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The effect of cyclic bending on the mechanical properties and dislocation structures of drawn steel bars

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Abstract Axisymmetric bar drawing increases the strength and decreases the ductility of metals. The recovery of these final mechanical properties often employs costly annealing processes. This paper discusses the possibility of controlling the mechanical properties of AISI 1010 steel bars through cyclic bending after one or two drawing passes and between these two successive passes. It is shown that cyclic bending softens the drawn material and increases its uniform elongation. The attending dislocation structures are presented and related to the associated mechanical properties. It is considered that cyclic bending is of interest in the industrial control of the final mechanical properties of drawn AISI 1010 steel bars.

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Introduction

The monotonic cold working of initially annealed metals leads to an increasing strength and a falling ductility of the material. A typical example of this situation is the cold axisymmetric drawing of steel wire rod [1]. Considering fixed processing temperatures and strain rates, the work hardening resulting from cold working depends also on the strain path followed during processing [2–10]. A widely known example of this fact is the decrease in the reloading flow stress and the attending work hardening transients typical of the Bauschinger effect [11].

Successive processing by tension and torsion also leads to unusual hardening behaviors, displaying flow stresses on reloading which can be below or above the flow stress before the strain path change, as well as to work hardening transients involving increased or decreased hardening rates upon reloading, in comparison with those before the strain path change [12]. Another interesting phenomenon produced by strain path changes is caused by cold cyclic tension/compression strains. Coffin and Tavernelli [2] showed that such processing may harden or soften several metallic materials, depending on the pre-strain level and the initial and final cyclic strain amplitudes. Similar results were also observed for the multi-axial compression of aluminum cubes [7]. Corrêa et al [13] showed that cyclic plastic torsion softens steel and brass bars previously deformed in tension; the same happens for bars previously drawn under axisymmetric conditions [14, 15]. Such results can be of industrial value as a tool for controlling the final mechanical properties of metals processed by cold working, especially if it can lead to the elimination of heat treatments.

Cyclic tension/compression or torsion are difficult to implement industrially as tools for such a control; on the other hand, cyclic bending is common in industrial practice, and can be observed in the coiling, uncoiling, and straightening of flat and long products [16]. In addition, since 2001 the continuous bending under tension test has been applied to study aspects of incremental forming [17, 18]. Cyclic bending can also, of course, be deliberately integrated along industrial rolling and axisymmetric drawing lines in order to eventually soften the material and enhance hardening capability.

Previous results indicate that, for flat products, cold cyclic bending leads to less work hardening than cold rolling, for initially annealed aluminum and commercial-purity copper. In addition, such bending caused softening and increased the ductility of previously flat cold rolled aluminum and copper [19, 20].

The aim of this paper is to analyze the effects of cyclic bending on the mechanical properties of previously cold drawn cylindrical bars of steel and to follow the attending changes in the dislocation structures of the material.

Material and experimental procedure

Commercial steel bars (AISI 1010) with a diameter of 3.18 mm and 1000 mm long were annealed in vacuum at 850 °C for 2400 s and cooled inside the furnace. Drawing of these bars was conducted in a hydraulic bench with up to two passes. Table 1 presents the characteristics of the dies used during drawing. Drawing was carried out at room temperature, at a speed of 20 mm/s, using molybdenum disulfide as lubricant. The strain rate during this process was $\sim 4\ s^{-1}$.

Cyclic bending was carried out at room temperature with a special fixture adapted to the hydraulic bench used for drawing. Figure 1 illustrates the special fixture used for cyclic bending and the bar path. The smaller pulley supports the material entering the cyclic bending unit, assuring an adequate bending in the first processing pulley. One pass of cyclic bending corresponded to two passages of the bar through the cyclic bending unit, with a 90° rotation around the bar axis between each passage. The strain amplitude (ε) at the bar surface during bending is determined as:

$$\varepsilon = \ln\left(1 + \frac{1}{\frac{2R}{d} + 1}\right) \quad (2.1)$$

where R is the pulley radius (26 mm) and d is the bar diameter. This equation gives strain values of ~ 0.051 and

