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# THE EFFECT OF CYCLIC TORSION ON THE DRAWING STRESS OF 304 STAINLESS STEEL AND 6063 ALUMINUM ALLOY BARS

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***Abstract.*** *The occurrence of strain softening of prestrained metals as a result of cyclic deformation has been previously observed in terms of tensile mechanical properties and some microstructural aspects. The investigations have revealed the possibility of using these results in order to improve multiple-stage forming processes. In this paper, the effects of cyclic torsion on the drawing stress of metallic bars in multiple-pass drawing operations have been investigated. Drawing was performed with five passes. Cyclic torsion was carried out at room temperature, between the last two stages of drawing. Two materials were used in the experiments, 304 stainless steel and 6063 aluminum alloy, allowing the analysis of the influence of the structural features of the metal on the results. Cyclic straining led to a decrease in the stress level of the aluminum samples, whose magnitude depended on the number of drawing passes previously conducted on the material. On the other hand, for 304 stainless steel bars, drawing stresses remained almost unaffected by cyclic torsion, which confirms the dependence of the strain softening on metal characteristics.*

***Keywords****: drawing, cyclic straining, strain softening*

## 1. Introduction

One of the most important characteristics of cold forming operations is the work hardening of metals, whose magnitude increases as plastic monotonic deformation passes are conducted. On the other hand, under specific loading conditions, its possible to have less hardened structures or even to remove the effects of prior straining. Strain path change experiments, covering multiple stage operations (Wagoner and Laukonis, 1983, Doucet and Wagoner, 1989, Fernandes and Vieira, 1997, Rauch et al, 2002, Barlat et al, 2003) or cyclic deformation processes (Coffin and Tavernelli, 1959, Armstrong et al, 1982 , Richert and Korbel, 1995, Lukás and Kunz, 2002, Corrêa et al, 2003a) have revealed the phenomenon.

Previous investigations have shown the effects of cyclic torsion on the tensile behavior of 6063 aluminum alloy and low carbon steel drawn bars (Aguilar et al, 1999, Aguilar et al, 2000). For both materials, strain softening was observed, whose magnitude depended on the previous drawing deformation and on the torsion parameters employed in the experiments. Figure 1 shows some examples of these studies. The percent changes in the mechanical properties, taken with reference to the material not twisted, are displayed. Cyclic torsion led to the decrease of the yield and tensile strength, as well as to the increase of the ductility of the metals.

The aim of the present paper is the analysis of the effects of cyclic torsion on the drawing stresses of metals in multiple-pass drawing operation, considering the influence of the structural characteristics of the materials on the results.

## 2. Materials and Methods

The materials used in this study were the 6063 aluminum alloy and the 304 stainless steel, whose chemical compositions are presented in Tab. 1. The specimens, bars with 6.40mm of diameter and 390mm of length, were annealed at 400°C for 3600s (6063 aluminum alloy) and at 1000°C for 1200s (304 stainless steel), and furnace cooled to room temperature. Final homogeneity was verified through metallography and Vickers hardness.

Two groups of experiments were carried out in the work. The first one corresponded to the conventional multiple-pass drawing operation. The second involved the use of cyclic torsion between the last two stages of drawing considered in the analysis.

