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Substructural evolution during cyclic torsion of drawn low carbon steel bars

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Abstract

Strain softening effects have been previously observed in drawn low carbon steel bars as a result of cyclic torsion experiments. In this paper, the substructural aspects related to the phenomenon have been investigated. Single pass drawn bars were subjected to a quarter, to a half, to a full torsion cycle and to 10 such cycles. Transmission electron microscopy revealed the development of extended microbands crossing the former dislocation arrangement of the drawn metal, which evolves to a rectangular shaped subgrains structure as torsion deformation is conducted.

Keywords: Substructure; Cyclic torsion; Drawing; Strain softening

1. Introduction

The microstructural evolution of metals during cold plastic straining operations has been widely investigated, using both experimental and theoretical approaches [e.g. Refs. 1–5]. The analyses have been focused on the relationship between the substructural patterns, the dislocation motion mechanisms and the flow behavior of the materials, especially for face centered cubic pure metals and alloys [1].

Although these studies have been mainly carried out with monotonic deformation processes, an increasing interest has been observed in the analysis of the work hardening of materials under strain path change operations [e.g. Refs. 6–17]. The investigations, also covering the mechanical behavior and the structural aspects of the metals, have been chiefly concentrated on multiple stage standard tests [6–12], occasionally involving rolling [13–15] or cyclic straining [16–19]. Among several results, the occurrence of strain softening of prestrained samples during cyclic deformation [16,17] was found to be one of the most significant phenomenon in the experiments, pointing out the possibility of using strain path change responses in order to improve multiple-stage forming operations. Nonetheless, only a small number of processes have been developed based on the association of commercial forming operations and cyclic deformation, e.g. the CEC method, involving extrusion and compression, and the KOBO system, successfully applied to forging and extrusion [20,21]. The evaluation of other conventional and technologically relevant forming processes, such as drawing, seems to be far fewer.

Regarding the study of future improvements in multiple-pass drawing operations, our previous work has shown the occurrence of strain softening effects in predrawn low carbon steel bars as a consequence of cyclic deformation [22]. The analysis was carried out through the comparison of the subsequent tensile behavior of the drawn metal before and after cyclic straining. Fig. 1 presents some results related to these experiments. Cyclic torsion (10 cycles) led to a decrease in the strength as well as to an increase in the ductility of the material, whose magnitude depended on the die semi-angle considered in the prior forming process.

The aim of the present paper is the analysis of the substructural aspects related to the strain softening phenomenon exhibited in Fig. 1, considering the study of the internal dislocation arrangements of the drawn metal developed during the first torsion cycle and after 10 cycles.

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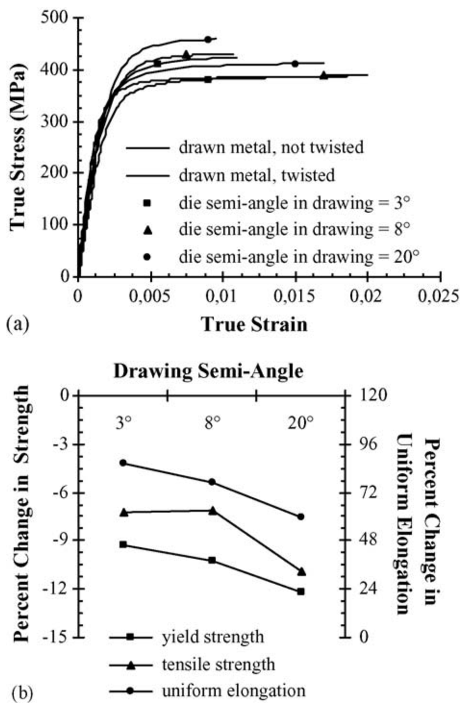

Fig. 1. Effect of cyclic torsion (shear strain amplitude = 2.8%, number of cycles = 10) on the tensile behavior of drawn low carbon steel bars (area reduction in single pass drawing = 20%): (a) true stress–true strain curves and (b) percent change in the mechanical properties [17].

2. Material and methods

The material used in this research was a low carbon steel with the following chemical composition (weight percent): 0.12C, 0.47Mn, 0.08Si, 0.016P, 0.013S. The as-received 6.40 mm diameter bars were cut into specimens of 390 mm length, which were annealed in vacuum at 850 °C for 2400 s. Final Vickers hardness of 97 ± 7 HV and grain size of 39.3 ± 5.6 μm were observed in the samples.