Table 1 Characteristics of the dies used for drawing

Die	Final diameter (mm)	Semi-angle (°)
1st pass	2.9	8
2nd pass	2.6	8

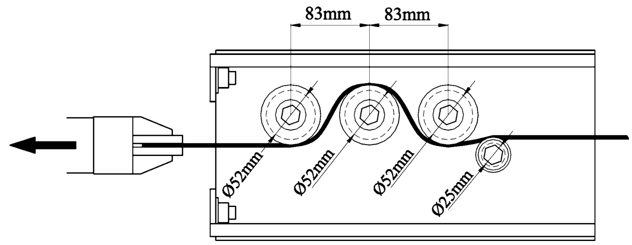

Fig. 1 Illustration of special fixture used to perform cyclic bending in the bars

Table 2 Notations for the various processing conditions

Condition	Notation
Annealed	AN
Drawn in 1 pass	D1
Drawn 2 passes	D2
Drawn 1 pass and cyclically bent 1 pass	D1CB1
Drawn 1 pass and cyclically bent 2 passes	D1CB2
Drawn 2 passes and cyclically bent 1 pass	D2CB1
Drawn 2 passes and cyclically bent 2 passes	D2CB2
1 Cyclic bending between the 2 drawing passes	D1CB1D2
4 Cyclic bendings between the 2 drawing passes	D1CB4D2
8 Cyclic bendings between the 2 drawing passes	D1CB8D2

0.047 for each bending for the bars drawn in 1 and 2 passes, respectively. Each cyclic bending pass involves 3 bendings and 3 unbendings, thus imposing a cumulative superficial strain of ~ 0.3 per pass. The exit speed of the bar during this process was similar to that in drawing (20 mm/s), leading to a strain rate of $\sim 0.05\ s^{-1}$. Table 2 presents the notations used for the various conditions under which the material was analyzed.

The mechanical properties of the bars after the various processing conditions were determined by tensile tests, utilizing an Instron 5582 universal tester. The specimens were 150 mm long, and a constant cross head displacement speed was used. The initial strain rate was $1.0 \times 10^{-4}\ s^{-1}$. An electronic extensometer with a gage length of 50 mm was attached to the specimens up to the maximum load (uniform strain), and a load cell with 100 kN of capacity was used. Test data were conventionally transformed into true-stress–true strain data up to the necking true strain [21].

The sub-structural aspects of the processed specimens were observed using a transmission electronic microscope JEOL-JEM, operated at 200 kV. Analyses were performed in specimens taken longitudinally and close to the specimen surface. Sample preparation involved initial mechanical polishing, followed by electrolytic thinning with a solution of perchloric acid and ethanol.

Experimental results and discussion

Drawing of annealed bars

The true-stress–true-strain curves up to the uniform strain for the annealed material (specimen AN) and for the specimens drawn in one pass (D1) and two passes (D2) are presented in Fig. 2. It is observed that drawing increased the strength and decreased the ductility of the material.

Transmission electron microscopy images show that the structure of the steel after annealing is characterized by large grains almost free of dislocations in their interior, as shown in Fig. 3. Some grains of the annealed sample, usually close to pearlite nodules, displayed higher dislocation density, as shown in Fig. 4 (see the lower grain).

Figures 5 and 6 display the typical dislocation structures observed in the material after 1 drawing pass (specimen D1) and after 2 drawing passes (specimen D2), respectively. As expected, there is an increase in the dislocation density and a decrease in the dislocation cell size, which can be associated with the increasing flow stresses of the material after each drawing pass. In addition, the dislocations tend to arrange themselves into elongated cells, as previously observed in the literature [22, 23].

