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Superficial and structural aspects of the cyclic strain softening in 6063 aluminum alloy bars

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Abstract

The performance of metallic products is profoundly affected by the final mechanical properties of the material. On the other hand, these final properties are directly linked to the employed manufacturing operations. In the case of cold forming processes, the work hardening is the most important phenomenon observed during plastic straining. For cyclic processing, however, unusual flow behaviors are observed, characterized by the development of saturation stresses and by the occurrence of strain softening in prestrained metals.

In this paper, the strain softening associated with the cyclic deformation of pre-strained metals is investigated. Annealed and drawn 6063 aluminum alloy bars are subjected to cyclic torsion. The structural and superficial aspects are analyzed. The work softening is caused by the restructuring of the dislocation arrangements due to cyclic torsion. The occurrence of deformation bands is also associated with the subsequent mechanical behavior of the material.

Keywords: Strain path; Cyclic straining; Work hardening

1. Introduction

The structural features of cold plastic deformation in metals have been extensively investigated both in laboratory tests and in industrial operations [1–9]. Many aspects of the problem have been analyzed, with emphasis on the relationship between the structure evolution and the macroscopic hardening behavior [4–7], and on the influence of strain rate [5,8], temperature [5,8], heat treatments [9] and material characteristics [3,4].

The above aspects have been covered basically for monotonic straining. On the other hand, similar analyses for cyclic deformation are far fewer. The atypical results attained in cyclic straining, such as the saturation flow stress state [10–14] and the strain softening of pre-strained materials [10,15–22], have been leading to an increasing interest in this subject. Reported results usually involve standard mechanical tests, such as tension/compression [11,15,16], multidirectional compression [10], and cyclic torsion experiments [17]. The association of forming processes with laboratory tests, typified by compression/extrusion [12–14] and cyclic torsion/extrusion [22], has shown possible applications of the phenomena to industrial situations.

Previous investigations studied the effect of cyclic torsion on the mechanical behavior of 6063 aluminum alloy and low carbon steel drawn bars [18–21]. Fig. 1 shows the final tensile properties of annealed and single pass drawn 6063 aluminum alloy samples, before and after cyclic deformation [18,19]. The percent change in the mechanical properties, taken with reference to the material not twisted, is also displayed. Large cyclic torsion strains caused a decrease of strength and an enhanced ductility in the pre-drawn material, whereas strengthening and a decreased ductility prevailed in annealed samples. This indicates that cyclic torsion caused strain softening in the former and strain hardening in the latter. The magnitude of these phenomena depends on the material, drawing variables and cyclic torsion parameters.

The present paper presents an analysis of the structural and superficial aspects in an initially annealed or pre-drawn

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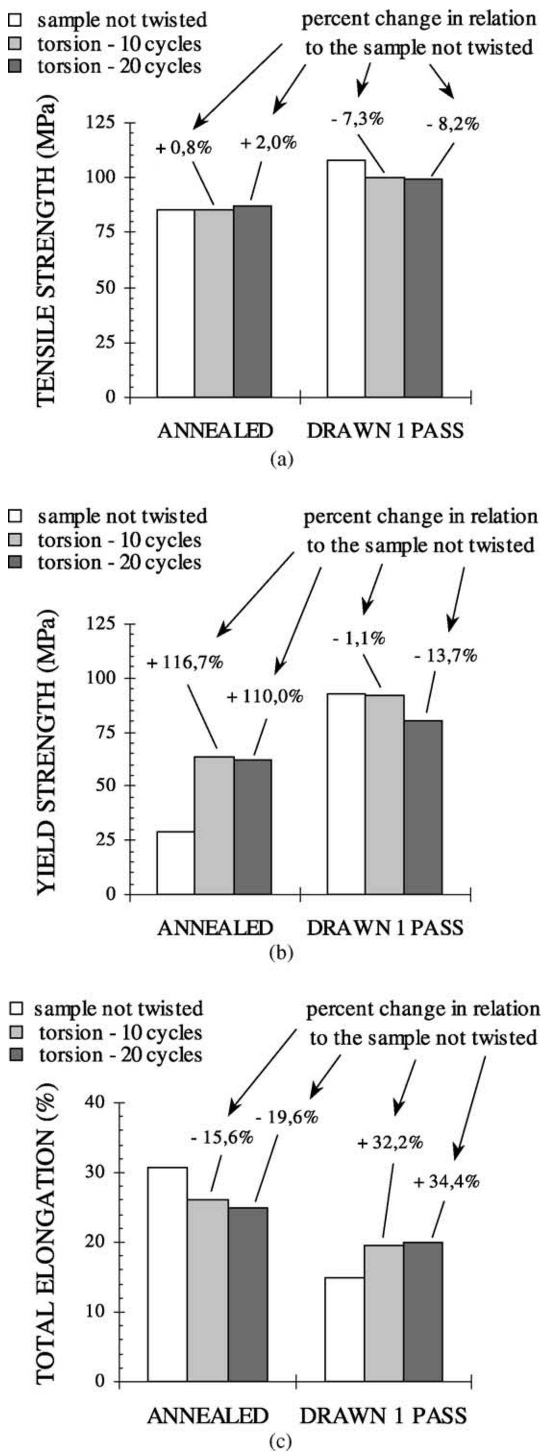