Single pass drawing was carried out in a hydraulic draw bench, at a speed of 17 mm/s. The parameters employed in the experiments were: reduction in area = 20% and die semi angle = 8°. Lubrication was performed with a molybdenum disulfide paste.

Torsion was conducted at room temperature, in a specially adapted bench lathe, whose details have been described in Ref. [23]. Similarly to the experiments corresponding to the results in Fig. 1, the cyclic plastic shear strain amplitude considered in the study was 2.8%, represented by an angle of 180°. Four sequences of torsion tests were completed in the investigation, according to Fig. 2. The first one, corresponding to a quarter of a torsion cycle, consisted of an anti-clockwise torsion of the drawn bar (Fig. 2(a)). The second, equivalent to a half of a straining cycle, involved an anti-clockwise followed by a clockwise torsion of the drawn metal, which returns to the initial position (Fig. 2(b)). The third, representing a full deformation cycle, comprised the procedure described above and the torsion of the sample in the direction opposite to the previous one (Fig. 2(c)). Finally, 10 torsion cycles analogous to that presented in Fig. 2(c) were carried out in the drawn bar.

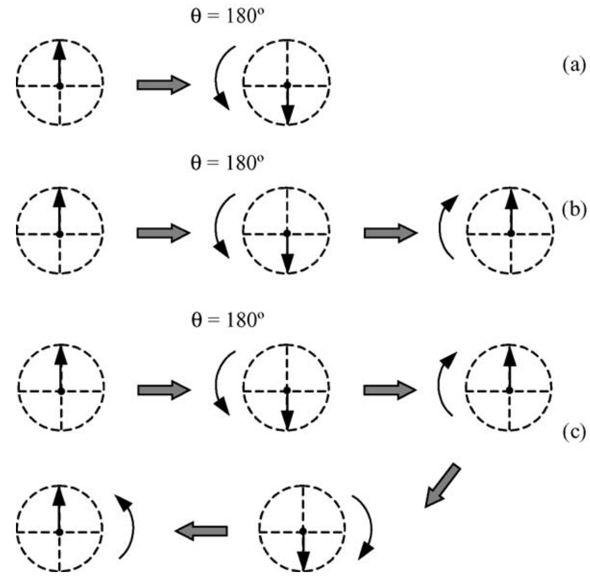

Fig. 2. Cyclic torsion of the drawn bar: (a) a quarter of a torsion cycle, (b) a half of a torsion cycle, (c) a full torsion cycle.

Transmission electron microscopy was performed in a JEOL JEM 200C microscope, at an operating voltage of 200 kV. The substructural analysis was conducted close to the surface of the drawn metal and of the twisted drawn specimens, prepared according to the experiments presented in Fig. 2. The samples were taken parallel to the axis of drawing.

3. Results and discussion

The substructural features of the metal after drawing are displayed in Fig. 3. Elongated cell blocks or subgrains enclosed by dense dislocation walls are observed, as well as tangles and ordinary cells in the interior of these dislocation patterns. Similar internal configurations have been previously reported by Strauven and Aernoudt [24], whose investigation revealed the following sequence of dislocation arrays as deformation was conducted in drawing: thick walled cells, elongated subgrains

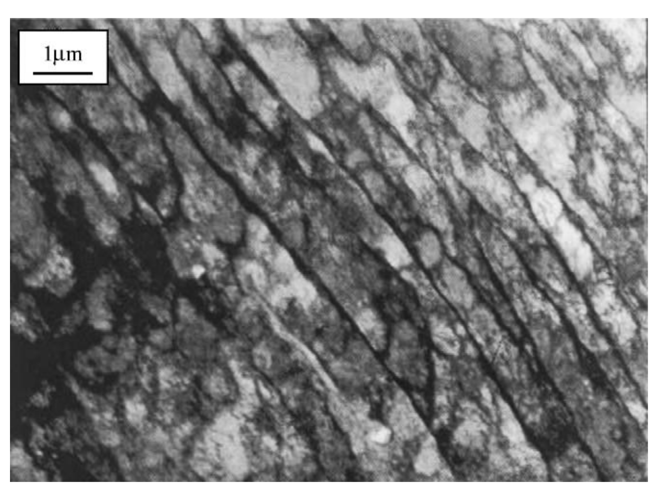

Fig. 3. Substructural aspects of the drawn low carbon steel.