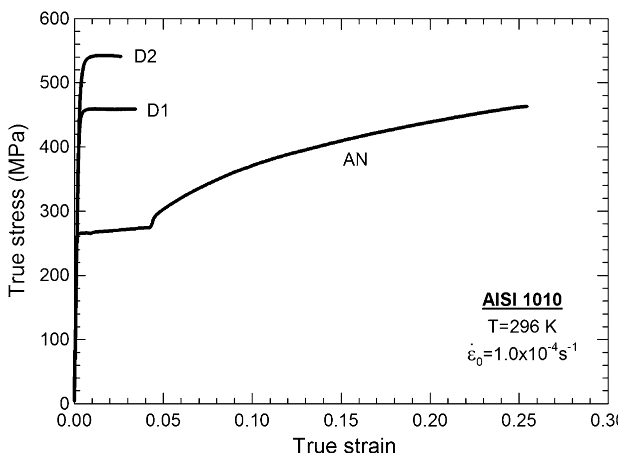

Fig. 2 True-stress–strain curves for the specimens: annealed (AN), drawn with 1 (D1), and with 2 (D2) passes

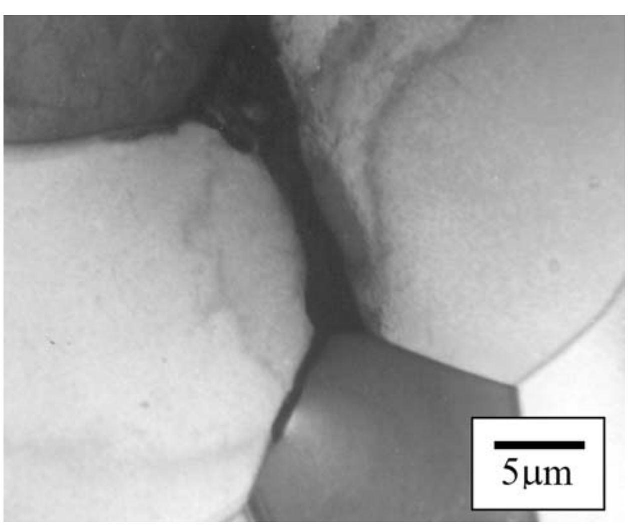

Fig. 3 TEM picture showing large, almost dislocation free, grains in the annealed AISI 1010 steel specimen

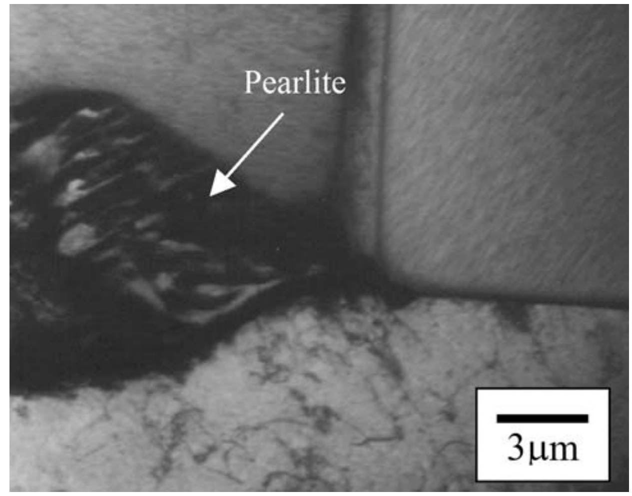

Fig. 4 TEM picture showing dislocations in grains close to the pearlite nodule in the annealed AISI 1010 steel

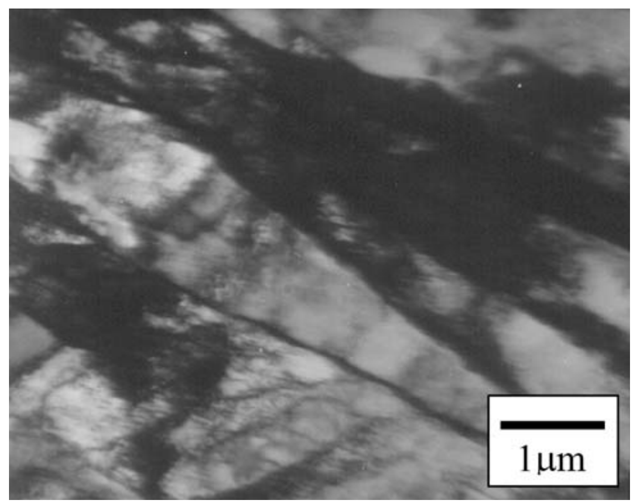

Fig. 5 TEM picture showing dislocation structure in the AISI 1010 steel after 1 drawing pass (specimen D1)