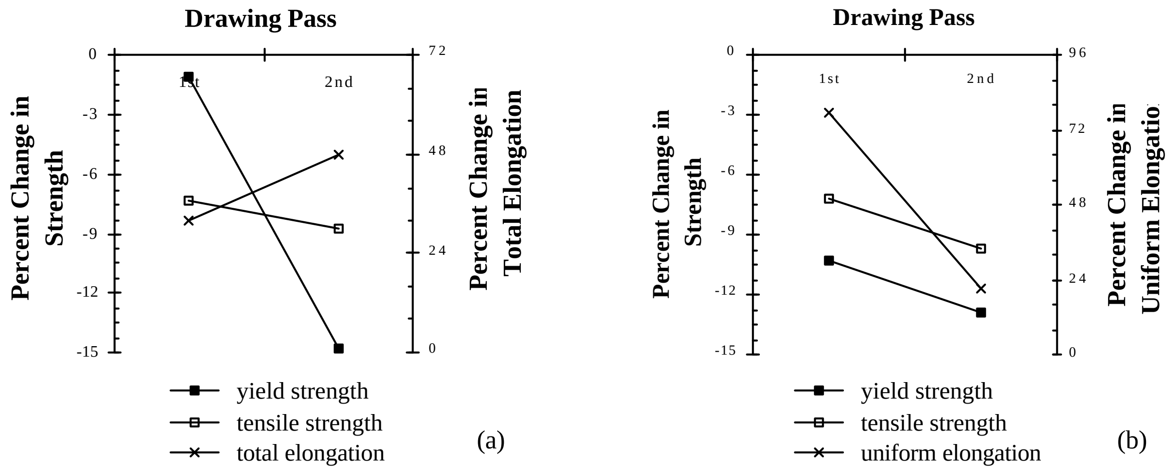


Figure 1 – Percent change in the tensile properties of drawn bars as a result of cyclic torsion (10 cycles, strain amplitude per cycle = 2.8%): (a) 6063 aluminum alloy and (b) low carbon steel (Aguilar et al, 1999, Aguilar et al, 2000).

Table 1. Chemical composition (weight percent) of the 6063 aluminum alloy and the 304 stainless steel.

| 6063 aluminum alloy | | | | | 304 stainless steel | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Si | Fe | Mg | Mn | Zn | C | Cr | Ni | Mn | Si |
| 0.431 | 0.151 | 0.472 | 0.068 | 0.007 | 0.050 | 17.960 | 8.350 | 1.360 | 0.124 |

Drawing was performed with five passes in an Instron model 4482 machine, with a specially designed system for the process, at a crosshead speed of $6.67 \times 10^{-1}$mm/s. The parameters employed in the tests were analogous to those used in previous investigations (Aguilar et al, 1998, Corrêa et al 2001): die semi-angle = 8° and reduction in area = 20%. Lubrication was performed with a Molybdenum disulfide paste.

Torsion was conducted in an adapted bench lathe, whose details were reported elsewhere (Aguilar et al, 1998). Ten cycles of deformation were applied to the drawn bars, with a plastic shear strain amplitude per cycle = 2.8%, leading to the torsion angles shown in Tab. 2. Similarly to the drawing operation, torsion conditions were chosen according to previous results (Aguilar et al, 1998, Corrêa et al 2001).

Table 2. Torsion angles.

| cyclic straining between | | | |
|---|---|---|---|
| $1^{st}$ and $2^{nd}$ passes | $2^{nd}$ and $3^{rd}$ passes | $3^{rd}$ and $4^{th}$ passes | $4^{th}$ and $5^{th}$ passes |
| 115° | 128° | 144° | 160° |

## 3. Results and Discussion

Figure 2 presents the effects of torsion on the drawing stress of the 6063 aluminum alloy bars. Cyclic straining led to a decrease in the stress level, whose magnitude depended on the number of drawing passes previously conducted on the material. In addition to some irregularities observed in the curves, probably associated with lubrication problems, a pronounced increase in the stress values of the drawn/twisted samples at the end of the experiments is verified. These results are related to the sections of the bars that served as gripping regions during torsion and, therefore, remained almost unaffected by the test. In order to compare the four situations, average drawing stresses for both types of experiments, conventional drawing and drawing/cyclic torsion tests, are shown in Fig. 3, as well as the percent change in the original values (connected to the purely drawn metal). In general, the effects of cyclic deformation became more pronounced as the number of forming passes increased (except for the $4^{th}$ drawing pass): the reduction in the stress values varied from ~ 3% ($2^{nd}$ pass) to ~15% ($5^{th}$ pass).

The results displayed in Figs. 2 and 3 are similar to those already reported for low carbon steel bars (Corrêa et al, 2001). For this metal, however, the maximum decrease in the drawing stress as a result of cyclic torsion was reached in the $4^{th}$ pass. This strain softening phenomenon, previously observed in tensile experiments (Fig. 1) and confirmed in Figs. 2 and 3, was found to be related to the restructuring of the dislocation arrangements in cyclic straining, which seems to promote a reversible dislocation motion mechanism, leading to the mechanical recovery of the material (Corrêa et al, 2003b, Aguilar et al, 2000). The reduction in the dislocation density, the formation and propagation of microbands and the development of a subgrain like microstructure are the main features observed in the analysis.

