with an accessory specially designed for the process, at a crosshead speed of 6.67×10^{-1} mm s^{-1}. The parameters employed in all experiments were selected according to previous investigations [22,23]: die semiangle = 8° and reduction in area per pass = 20%. Lubrication was performed with a molybdenum disulfide paste.

Torsion was carried out in an adapted bench lathe, whose details where given elsewhere [22]. Ten cycles of deformation were considered in each stage of experiment, with a plastic shear strain amplitude of 2.8%, achieved through the use of the following torsion angles, calculated using Eq. (1): 115° (cyclic straining between the 1st and the 2nd passes of drawing), 128° (between 2nd and the 3rd passes), 144° (between the 3rd and 4th passes) and 160° (between the 4th and 5th passes). Similarly to the drawing operation, cyclic torsion parameters were chosen based on previous results obtained in aluminum and low carbon steel experiments [22,23]

$$\gamma = r\theta/L \tag{1}$$

where γ is the torsion straining, r the radius and L the useful length of the bar.

Transmission electron microscopy TEM was completed in specimens drawn in one and two passes, before and after cyclic torsion. A JEOL JEM 200C microscope was used in the analysis, at an operating voltage of 200 kV. The samples were taken close to the surface of the bars, parallel to the axis of drawing.

3. Results and discussion

The effect of cyclic torsion on the drawing stress of the bars strained up to five passes is shown in Fig. 2. In this case, cyclic deformation was only applied between the last two stages of forming. In general, the cyclic torsion led to a decrease in the drawing stress, whose magnitude seems to depend on the number of deformation passes previously conducted on the material. In addition to some irregularities observed in the curves, certainly related to lubrication problems, an abrupt increase in the stress level of the drawn/twisted sample at the end of the experiments is verified. This phenomenon confirms the occurrence of work softening as a result of cyclic deformation. During torsion, the end section of the bar served as a gripping region, remaining unaffected by the cyclic straining test. Therefore, on the subsequent drawing operation, the stress values associated with this area were analogous to those observed for the non-twisted metal.

Fig. 3 presents the results related to the use of cyclic straining in between every drawing pass. As expected, similarly to the curves shown in Fig. 2, reduced drawing stresses are exhibited. In this case, however, enhanced values at the end of the drawn/twisted sample tests are less pronounced or even non-existent. This is connected to changes in the length of the bars during the experiment. Considering Eq. (1), which expresses the relationship between sample dimen-