Cyclic bending of the bars drawn in 1 pass

Cyclic bending (in 1 or 2 passes) softens the material, as shown by the true-stress–true-strain curves for specimens D1, D1CB1, and D1CB2 in Fig. 7. There is also an appreciable increase in the material uniform strain (from a value of 0.033 to 0.129 and then to 0.144, respectively)

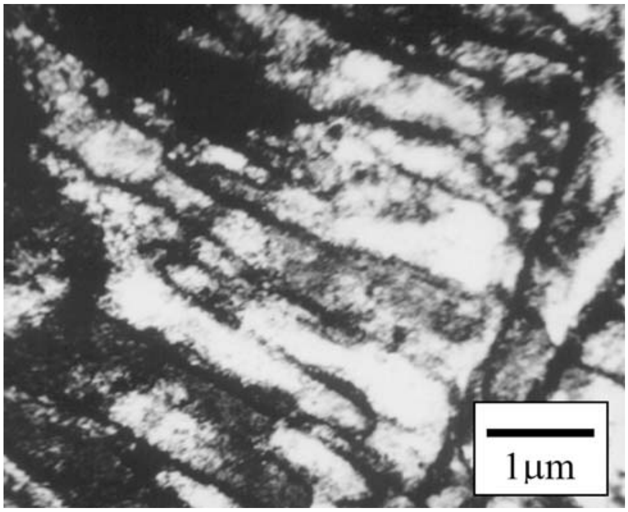

Fig. 6 TEM picture showing dislocation structure in the AISI 1010 steel after 2 drawing passes (specimen D2)

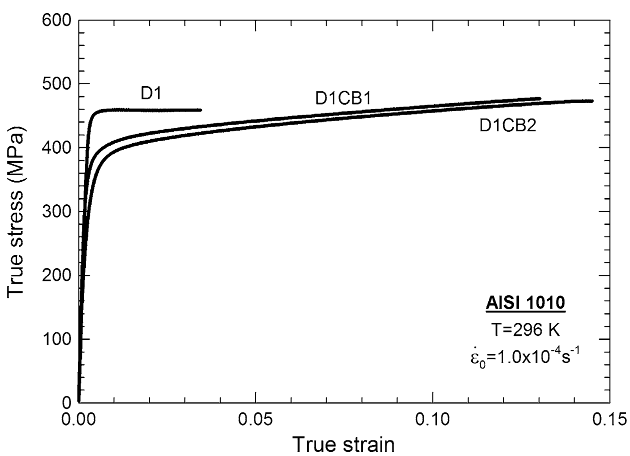

Fig. 7 True stress–strain curves up to the uniform strain for steel drawn in 1 pass (D1) followed by 1 cycle of cyclic bending (D1CB1) or 2 cycles of cyclic bending (D1CB2)

associated with an increased work hardening capacity after the cyclic bending. Figure 8 displays a typical dislocation structure of the material drawn in 1 pass and then cyclically bent in 1 pass (specimen D1CB1). Cyclic bending changed the shape of the dislocation cells (from elongated cells to a "block" type structure) and increased their size as can be observed by comparing Figs. 8 and 5. This change in dislocation structure provides a larger free path for dislocation movement and lower dislocation storage, resulting in the softening and increased uniform elongation shown in Fig. 7.

An increasing number of cyclic bending passes after drawing decreases the material strength and increases its uniform elongation, but at a decreasing rate with the number of passes. The flow curves in Fig. 7 show that the softening induced by the second pass of cyclic bending is

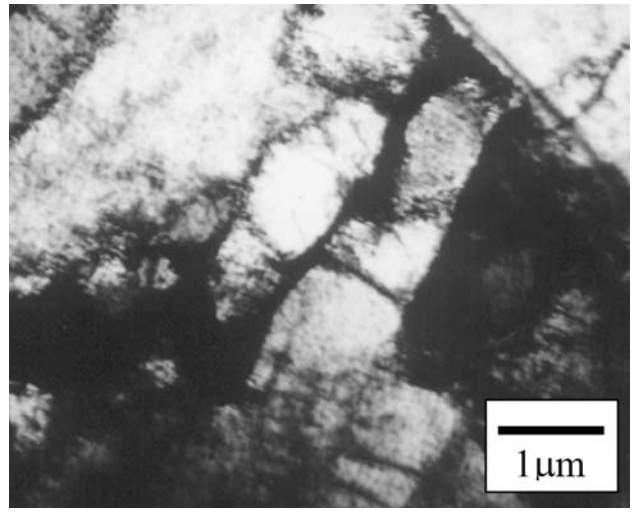

Fig. 8 TEM picture showing dislocation structure of the AISI 1010 steel drawn in 1 pass and cyclically bent in 1 pass (specimen D1CB1)

