MECHANICAL BEHAVIOUR OF AISI 430 PRESTRAINED IN ROLLING AND TENSION

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Abstract. This paper analyzes the influence of the type of prestrain (rolling or tension) and the amount of prestrain on the mechanical behavior of the as-received stainless steel AISI 430. The tests were performed in specimens with 0.60mm thickness at 0ºRD (Rolling Direction) and prestrained up to 10% and 14%, (effective strain), and later sheared monotonically in the same direction of the prestrain. These complex loading sequences, rolling/shear and tension/shear led to an unusual work-hardening behavior after the strain path changes. The material yields on reloading at a higher stress when compared with the monotonic loading, whatever the amount of the prestrain for both the loading sequences. For the rolling/shear sequence the decrease in the hardening rate after the strain path is more pronounced than for the tension/shear sequence, for both prestrain values. The obtained results demonstrate the dependence of the amount of the prestrain value and the first deformation mode on the mechanical behavior of the AISI 430 under orthogonal shear sequence.

***Keywords**: prestraining, strain path, rolling, shear test, work-hardening*

1. INTRODUCTION

In sheet metal forming processes such as deep drawing the material is submitted to complex strain paths with large plastic strains, which influence the mechanical behavior of metals, (Rauch *et al*. 2002 and Barlat *et al*. 2003). Recent research shows that the mechanical behavior of the metallic materials during the loading sequences depend mainly on the magnitude of the strain path change, that is characterized by the parameter α (cosine of the angles between the two vectors that represent the successive strain tensors, Schmitt et al. 1985) and on the material type, on the prestrain value and on the initial loading mode, (Schmitt *et al*. 1991; Fernandes and Vieira, 1997; and Peeters *et al*. 2002).

These strain path changes can generate unusual behaviors on the materials, such as work-hardening transients and instabilities that are correlated with the dislocation arrangements and the evolution of the crystallographic texture with the deformation mode, Nesterova *et al*. (2001). The Bauschinger effect (decrease in flow stress after reversing the direction of the deformation, commonly followed by and a temporary stagnation of the work-hardening) is associated with a partial disintegration of dislocation sheets, Gardey *et al*. (2005). For the cross hardening typical of orthogonal sequences such as tension/shear and shear/shear, the material presents a strong hardening followed by softening and then hardening again. In this case, TEM investigations (Rauch and Thuillier, 1993; Nesterova *et al*. 2001) reveal that these macroscopic effects are due the development and evolution of dislocation structures with intragranular localization of the deformation in microbands, Thuillier and Rauch (1995).

The aim of this work is to study the influence of the type and the amount of prestrain on the mechanical behavior of the as-received stainless steel AISI 430 (a ferritic stainless steel stabilized with niobium to prevent chromium oxide formation), employing two loading sequences: rolling/shear and tension/shear.

2. EXPERIMENTAL TECHNIQUES

AISI 430 stainless steel was used in the present experiments in the as-received state of sheets with 0.60 mm thickness at 0ºRD (Rolling Direction). The material was deformed using two loading sequences: rolling/shear and tension/shear with the same severity on strain path change, $\alpha = 0$, as defined by Schmitt *et al*. (1985).

2.1. Rolling/Shear sequence

In order to obtain the rolling/shear sequence, the AISI 430 sheets were rolled up to 10% or 14% effective strain, as defined by Hundy and Singer (1954-1955), using a Fröhling rolling mill with 200 mm diameter cylinders and rolling speed of 6.25 m/min, Fig.1.

Figure 1. Fröhling rolling mill.

The subsequent shear tests were conducted at 0º from the rolling direction using the same planar simple shear device presented by Lopes *et al*. (2007). This work employed the same AISI 430 stainless steel, in order to show the efficacy of the shear test to perform strain path changes through two loading sequences: orthogonal and Bauschinger (parameter $\alpha = 0$ and -1, respectively), Fig. 2. The Instron 5582 Test Machine then was adapted for shear testing, Fig. 3a, and the cross-head speed determined so that the shear strain rate was $0.002 s^{-1}$. The shear samples were 0.53 mm or 0.55 mm thick (t), 50 mm long (L), 15 mm wide (w) with a shear zone width of 3.50 mm (b), Fig. 3b.

