THE EFFECT OF CYCLIC BENDING ON THE MECHANICAL PROPERTIES OF DRAWN STEEL BARS

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Abstract. *Many papers have shown that the work hardening of metals depends on its deformation history, or strain path, besides the temperature and strain rate. Monotonic straining normally hardens metals but changes in the strain path can lead to softening. This is particularly effective for cyclic straining. Thus, the use of a monotonic straining associated with cyclic straining enables the control of materials properties. The present paper shows that monotonic straining by drawing increases steel strength and decreases ductility. It is also shown that cyclic straining by cyclic bending decreases the drawn steel flow stress and increases elongation in tensile tests. The main point of the present paper is to show that different combinations of strength and ductility can be attained by mixing drawing and cyclic bending.*

1. Introduction

Metals behavior is described, as a rule, by a monotonic hardening with increasing strain. However, it has been observed that progressive strain hardening may not occur during cold forming operations. Changes in loading conditions such as the forming temperature, the strain rate and the strain-path lead to changes in the metal behavior.

Experiments with nickel and steel (Longo and Reed-Hill 1972, 1974) initially strained at 77K and later at 370K and 570K showed that the strain hardening rate decreases when the straining temperature increases. Tanner et al. (1999) studied the effect of changes in temperature during copper straining and showed that the strain hardening rate increased when the temperature decreased.

Tanner et al (1999) also showed that changes in the strain rate during testing also conducted to deviations in the work hardening behavior: increasing the strain rate enhanced the material strain hardening rate.

Polakowski and Palchoudhuri (1954) verified that the mechanical behavior of metals subjected to cold forming followed by cyclic straining is not characterized by strain hardening. Their results showed that drawn nickel exhibited softening caused by application of alternated compressive stresses. Coffin and Tavernelli (1959) also studied the mechanical behavior of metals subjected to cyclic deformation. They observed that hardening or softening may occur depending on the level and the type of pre-straining and also on the amplitude of deformation in the fatigue test. Hardening occurs in annealed metals while softening occurs in strained metals when cyclic strains are applied. Aguilar et al (2000) showed that drawn mild steel softened when subjected to cyclic torsion straining.

The control of the mechanical properties of metals using changes in strain rate and temperature are difficult, however changes in strain path, especially employing cyclic strains seems to be an interesting alternative for such a control. Drawing is an important industrial process of cold forming to produce wire, bars and tubes with excellent superficial finish and dimensional control. In this process the metal is highly deformed, causing its hardening and loss of ductility, which may lead to the need of annealing in some cases. Cyclic straining can be applied to reduce hardening of drawn wires, through the cyclic bending on rolls. This paper shows that the increase in steel strength produced by drawing process is related to a decrease in ductility. It is also shown that cyclic bending is an effective way to soften drawn steel, thus the combination of drawing and cyclic bending enables the control of steel bars mechanical properties.

2. Experimental Procedure

Experiments were performed on low carbon steel bars with 3,18mm diameter. The material composition is presented in table 1.

Table 1: Steel composition.

C	Mn	S	P	Si
0,108	0,51	0,014	0,019	0,202

Drawing was performed in a hydraulic draw bench with molybdenum dissulfide as lubricant . The dies used had a semi angle of 8º and final diameter of 2,9mm and 2,6mm for the first and second pass respectively.

Cyclic bending was carried in a special system adapted to the drawing machine. An illustration of the system is presented in figure 1. It consists of three aligned rolls with 52mm diameter and distant 83mm from each other. The bar is cyclically bent as shown in the figure. For one pass of cyclic bending the bar passed twice through the system with an intermediate rotation of 90º by its axis. After the process the initial and final portions of the bars were cut. Theses regions had only partly crossed the system and had different strain level than the rest of the bars.

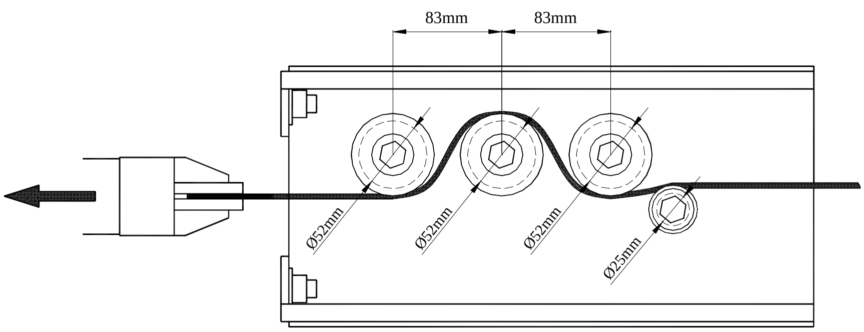

Figure 1 –Cyclic bending system.