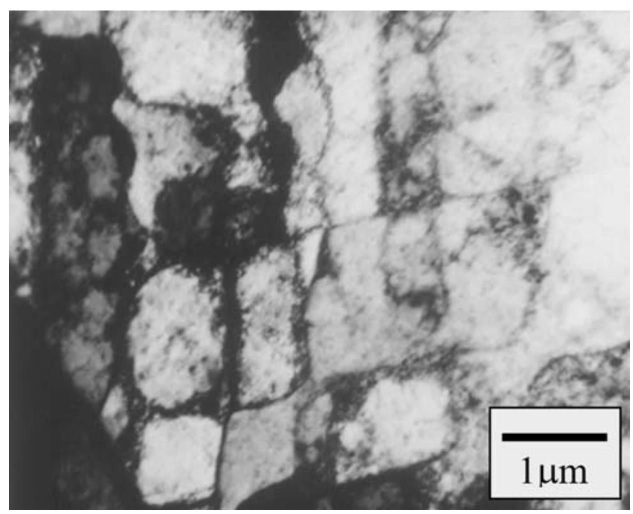

Fig. 9 TEM picture showing dislocation structure of the AISI 1010 steel drawn in 1 pass and cyclically bent in 4 passes (specimen D1CB4)

less pronounced than the first. The increase in number of passes of cyclic bending leads to a decrease in the overall dislocation density in the material, as well as to thinner dislocation walls between these cells as exemplified in Fig. 9, which shows the typical dislocation structures found in the material drawn in 1 pass and then submitted to 4 cyclic bending passes (specimen D1CB4).

Cyclic bending of the bars drawn in 2 passes

The experimental results for the specimen drawn with 2 passes (specimen D2) and then cyclically bent in 1 (D2CB1) and in 2 passes (specimen D2CB2) are similar to

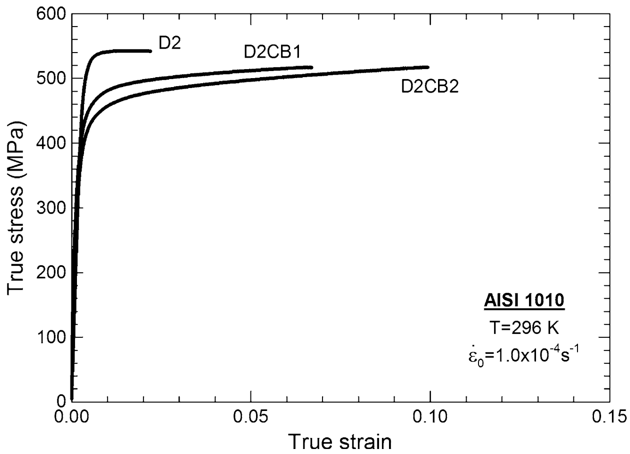

Fig. 10 True stress–strain curves up to the uniform strain for steel drawn in 2 passes (D2) followed by 1 pass of cyclic bending (D2CB1) or 2 passes of cyclic bending (D2CB2)

those of the material drawn in 1 pass only. Figure 10 shows that the successive cyclic bending led to an increasing softening of the drawn material and to higher uniform elongations (specimen D2CB2, for example, exhibited an uniform elongation of 0.10, a five fold increase in relation to the value of 0.02 for specimen D2), associated with an increased work hardening capacity.