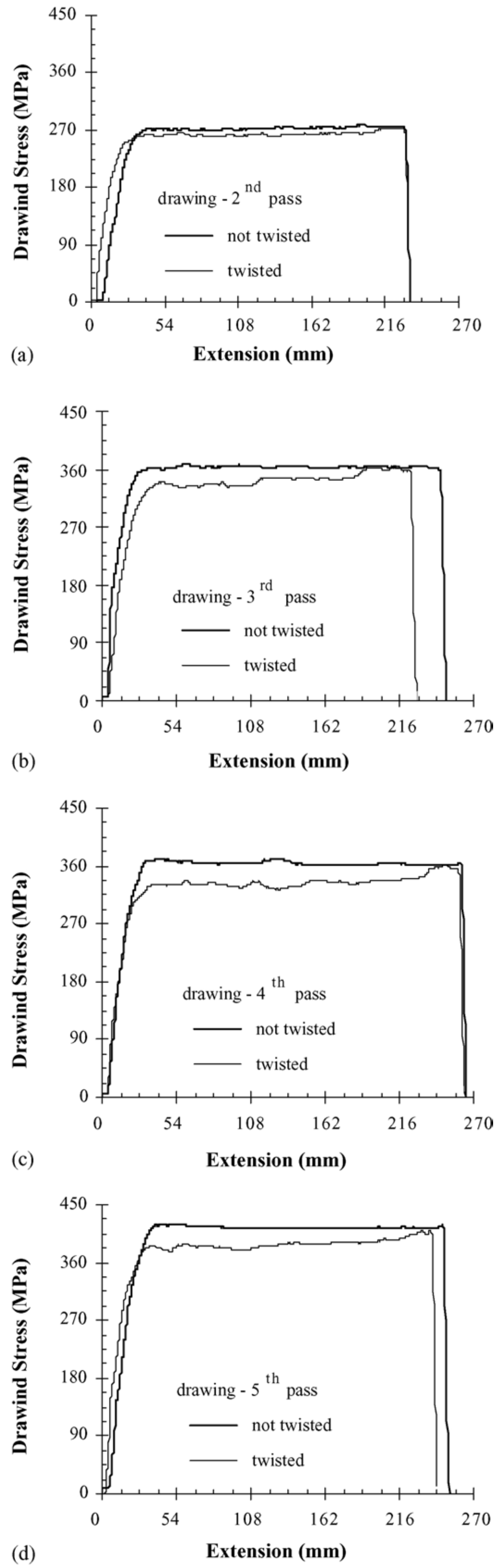

Fig. 2. Effect of cyclic torsion on the drawing stress of low carbon steel bars – cyclic straining conducted between: (a) 1st and 2nd, (b) 2nd and 3rd, (c) 3rd and 4th and (d) 4th and 5th passes.

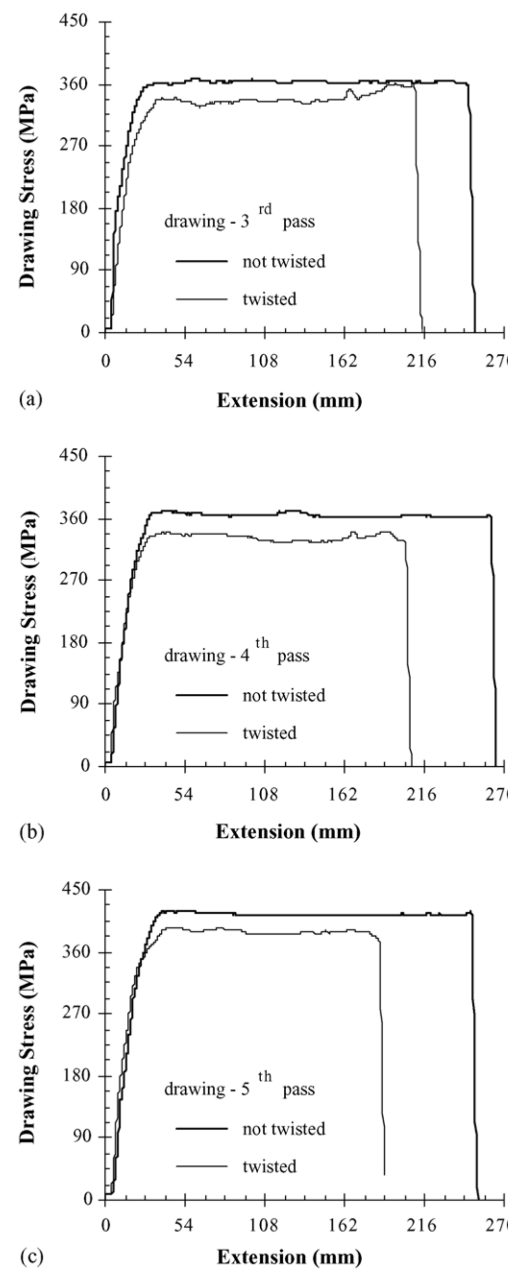

Fig. 3. Effect of cyclic torsion on the drawing stress of low carbon steel bars – cyclic straining conducted in between every pass: (a) 3rd, (b) 4th and (c) 5th passes.

sions and torsion deformation, and the successive decrease in the bar radius caused by drawing, some modifications in the specimens length had to be performed in order to maintain the cyclic deformation amplitude equal to 2.8. Despite the application of cyclic torsion after every drawing pass, the magnitude of the decrease in the stress level seems to be analogous to that obtained for the samples twisted only between the last two stages of forming, suggesting the occurrence of non-cumulative strain softening effects. These results are confirmed in Fig. 4, which displays the average drawing stresses and the percent change in the "original" values (related to the purely drawn material), for both experimental conditions. The modest difference among the curves indicates that subsequent drawing operation is able to remove the effects promoted by torsion in the pre-drawn bars. The curves shown in Fig. 4 also reveal the occurrence of an increasing relationship between reduction in drawing stress and stage of forming up to the 4th pass, at which the maximum value is reached.

The results displayed in Figs. 2–4 indicate that the effects of torsion on the drawing stress were less pronounced than those previously observed on the mechanical properties of the material [23]. In order to enhance these effects, a complete evaluation of the process should be performed, covering the influence of the prestraining value and the cyclic deformation parameters on the percent change in average stress. Several investigations have shown the importance of these factors on the mechanical behavior of metals under similar circumstances [6,7,12,13]. In the present study, the prestraining value is related to the die semiangle and the reduction in area per pass, whereas the cyclic deformation parameters are the strain amplitude and the total number of cycles. Former experiments, carried out in 6063 aluminum alloy and also in low carbon steel, exhibited the influence of them on the mechanical properties of the materials [22,23].