Tensile tests were conducted in an Instron machine model 4482. The samples had a length of 100mm and different diameters depending on the number of drawing passes: 3,18mm in the as received condition, 2,9mm after the first drawing pass and 2,6mm after the second. The initial strain rate in the tests was $1{,}667.10^{-4}\ s^{-1}$. Load data were captured by a load cell with 100kN capacity and displacement data was captured by an electronic extensometer with 50mm of gauge length. Direct measurements of the minimum diameter and instantaneous load were performed after necking.

To evaluate de yield stress and the ultimate tensile stress, a conventional stress-strain curve determined by the equations 1 and 2 was used.

$$e = \frac{\Delta h}{50mm} \tag{1}$$

$$s = \frac{L}{A_0} \tag{2}$$

where e is the conventional strain, Δh is the displacement measured by the extensometer (50mm of gauge length), s is the conventional stress, L is the load and A_0 is the initial cross section area. The yield stress was considered as the stress at the intersection between the conventional curve and a line that begun at 0,002 of strain, parallel to the elastic portion of the curve. Ultimate stress was considered the maximum stress reached in the conventional curve.

Effective true stress-effective true strain curves, that henceforth will be called SS curves, were determined using equations 3 and 4 up to plastic instability and equations 5 and 6 after it.

$$e = \ln(e+1) \tag{3}$$

$$s = s*(e+1) \tag{4}$$

$$e = 2*\ln\left(\frac{d_0}{d_i}\right) \tag{5}$$

$$s = \frac{L}{A_i} \tag{6}$$

where ε is the effective true strain, σ is the effective true stress, d_0 is the initial workpiece diameter, d_i is the instantaneous diameter and A_i is the instantaneous workpiece cross section area.

Several marks, distant from each other the value of the bar diameter, were made in the tensile test workpieces prior testing. Equation 7 was used to evaluate the workpiece elongation to failure:

$$\text{elongation}\,(\%) = \frac{10d_f - 10d_o}{10d_0}*100 \tag{7}$$

where $10d_f$ is the distance between 10 marks in the workpiece, around the rupture region, after the test.

Uniform elongation was determined as the intersection between the SS curves and the strain-hardening rate curves, determined by the use of equation 8:

$$\text{Strain - hardening rate} = \frac{ds}{de} \tag{8}$$

Different conditions were analyzed and henceforth specific notations will be used to describe these conditions. The as received condition will be referred as AR, the drawn material will be referred as D1 and D2 for 1 pass and 2 passes respectively and D1CB and D2CB will refer to the material that was drawn in 1 and 2 passes respectively followed by cyclic bending.

3. Experimental results

SS curves of the bars in the as received condition and drawn in 1 and 2 passes are presented in figure 2. As expected, drawing hardens the material and the SS curves of the drawn bars are over the curve of the as received one.

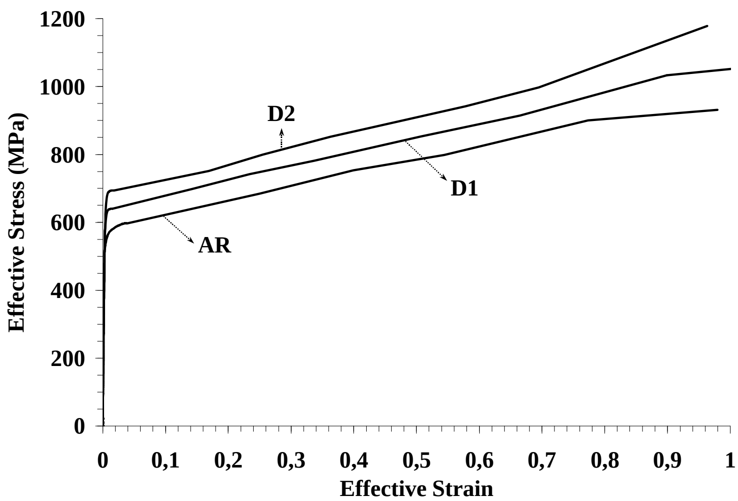

Figure 2 – SS curves of the bars in the as received condition (AR) and after 1 (D1) and 2 (D2) drawing passes.