Figure 11 displays a typical dislocation structure observed in specimen D2CB2. The cyclic bending led to an increase in the cell size and a decrease in the dislocation density inside the cells in comparison with the material subject to 2 passes of drawing only (Fig. 6); in addition, the cells changed from an elongated to a "block" shape. This change in dislocation structure increases the free path for dislocation movement, thus leading to a decrease in the drawn material strength and to an increase in its subsequent work hardening rate, resulting in a substantial increase in its uniform elongation. The "block' shape of the dislocation cells displayed in Figs. 8, 9, and 11 is quite similar to that observed in drawn bars submitted to cyclic torsion [23], and seems to be a general result of dynamic recovery caused by cyclic straining after monotonic cold straining.

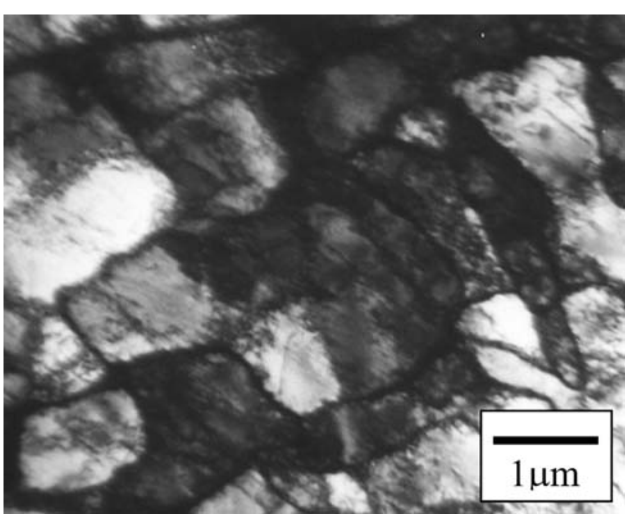

Fig. 11 TEM picture showing dislocation structure of the AISI 1010 steel drawn in 2 passes and cyclically bent in 2 passes (specimen D2CB2)

Cyclic bending between drawing passes

Further experiments, involving cyclic bending between the two successive drawing passes were also carried out. Figure 12 shows that 1 cyclic bending pass between drawing passes 1 and 2 (curve D1CB1D2) led to a similar strength to that obtained through 2 drawing passes. It is observed that curves for specimens D2 and D1CB1D2 almost coincide, meaning that the second drawing pass practically erased any previous softening caused by the intermediate cyclic bending.

A higher number of cyclic bending passes between the two drawing passes (curve D1CB4D2 for 4 cyclic bending passes and curve D1CB8D2 for 8 cyclic bending passes between the 2 drawing passes) led to slight softening in the material. The softening rate, however, decreases with the number of intermediate cyclic bending passes. Figure 12 also indicates that the uniform elongation of the specimens submitted to intermediate cyclic bending between two successive drawing passes (specimens D1CB1D2, D1CB4D2 and D1CB8D2) is lower than that obtained after only 2 drawing passes (specimen D2). The curves for 2 drawing passes followed by 1 cyclic bending pass (curve D2CB1) or by 2 cyclic bending passes (curve D2CB2) are

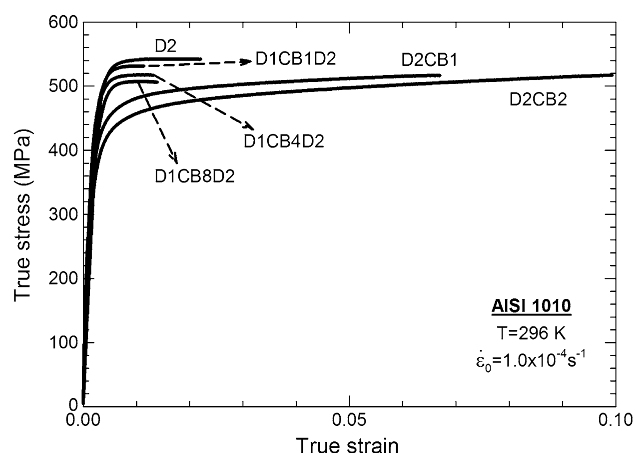

Fig. 12 True stress–strain curves up to the uniform strain for specimens drawn in 2 passes (curve D2), drawn in two passes with 1, 4 and 8 intermediate cyclic bending passes (curves D1CB1D2, D1CB4D2 or D1CB8D2, respectively) and drawn in two passes followed by 1 and 2 cyclic bending passes (curves D2CB1 and D2CB2, respectively)