Fig. 1. Final tensile properties of annealed and drawn metal and the percent change in relation to the sample not twisted (cyclic torsion: 10 and 20 cycles, strain amplitude per cycle = 2.8%): (a) tensile strength, (b) yield strength and (c) total elongation [18,19].

6063 aluminum alloy, which underwent subsequent cyclic torsion. The results are associated with the above changes in the mechanical properties of the material and allow an interpretation of the observed strain hardening or softening phenomena.

Table 1
Chemical composition of a 6063 aluminum alloy (wt.%)

Si	Fe	Cu	Mg	Mn	Al
0.431	0.151	0.016	0.472	0.068	Balance

2. Experimental techniques

The experiments were performed on a 6063 aluminum alloy, whose chemical composition is given in Table 1. The material was obtained in the form of 3.20 mm radius bars. The metal homogeneity and its previous strain hardening/processing were verified through metallography and hardness tests. The as-received material displayed an average Vickers hardness of 67 ± 7 HV. The specimens (3.20 mm in radius and 390.00 mm in length) were annealed at 400 °C for 3600 s and furnace cooled to room temperature. The final average Vickers hardness was 36 ± 1 HV.

All tests were conducted at room temperature. One pass drawing was completed in a hydraulic draw bench, at a speed of 17 mm/s. Lubrication was performed with a molybdenum disulfide paste. Die semi-angle and reduction in area were 8° and 20%, respectively. Cyclic torsion was carried out in a specially adapted bench lathe, whose details were reported elsewhere [18]. The plastic surface strain amplitude per cycle was 2.8%, leading to a torsion angle of 160° (annealed sample) and 180° (drawn specimen). The total number of cycles applied was 10 and 20.

The substructure analysis was performed using a JEOL JEM 200C transmission electron microscope (TEM) at an operating voltage of 200 kV. Thin foils were prepared from annealed, twisted (20 cycles), drawn and drawn–twisted (20 cycles) bars, taken parallel and close to the surface of the sample.

Optical and scanning electron microscopy (SEM) were also used for the investigation of cyclic strain effects. The superficial aspects were observed for the annealed, twisted and drawn–twisted bars, which were mechanically polished before cyclic torsion (10 cycles).

3. Results and discussion

The optical and SEM surface aspects of the annealed and drawn samples subjected to cyclic torsion are shown in Figs. 2 and 3. The vertical scratches derive from the mechanical polishing. Optical microscopy indicates the occurrence of inhomogeneous deformation in the annealed specimen, revealed by modest irregularities in the surface of the sample (Fig. 2a). The SEM analysis, however, did not allow any observation concerning these anomalous superficial features (Fig. 2b and c). Heterogeneous deformation is also observed in the optical micrograph of the drawn bar (Fig. 3a). In this case, however, a "wavy" aspect and longitudinal markings on the surface of the specimen are clearly verified. The SEM