The TEM micrographs of the metal drawn in one and two passes are shown in Fig. 5. Single-pass drawing led to the development of an elongated subgrain/cell block structure, with extended microbands and dense dislocation walls (Fig. 5(a)). Further drawing deformation (2nd pass) promoted a decrease in the boundaries spacing, as well as an increase in the dislocation density and the occurrence of tangles (Fig. 5(b)). Similar substructure patterns were previously described by Strauven and Aernoudt [24], whose investiga-

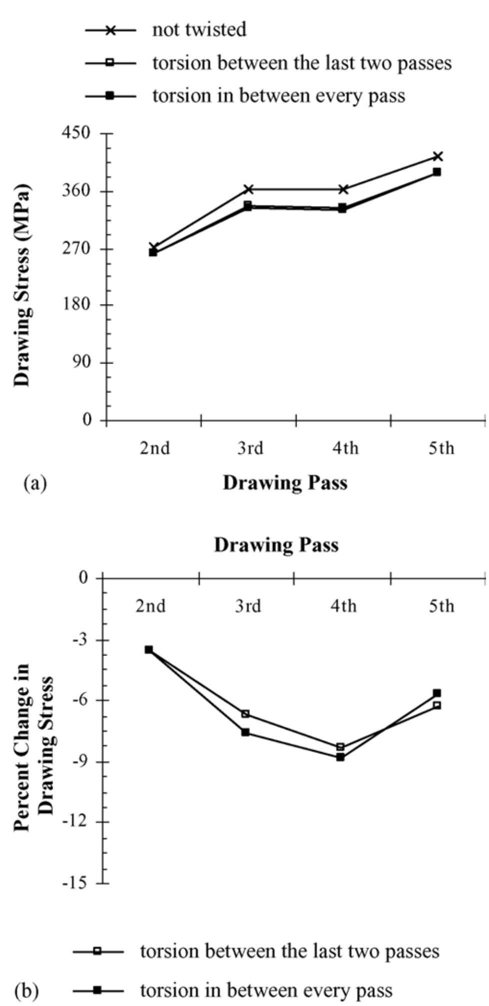

Fig. 4. Effect of cyclic torsion on the drawing process of low carbon steel bars: (a) drawing stress and (b) percent change in drawing stress.

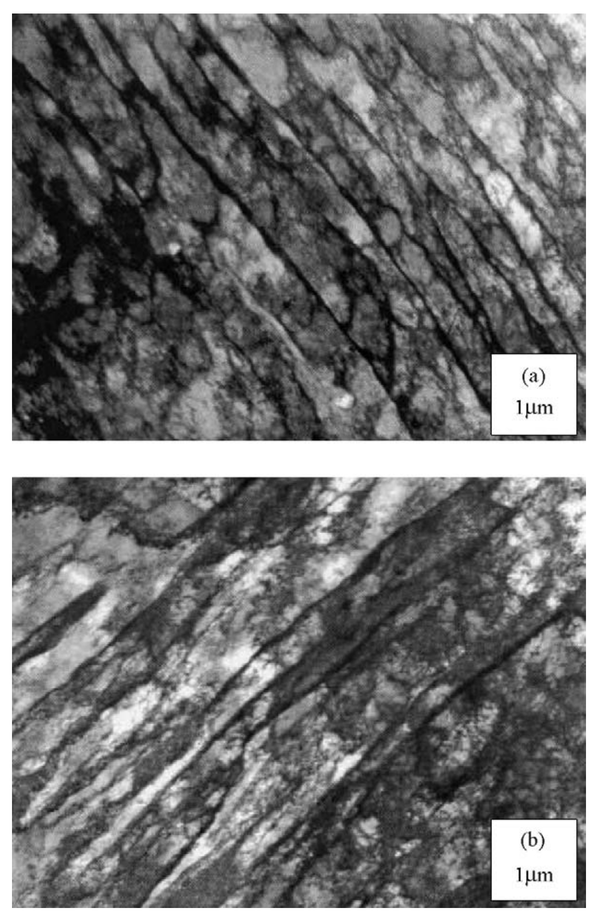

Fig. 5. Substructural aspects of the drawn low carbon steel sample: (a) one pass and (b) two passes of drawing.