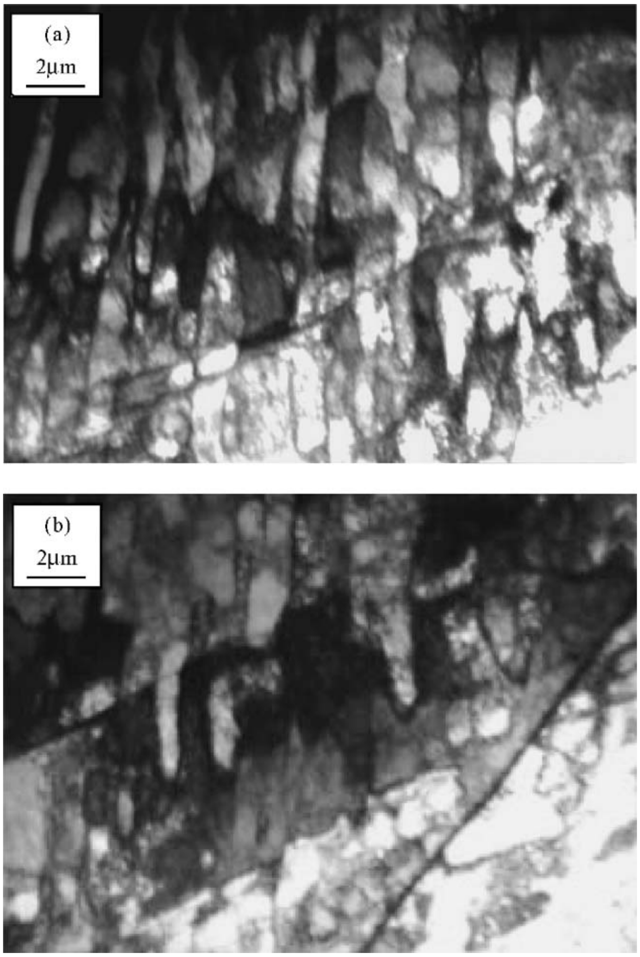

Fig. 4. Substructural aspects of the drawn low carbon steel during cyclic straining: a quarter of a torsion cycle.

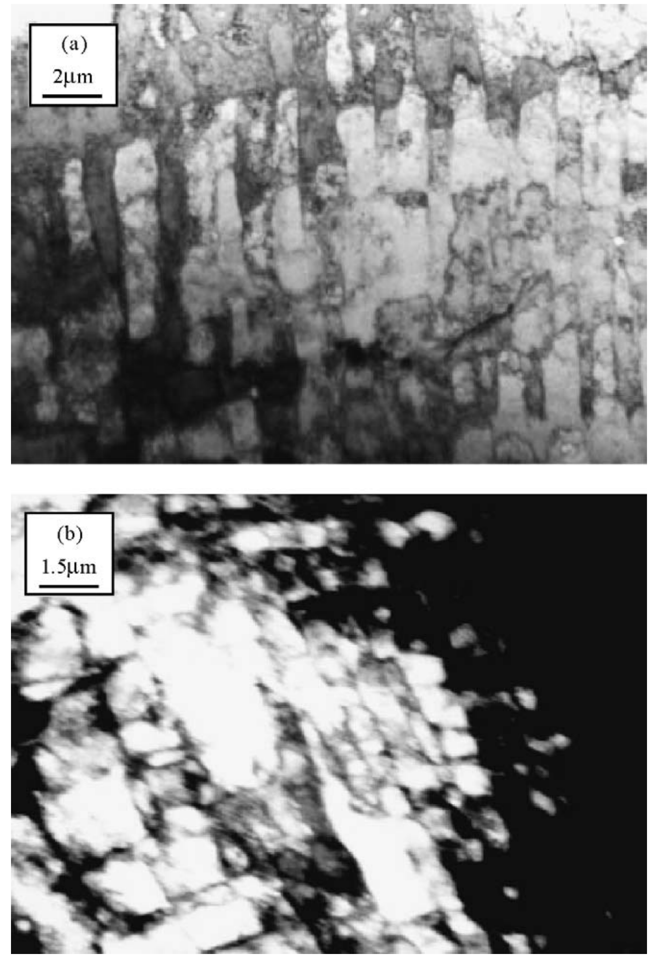

Fig. 5. Substructural aspects of the drawn low carbon steel during cyclic straining: a half of a torsion cycle.

with walls parallel to the wire axis and sheet- and needle-like subgrains.