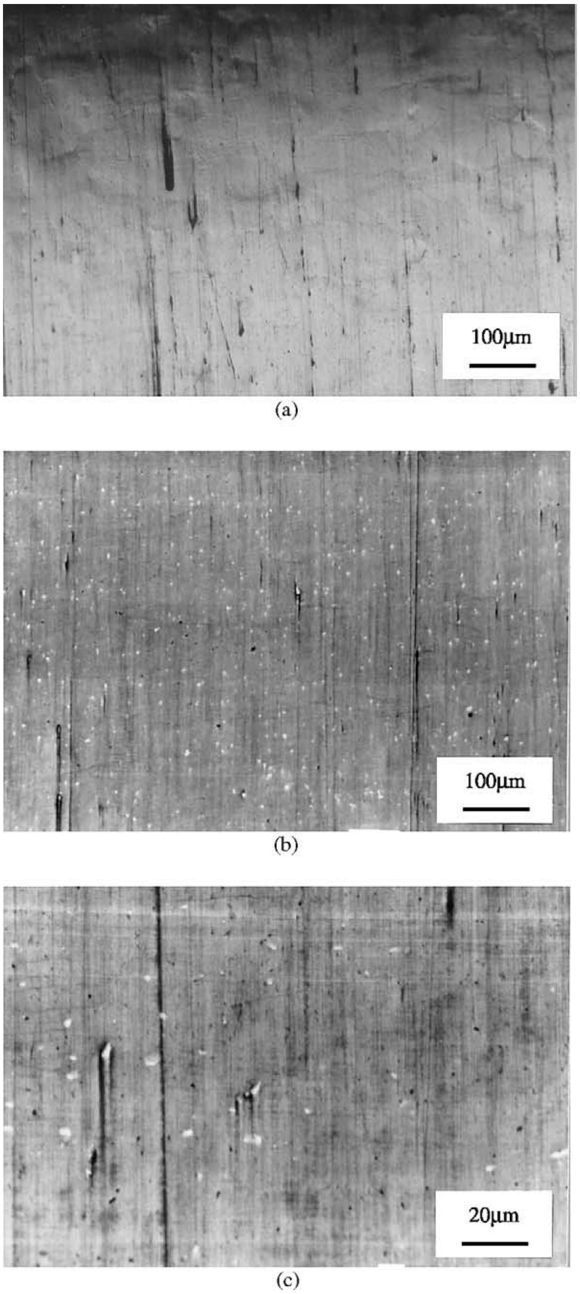

Fig. 2. Surface aspects of the annealed sample after cyclic torsion, 10 cycles: (a) optical and (b) and (c) scanning electron micrograph.