However the typical strain hardening behavior observed in drawing is not observed after cyclic bending. Straining the material by cyclic bending actually softens the material. Figure 3 shows the SS curves of the bar drawn in one pass and the bar drawn and cyclic bent. The SS curve of the bar cyclic bent is below the curve of the bar just drawn.

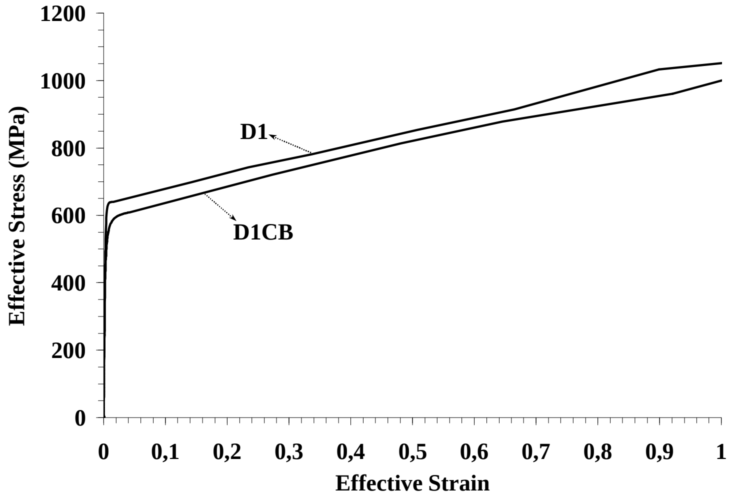

Figure 3 – Effective stress-effective strain curves of drawn in 1 pass bars without (a) and with (b) cyclic bending.

The same trend to decrease the material strength by cyclic bending is observed in the bar drawn in 2 passes as shown in figure 4. The SS curve of the material drawn in 2 passes and cyclically bent is below the curve of the material just drawn.

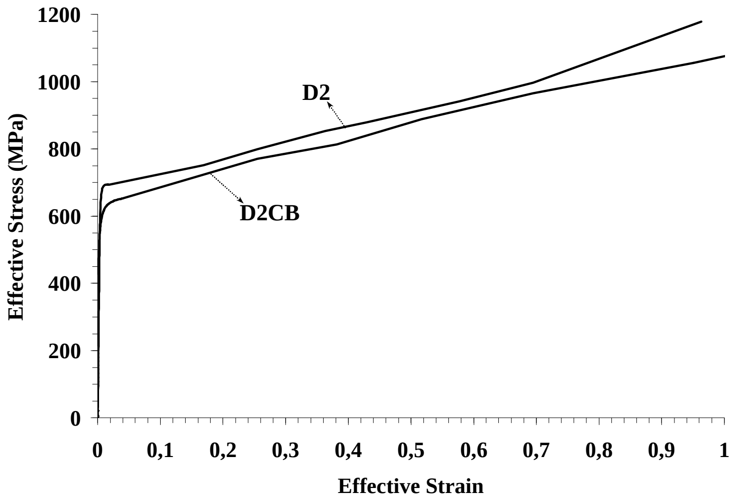

Figure 4 – Effective stress-effective strain curves of the bars drawn in 2 passes without (a) and with (b) posterior cyclic bending.

Although the softening effect caused by cyclic bending is observed in the whole SS curve, it is more pronounced in the beginning of plastic deformation. Figure 5 shows the SS curves (continuous lines) and the strain hardening rate curves (dashed lines) up to plastic instability in the tensile test of the bars drawn in 1 and 2 passes and drawn in 1 and 2 passes and cyclic bent. It is observed that the yield stress of the bar subjected to 2 passes of drawing and cyclic bending is lower than the yield stress of the bar drawn in only one pass but, the flow stress of the former quickly increases and becomes higher than the latter. The higher strain hardening capacity of the bars cyclically bent is verified by the higher strain hardening rate curve, that delays the intersection with the SS curve and increases the uniform elongation.