Fig. 4 shows the TEM micrographs of the drawn bar subjected to an anti-clockwise torsion of 180°, corresponding to a quarter of a straining cycle. Torsion led to the development of extended dislocation arrangements, crossing the previously formed subgrain/cell block configuration. Analogous structural patterns have been observed in studies covering the events related to strain path change or cyclic straining of prestrained interstitial free and mild steel, aluminum and copper samples [6,12,21,25–27]. The extended dislocation arrangements have been defined as microbands, described by Korbel and Martin [25] as long thin bands parallel to slip planes, often formed across the width of the grain, superimposed to the primary structure. Thuillier and Rauch [12], also reporting the main features of these internal arrays, revealed as a necessary condition for the development of microbands the occurrence of the deformation practically in only one slip system during reloading, which would have been latent during prestrain. Based on the examination and on the description of the structural aspects of the micrographs presented in the investigations mentioned above, it is assumed that the elongated arrangements crossing the preformed dislocation sheets exhibited in Fig. 4 are microbands. A partial dissolution of the cellular structure inside the primary dislocation boundaries is also exhibited in Fig. 4. This disintegration process also reached the subgrain boundaries, which appear to have evolved from a continuous straight morphology to a somewhat diffuse configuration. More details associated with the relationship between the development of microbands and the strain path change are given at the end of this paper.

The substructural aspects of the drawn metal after a half of a torsion cycle are presented in Fig. 5. The events observed during the first step of deformation (Fig. 4) seem to become more pronounced as cyclic torsion straining advances. The disruption of the cells is clearly observed (Fig. 5(a)) and so is the increased number of elongated microbands crossing the material (Fig. 5(b)). Moreover, the intersection of the dislocation sheets [12] arising from drawing and the microbands developed in torsion, seems to induce the formation of a new set of subgrains, with low dislocation density and rectangular shape.

Fig. 6 shows the TEM images of the metal after a full torsion cycle. Pronounced changes are observed in comparison with the results displayed in Figs. 4 and 5. Elongated microbands and rectangular subgrains are also exhibited, composed of well-defined dislocation walls and some tangled areas. On the other hand, contrasting with the previously mentioned substructure

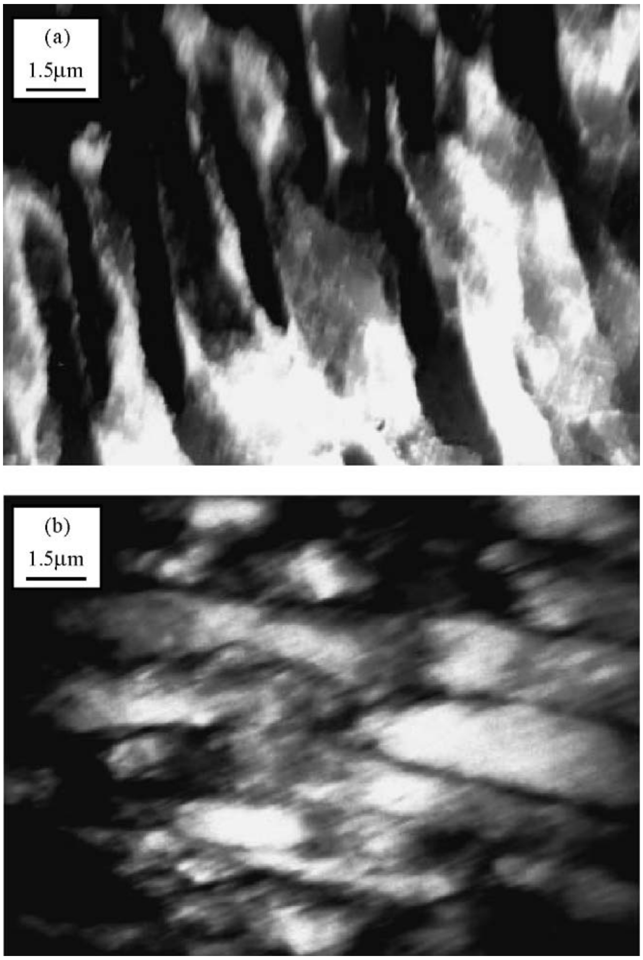

Fig. 6. Substructural aspects of the drawn low carbon steel during cyclic straining: a full torsion cycle.