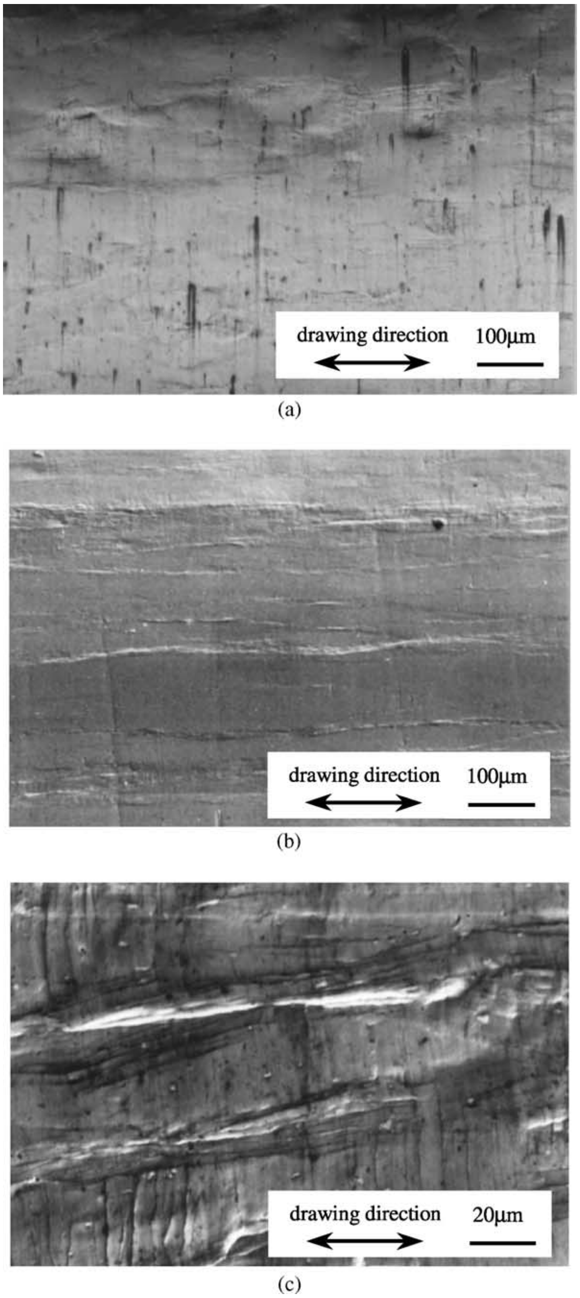

Fig. 3. Surface aspects of the drawn sample after cyclic torsion, 10 cycles: (a) optical and (b) and (c) scanning electron micrograph.

observations (Fig. 3b and c) confirm the presence of these linear markings in the bar, along its axial direction and parallel to each other. These unusual features, however, are not a consequence of the die–metal interaction during drawing process. The circumferential polishing totally eliminated all eventual longitudinal scratches caused by drawing, as illustrated in Fig. 4.

Surface features similar to those in Fig. 3 were observed in aluminum alloys and low carbon steel [6,7,12–14], which underwent various mechanical processes that included strain path changes, such as rolling/compression [7], rolling/tension [6] and cyclic extrusion/compression [12–14]. Strain localization in bands was found to be the dominant mode of plastic flow in these experiments, involving the nucleation of microbands and their subsequent conversion into macroscopic shear bands [23]. The strain path change induced the activation of new slip systems, providing an easy path for dislocation glide, leading to an avalanche type mechanism [5,6]. As deformation increases, the microbands spread across several grains, penetrating grain boundaries and other bands. The propagation of the bands corresponds to large deformations in the specimen, representing, however,

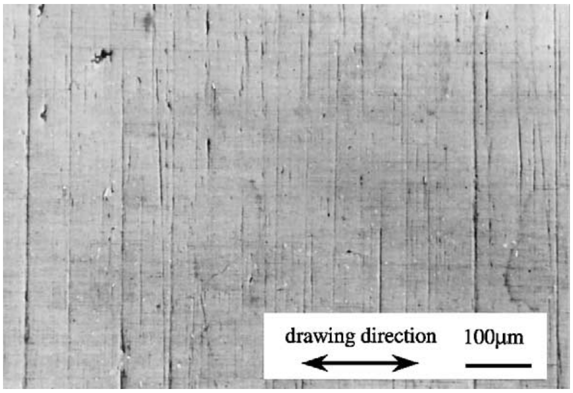

Fig. 4. Scanning electron micrograph of the drawn metal before cyclic torsion.

a modest contribution to the hardening of the material [6]. This structural evolution is related to the strain softening of the metal.

The dislocation structures developed in the mechanical processing of 6063 aluminum alloy bars are shown in Figs. 5 and 6. Randomly distributed precipitates ($FeAl_3$, Fe_3SiAl_{12} and Mg_2Si), typified in Fig. 5a, were identified and are observed in the micrographs. A few areas with dispersed dislocations can be seen in the annealed metal (Fig. 5a), in contrast with the intense and regular cell structure observed in the twisted material (Fig. 5b). Fig. 6 presents the effect of cyclic deformation on the dislocation microstructure of the drawn bars. Drawing also led to the development of an intense cell structure, which displayed, however, irregular cell sizes and wall thicknesses (Fig. 6a), if compared to the material that was only twisted (Fig. 5b). Cyclic torsion promoted an evolution of this dislocation cell structure, involving the increase in cell size, the reduction in tangled areas in their interior and to less sharply defined cell boundaries (Fig. 6b).