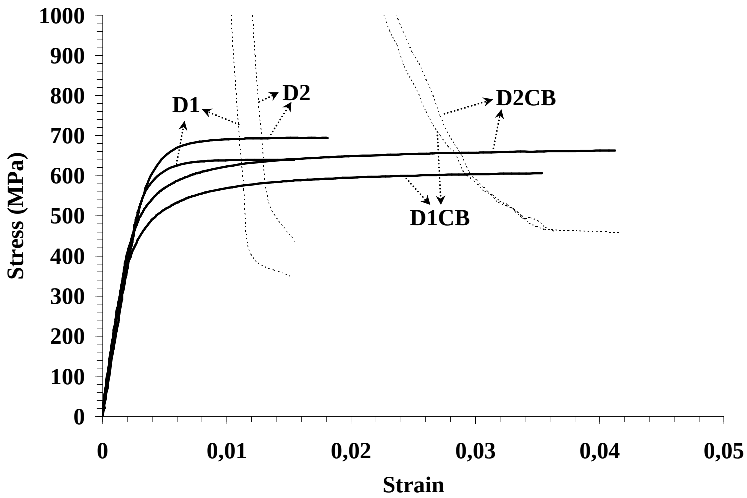

Figure 5 – Stress-strain and strain hardening rate curves of the bars drawn in 1 and 2 passes and drawn in 1 and 2 passes and cyclic bent.

Table 2 presents the results of yield stress, ultimate tensile stress, uniform elongation, elongation to failure and ratio between yield and ultimate stress for the samples analyzed. The material strength increases with drawing and the elongation to failure decreased, as expected. However, additional straining by cyclic bending reduces the yield and ultimate stress of the bars and increases the uniform and total elongation.

The comparison of the samples drawn in 1 pass and drawn in 2 passes and cyclic bent shows that cyclic bending does not only eliminate the increase in the material strength due to the second drawing pass but also increases the elongation to failure. It is worth to note that the uniform elongation of the latter is almost three times higher than the former.

An important parameter of safety is the relation between the ultimate and the yield stress, because it determines how much the material will deform before its load carrying capacity becomes unstable Drawing reduces this relation but cyclic bending increases it up to values higher than in the as received condition. In this way cyclic bending can be used to increase the safety of components utilizing drawn bars.

Table 2 – Mechanical properties of the steel bars in different conditions.

	Yield Stress (MPa)	Ultimate Stress (MPa)	Uniform Elongation	Elongation to failure (%)	Ultimate Stress/ Yield Stress
AR	532,15	575,79	0,031	13,16	1,082
D1	611,93	631,48	0,011	9,06	1,032
D2	652,76	678,88	0,013	7,67	1,040
D1CB	527,14	587,29	0,029	12,12	1,114
D2CB	559,73	633,87	0,029	11,83	1,132

4. Discussion

It is generally accepted that the stress required to produce plastic deformation (the flow stress) increases with accumulated plastic strain due to the accumulation of dislocations that get trapped after producing deformation (Lopes et al, 2004). This behavior was observed, in the present work, in drawing: when increasing the bar strain level, the flow stress also increased.

However the strain added by cyclic bending does not increase the flow stress, it actually decreases it. The softening effect is observed not only in the material strength but also in the elongation, which increases after the application of cyclic bending. The behavior of metals during cyclic deformation differs from monotonic deformation as the former exhibits lower saturation stresses. This is attributed to enhanced dynamic recovery mechanisms, associated with lower energy dislocation arrangements and strain localization in shear bands (Corrêa et al, 2003) (Korbel and Bochniak, 2004).

Softening of drawn steel (Aguilar et al, 2000) and aluminum (Aguilar et al, 1998), by the use of cyclic torsion, have already been observed. However the use of cyclic bending seems to be more adequate to industrial processes, in particular to wire drawing processes where the material can be cyclic bent in the rolls. The softening effect triggered by cyclic bending could be used to decrease the loss of ductility associated with successive drawing passes, and eventually replace annealing in some cases.

5. Conclusions

Drawing increases the material strength and this effect is higher when the number of drawing passes increases. Simultaneously, material ductility is reduced.

Additional strain by cyclic bending reduced the strength of drawn bars and increases their ductility. The softening effect produced by cyclic bending is higher when the material has been deformed to a higher level. The reduction in the yield stress and the increase in the elongation are higher in the bars drawn twice than in the bars drawn once.

The relation between ultimate and yield stresses increases after cyclic bending.

6. Acknowledgements

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8. Responsibility notice

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