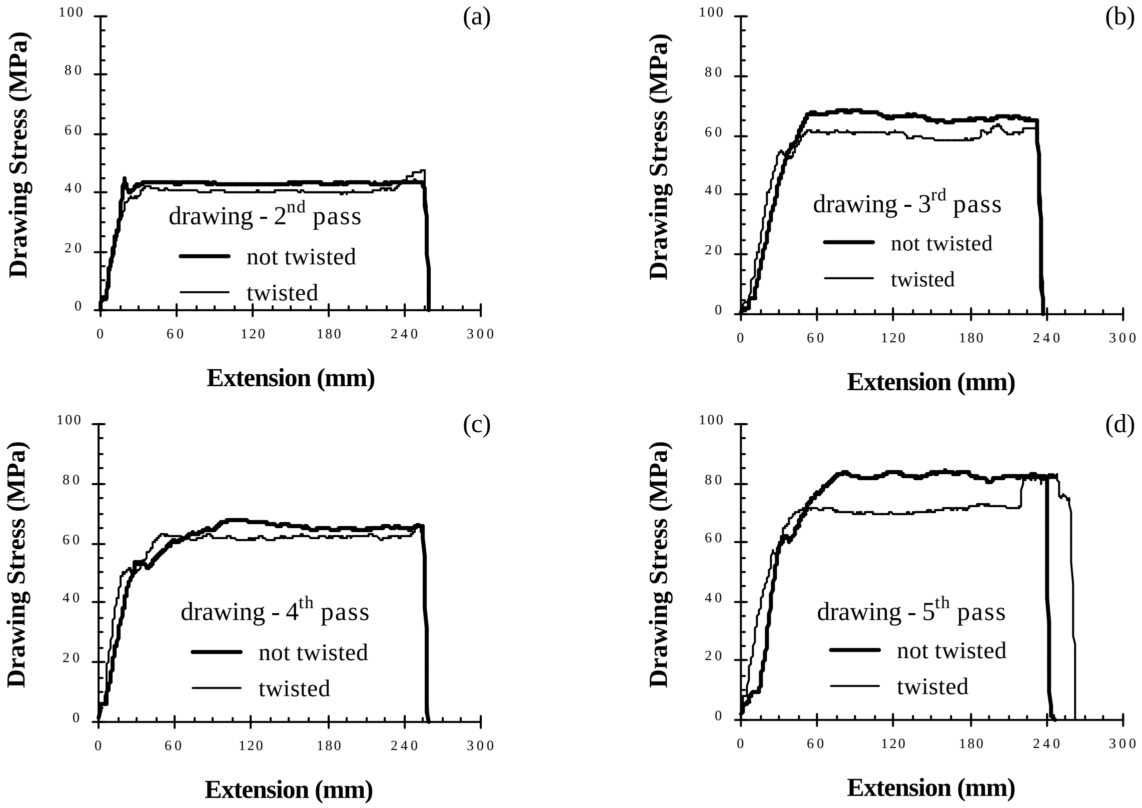


Figure 2 – Effect of cyclic torsion on the drawing stress of aluminum bars – cyclic straining conducted between: (a) 1st and 2nd, (b) 2nd and 3rd, (c) 3rd and 4th and (d) 4th and 5th passes.