The effective strain and effective stress were calculated from the shear strain and shear stress, respectively, using the parameter 1.84 as detailed in Rauch (1992). Eq. (1) and (2) were used to relate the effective stress, σ_{eff}, and effective strain, ε_{eff}, to the shear stress, τ, and shear strain, γ.

$$\varepsilon_{eff} = \gamma/1.84 \quad (1)$$

$$\sigma_{eff} = 1.84\tau \quad (2)$$

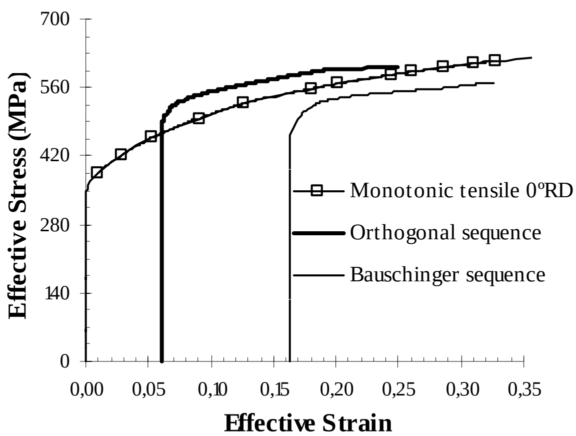
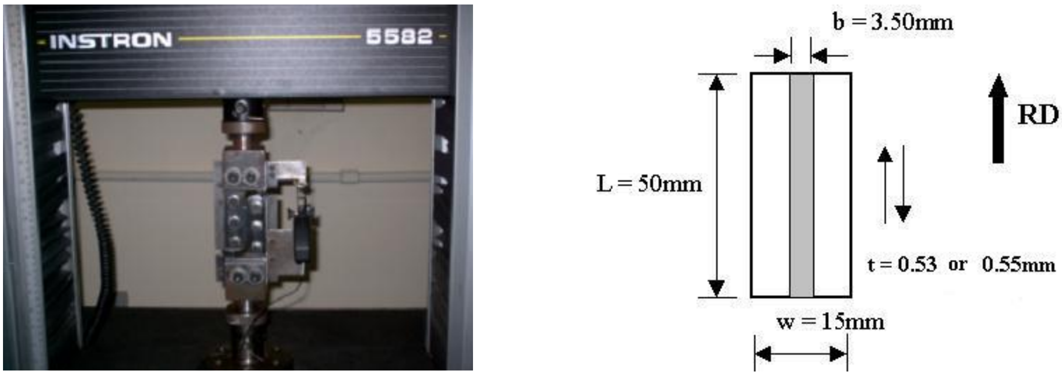


Figure 2. Effective stress – effective strain curve for AISI 430 under orthogonal and Bauschinger sequences (Lopes *et al*. 2007).

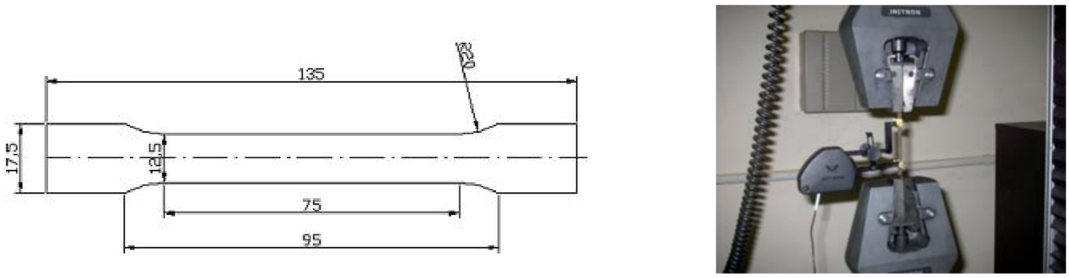


(a) (b)

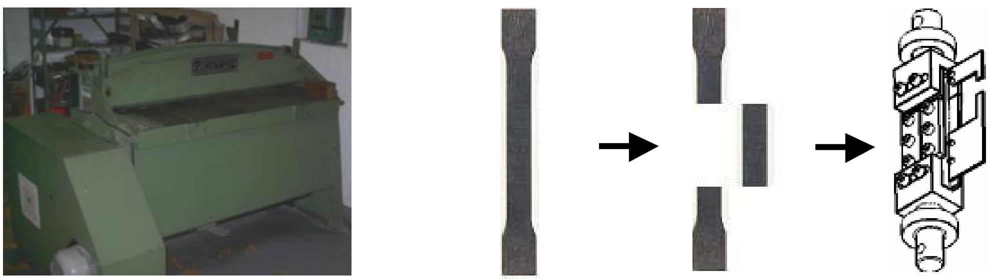
Figure 3. (a) Simple shear device mounted in the Instron 5582 Tests Machine; (b) geometry of the shear sample.

2.2. Tension/Shear sequence

For the tension/shear sequence, uniaxial tension tests in the rolling direction were carried out to prestrain the sheet before conducting the shear tests. The cross-head speed for the tension tests was 9 mm/min, resulting in the same strain rate used for shear tests, $0.002s^{-1}$. Samples with the geometry shown in Fig. 4(a) with thickness 0.60 mm were prestrained in tension up to 10% or 14% effective strain using an Instron Test Machine, Fig. 4(b). After the tension tests, the specimens were cut using a shear, Fig.4(c) and then the shear test was performed in the same direction of the previous tensile straining, Fig. 4(d). The severity on strain path change was equal the last sequence, $\alpha = 0$.



(a) (b)



(c) (d)

Figure 4. (a) Geometry of the tension sample; (b) tension test; (c) Newton shear; (d) simple shear in samples prestrained by tension.