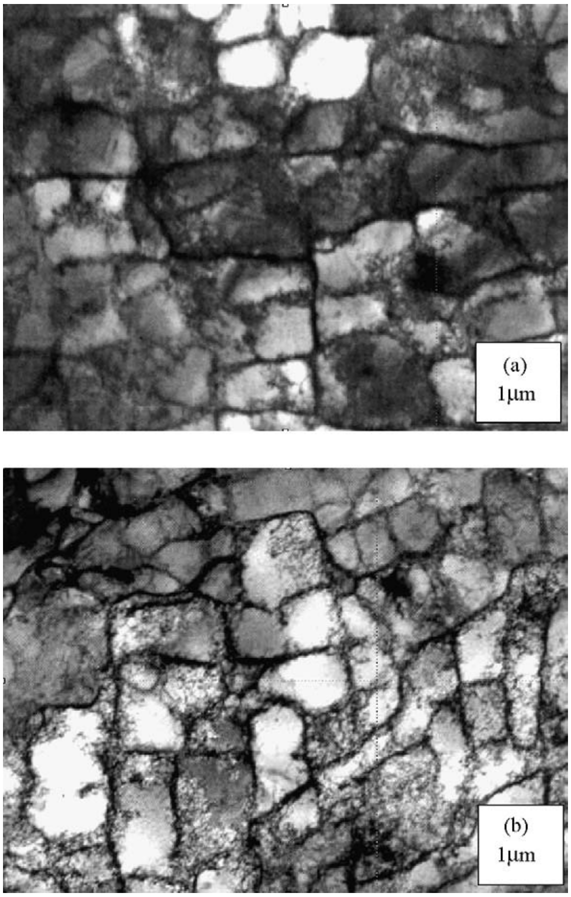

Fig. 6. Substructural aspects of the drawn low carbon steel sample after cyclic torsion: (a) one pass and (b) two passes of drawing.

tion reported the following sequence of internal arrangements with increasing drawing deformation: ordinary cells, elongated subgrains and sheet- and needle-like subgrains.

Fig. 6 displays the substructural aspects of the drawn metal after cyclic straining. Torsion led to pronounced changes in the former dislocation configuration, inducing the development of an almost homogeneous chess-board like microstructure, consisting of rectangular shaped subgrains, with reduced dislocation density and tangled areas. These results are in conformity with the macroscopic behavior of the material, observed in terms of drawing stresses (Figs. 2–4) and tensile properties (Fig. 1). The change in the deformation mode from drawing to torsion leads to the activation of new slip systems, which had been inactive during prestraining. At this moment, dislocations previously accumulated at barriers such as tangles and microbands are able to move through the metal. As cyclic torsion is conducted, a reversed motion mechanism takes place, promoting the occurrence of dislocation annihilation processes and the internal, lower energy, rearrangement of dislocations in the drawn bar. The final substructural configuration of the samples (Fig. 6) presents a lower density of dislocations, in comparison with the results displayed for the prestrained material (Fig. 5). Therefore, the restructuring of the dislocation arrangements drove the drawn bars to a less hardened state, promoting a mechanical recovery of the metal. Analogous results were observed in the structural evolution of aluminum alloys during unidirectional/multidirectional compression and in cyclic extrusion/compression experiments [7,14–16]. The first investigation, covering a quantitative study of the microstructural features of the precompressed material, revealed the occurrence of an increase in the cell size as cyclic deformation is performed. In the second case (the cyclic extrusion/compression analysis), an uniform chess-board like substructure, with diamond shaped cells or subgrains, was also exhibited. The investigations showed that this internal configuration had developed from the mutual crossing of microbands on the samples during cyclic straining. The studies also demonstrate that, as deformation increases, the microbands spread through several grains, converting into macroscopic shear bands. Prior optical and scanning electron microcopy exams in cyclically twisted aluminum drawn bars have revealed similar superficial characteristics [25]. Finally, one could conclude that, although a dislocation reorganization process is observed as a result of cyclic straining, the subsequent drawing deformation seems to be able to almost eliminate these microstructural changes, which explains the occurrence of non-cumulative strain softening effects on the material.

4. Conclusions

- Cyclic torsion between drawing passes led to a decrease in the drawing stress of low carbon steel bars, whose magnitude depended on the number of drawing passes in the operation.
- The reduction in the stress level was similar for both experimental conditions employed in this investigation: cyclic straining between the last two stages of drawing and cyclic straining in between every pass of drawing.
- Dislocation restructuring was found to be the strain softening mechanism related to the cyclic torsion of pre-drawn samples, comprising the evolution of microbands and subgrains into a chessboard like arrangement.
- The results brought out the feasibility of improving multiple-pass drawing operation making use of cyclic straining between forming stages.

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