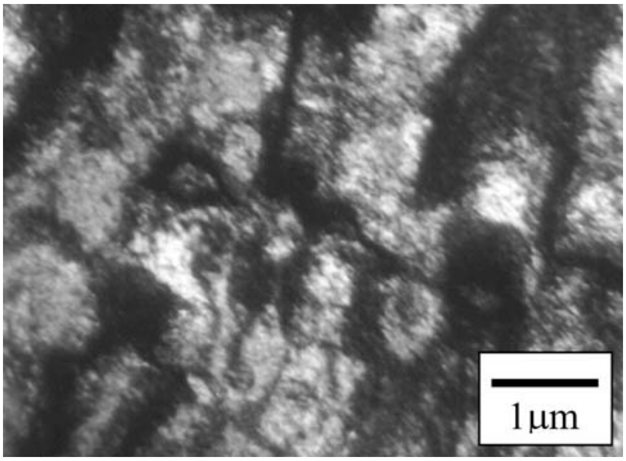

Fig. 13 TEM picture showing dislocation structure of the AISI 1010 steel drawn in 2 passes with one intermediate cyclic bending pass (specimen D1CB1D2)

also included in Fig. 12, for comparison with the results for cyclic bending between the drawing passes. It is clear that a final cyclic bending after drawing is much more effective in order to soften the material and increase its uniform elongation than cyclic bending between the drawing passes.

Figure 13 displays a typical dislocation structure found in specimen D1CB1D2. It can be observed that the "block" cell structure, observed in the specimens cyclically bent after one pass of drawing (Figs. 8 and 9) or after two passes of drawing (Fig. 11), is still basically kept, but the "blocks" are somewhat elongated and display a higher population of dislocations. Considering previous situations already discussed in the present paper, this modification in the dislocation structure is expected to cause a higher strength and lower uniform elongation of specimen D1CB1D2, in relation to specimen D2CB2, depicted in Fig. 12. Figure 14 shows the typical dislocation structure observed in the material subjected to 2 passes of cyclic bending between the 2 drawing passes. It is observed that a second cyclic bending pass between the 2 drawing passes (specimen D1CB2D2) led to a dislocation structure similar to that in Fig. 13, but with a lower dislocation density inside the cells, accounting for the lower strength of this material, in relation to specimen D1CB1D2, as shown in Fig. 12.

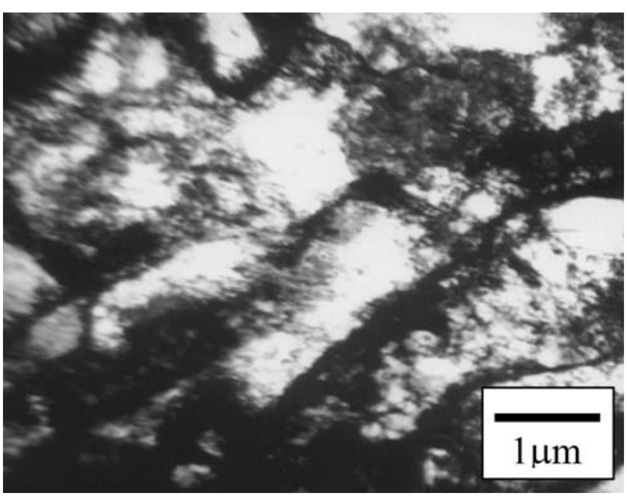

Fig. 14 TEM picture showing dislocation structure of the AISI 1010 steel drawn in 2 passes with two intermediate cyclic bending passes (specimen D1CB2D2)

Conclusions

- Cyclic bending softens and increases the uniform elongation in AISI 1010 cylindrical bars previously hardened by axisymmetric drawing.
- Cyclic bending leads to a change in the dislocation structure of the material, which evolves from elongated cells populated by dislocations to a "block" dislocation structure with larger cells than those in the as drawn material and populated with fewer dislocations.
- An increasing number of cyclic bending passes leads to a lower dislocation density inside the "blocky" cells and to thinner dislocation walls.
- Intermediate cyclic bending between two successive axisymmetric drawing passes is less effective, in order to soften the material, than cyclic bending passes after the final drawing pass.

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