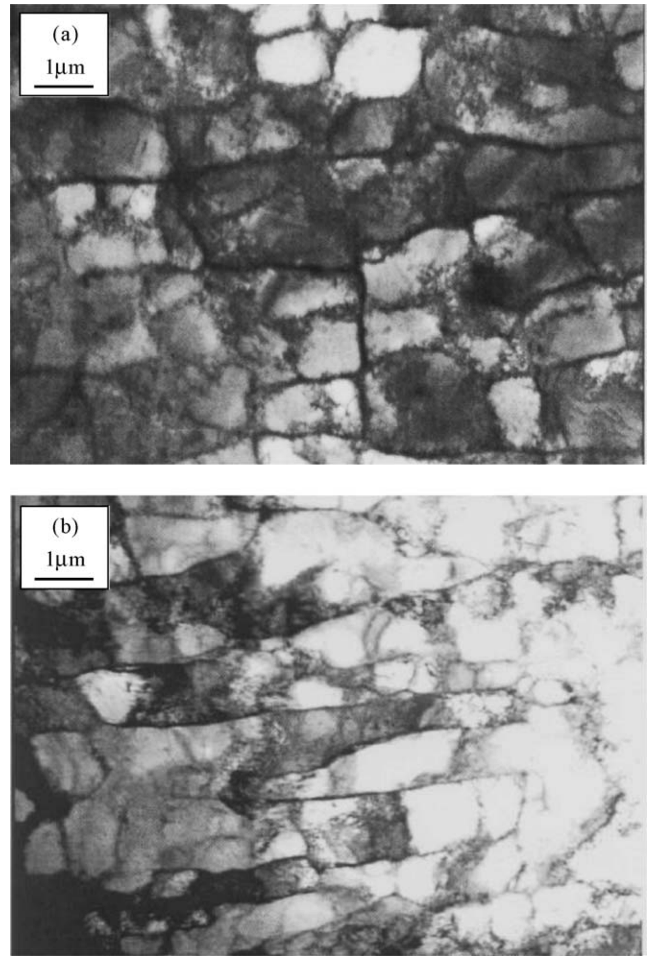

Fig. 7. Substructural aspects of the drawn low carbon steel after 10 cycles of torsion.

patterns, these dislocation arrangements are almost parallel to each other, spreading through the material in only one direction. No evidence of mutually intersecting microbands is observed, suggesting that the reverse torsion experiment was able to complete the restructuring process revealed in Figs. 4 and 5. In this case, the dislocation configuration in Fig. 6 seems to have evolved from the family of subgrains whose initial formation was indicated in Fig. 5.

The micrographs of the drawn bar after 10 torsion cycles are exhibited in Fig. 7. Repetitive cyclic straining led to the development of an almost homogeneous chessboard like microstructure, consisting of rectangular shaped subgrains with low dislocation density and tangled areas. Considering the TEM images displayed in Fig. 3 and the subsequent tensile behavior of the metal presented in Fig. 1, cyclic torsion drove the drawn bar to a less hardened state, involving an enhancement in the ductility and a reduction in the strength as a result of the dislocation rearrangement operation.

Substructural events analogous to those displayed in Figs. 4–7 have been already reported in strain path change and cyclic straining investigations. Similarly to the results shown in Fig. 4, which correspond to experiments involving a change in the deformation mode from drawing to monotonic torsion, the development of microbands superimposed on the previous dislocation arrangement and the partial dissolution of preformed boundaries have been observed in aluminum and interstitial free steel samples during two-stage tension and/or shear sequences [6–10], as well as in rolled copper, steel and aluminum specimens [25,28,29]. The disintegration of dislocation cell walls was associated with the internal plastic instability of the metals at the beginning of the reloading. In terms of the macroscopic mechanical behavior, the phenomenon is connected to the occurrence of a transient decrease or a stagnation of the work hardening rate of the materials [6,8–10]. On the other hand, the development of microbands was related to the activation of new slip systems during the strain path change, which provided an easy path for dislocation glide, leading to a dislocation avalanche type mechanism [25,28]. As deformation increases, the microbands spread over several grains, crossing grain boundaries and other structural barriers and finally evolving to microscopic shear bands [29]. Therefore, the propagation of the bands corresponds to large deformations in the specimen, representing, however, a modest contribution to the hardening of the material [28]. Regarding Figs. 5–7, the development of the new microstructural patterns as a result of the mutual crossing of microbands has been already revealed in aluminum cyclic extrusion/compression experiments

[21,30,31]. The analysis showed that this intersecting process takes place at early stages of cyclic straining and becomes more prevalent as deformation increases. Such restructuring induces the formation of an uniform chess-board like substructure, composed of diamond shaped cells or subgrains, similarly to the micrographs presented in Fig. 7, for the drawn metal after 10 cycles of torsion.

4. Conclusions

- The development of microbands crossing the previously formed dislocation structure was observed during the cyclic torsion of drawn low carbon steel bars.
- The formation of a new set of subgrains, with low dislocation density and rectangular shape, was observed in the area of intersecting microbands.
- Dislocation restructuring was found to be the internal mechanism related to the strain softening of the drawn bars during cyclic torsion.

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