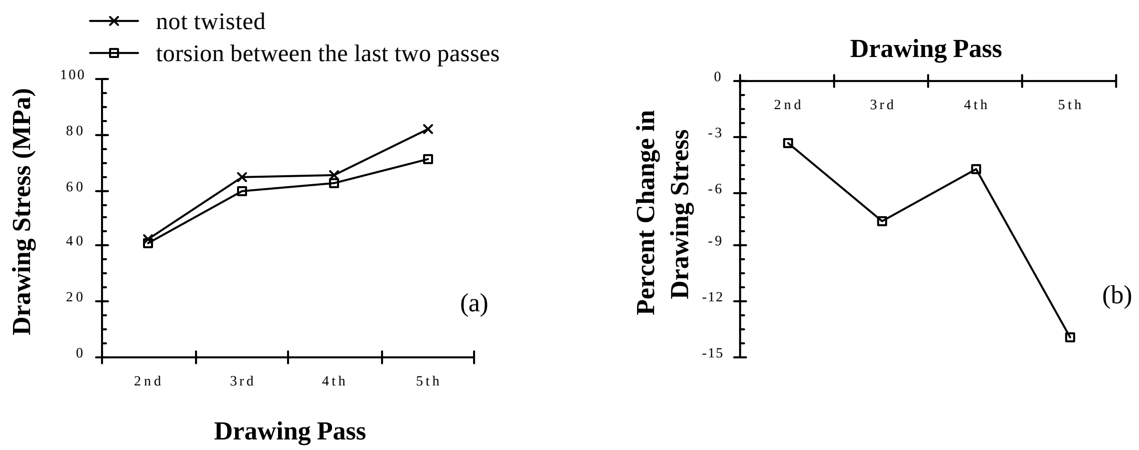


Figure 3 – Effect of cyclic torsion on the drawing process of aluminum bars: (a) drawing stress and (b) percent change in drawing stress.

The effects of cyclic straining on the drawing stresses of the 304 stainless steel bars are shown in Figs. 4 and 5. Contrasting with the results exhibited in the aluminum experiments, no significant changes are observed between the twisted and the non twisted samples. The maximum percent change in the stress values was less than 2%. Therefore, no softening effects were obtained through the cyclic straining of the drawn 304 stainless steel.

The differences in the results originating from strain path changes for the two metals considered in this work are connected to their distinct structural characteristics. Aluminum is a face centered cubic material with high stacking fault energy, marked by the intense occurrence of cross-slip, which leads to the establishment of a cellular dislocation structure (Bay et al, 1992) and low work hardening rates during plastic deformation. Its behavior can be compared with low carbon steel, which is a body centered cubic alloy and, thus, also related to the cross-slip deformation mechanism. On the other hand, the 304 stainless steel is a face centered cubic metal with very low stacking fault energy, associated with lower levels of dynamic recovery and then with the development of planar dislocation arrangements (Bay et al, 1992). Moreover, a phase transformation of austenite to martensite induced by plastic deformation is observed in this material, leading to the occurrence of very high work hardening rates. Therefore, it seems that the strain softening of prestrained metals as a result of cyclic straining is related to the previous formation of a cellular dislocation structure, which is sensitive to strain path changes.