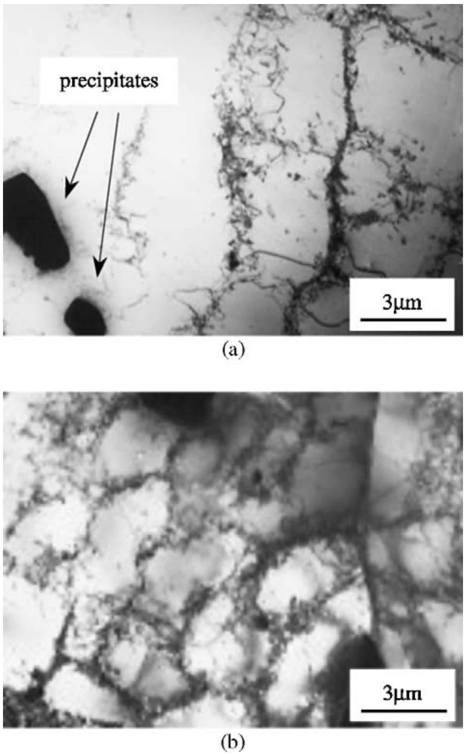

Fig. 5. Transmission electron micrograph of the annealed sample: (a) before and (b) after cyclic torsion, 20 cycles.

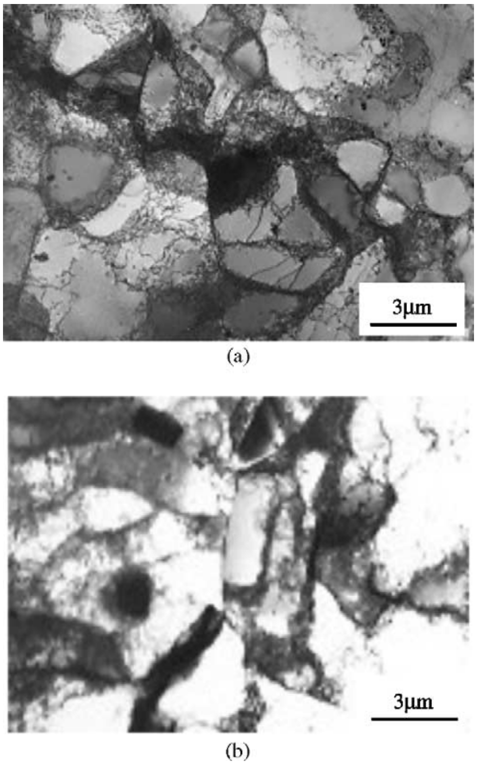

Fig. 6. Transmission electron microscopy of the drawn sample: (a) before and (b) after cyclic torsion, 20 cycles.

The above substructural aspects are in conformity with the tensile behavior of the material (Fig. 1 [18,19]). The strain softening observed in the prestrained metal is related to the restructuring of the dislocation arrangements in cyclic torsion, which seems to promote a reversible motion of dislocations, leading to mechanical recovery mechanisms. On the other hand, for the annealed aluminum, whose initial microstructure is associated with a modest presence of dislocations, cyclic straining led to an increase in the dislocation density and consequent strain hardening of the material. Similar results were obtained in low carbon steel investigations [20,21]. The effects of cyclic deformation on the structural features of the prestrained steel bars, however, seem to be more pronounced than those observed in 6063 aluminum alloy experiments. Analogous mechanical and microstructural behaviors were observed in unidirectional/multidirectional compression tests of commercially pure aluminum [10]. A quantitative study was performed on the structural aspects of this material: the strain softening was associated with an increase in the cell size accompanied by the reduction in their number, similarly to the present study.

The analysis of Figs. 2 and 3 and the results previously reported [5–7,23] indicate that strain localization in bands is an important deformation feature in the cyclic processing of the pre-drawn metal. The occurrence of dislocation restructuring (Figs. 5 and 6) in torsion is also connected with the unusual changes in the final mechanical properties of the metal. The strain softening of the cyclically twisted samples, clearly revealed in the subsequent tensile testing, results from both structural phenomena: the occurrence of deformation bands and the restructuring of the dislocation arrangements in the drawn bar.

4. Conclusions

The following aspects are of importance in the cyclic torsion of 6063 aluminum alloy bars:

- Cyclic torsion caused inhomogeneous superficial deformation in both annealed and drawn material.
- Superficial shear bands were developed only during the cyclic torsion of the drawn metal.
- A cell structure was observed in the annealed metal after cyclic torsion straining.
- Cyclic torsion promoted a restructuring of the dislocation arrangements of the drawn metal, leading to an increase in cell size, a reduction in the tangled areas and to less sharp cell boundaries.
- The strain softening associated with the cyclic processing of the prestrained metal is the result of the development of deformation bands and the restructuring of the dislocation arrangements.

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