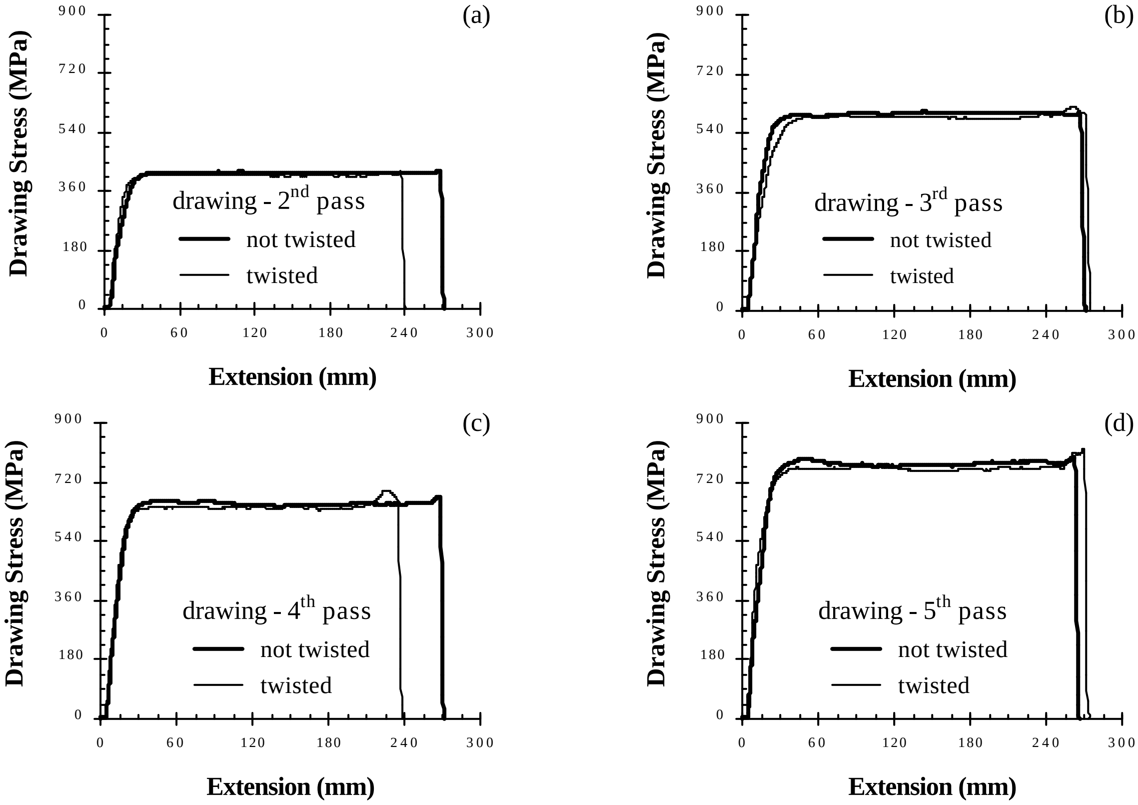


Figure 4 – Effect of cyclic torsion on the drawing stress of 304 stainless steel bars – cyclic straining conducted between: (a) 1$^{st}$ and 2$^{nd}$, (b) 2$^{nd}$ and 3$^{rd}$, (c) 3$^{rd}$ and 4$^{th}$ and (d) 4$^{th}$ and 5$^{th}$ passes.

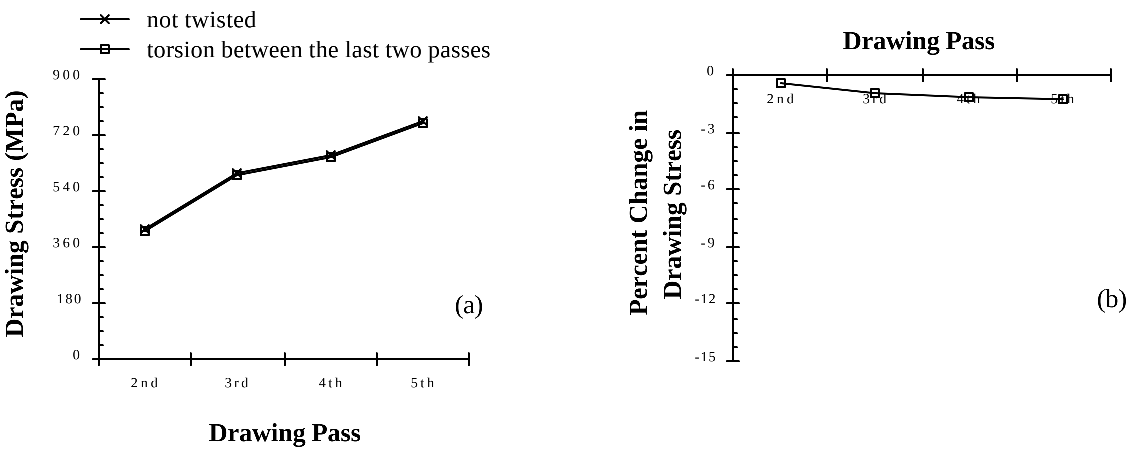


Figure 5 – Effect of cyclic torsion on the drawing process of 304 stainless steel bars: (a) drawing stress and (b) percent change in drawing stress.

## 4. Conclusions

- The effects of cyclic torsion on the drawing stress will depend on the structural and strain hardening characteristics of the metal considered in the experiments.

- Cyclic torsion led to a decrease in the stress level of the 6063 aluminum alloy bars during drawing operation. The strain softening effects became more pronounced as the number of deformation passes increased.
- No relevant changes in the drawing stresses as a result of cyclic straining were observed in the 304 stainless steel tests.

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