3. RESULTS

Figure 5(a) shows the monotonic tensile effective stress-effective strain curves of the AISI 430 as well the same curves after pre-straining by rolling up to 10% or 14%. Fig. 5(b) exhibits the normalized hardening rate-effective strain curves for these conditions. The onset of the strain localization occurs when the reduction in the hardening rate, θ, is sufficient to cause $\theta.1/\sigma$ to fall below unity, Zandrahimi *et al*. (1989).

For both 10% and 14% of prestrain, the second stage of deformation presents higher stress values when compared with the monotonic loading, but the difference between them is small. Fig. 5(b) displays hardening rate transients for both prestrain values. For 10% the transient stage is shorter than that observed for 14%, and involves a rapid hardening rate recovery.

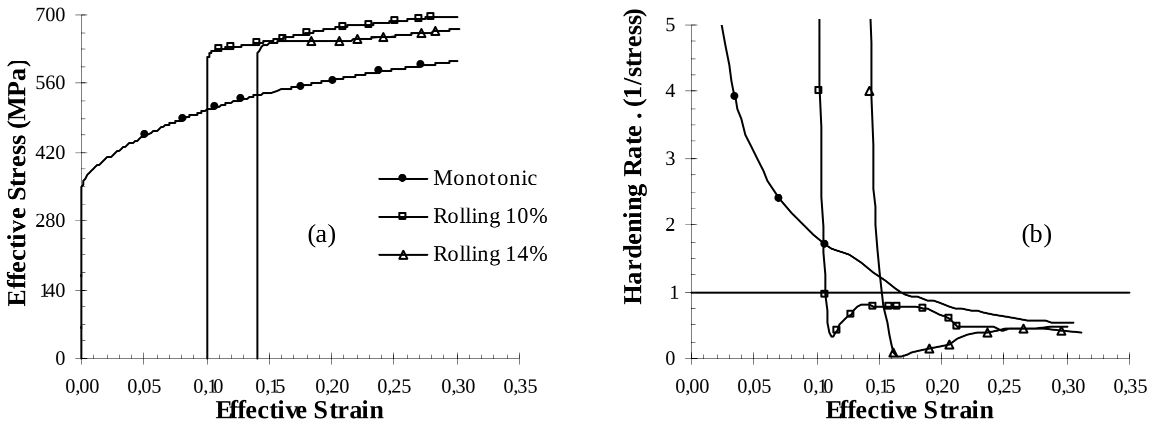


Figure 5. Rolling/shear sequence with prestrain up to 10% and 14%, effective strain (a) effective stress-strain curves; (b) normalized strain-hardening rate versus strain curves.

Figure 6 presents the same type of curves shown in Fig. 5 but now for the other initial loading mode: tension. For this situation, the flow curves after both prestrain values are also above the curve for the monotonic test. The increase in the yield stress after the strain path change, however, is lower than that observed in the rolling/shear sequence. Hardening rate transients are also observed in this loading sequence, but the transients are milder than for the rolling/shear sequence.

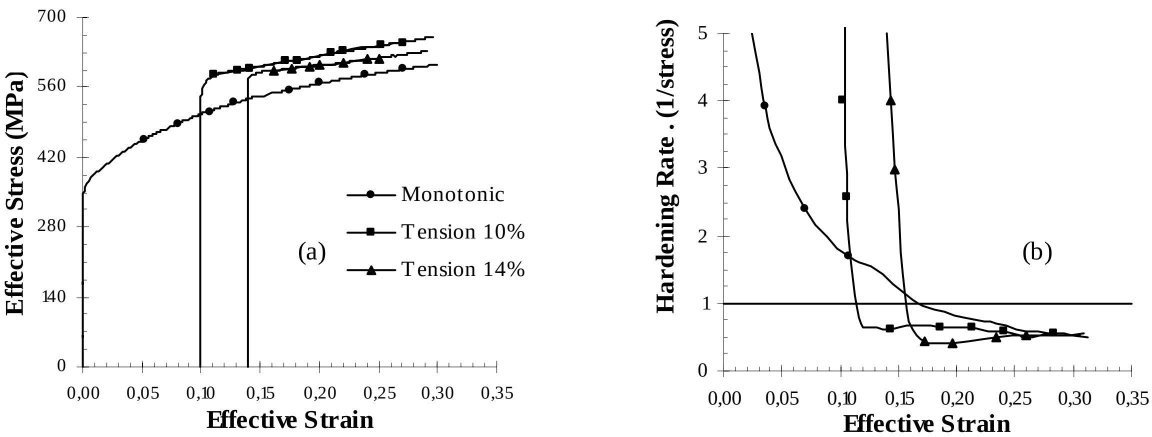


Figure 6. Tension/shear sequence with prestrain up to 10% or 14% (a) effective stress-strain curves; (b) normalized strain-hardening rate versus strain curves.

The effect of the two types of prestrain for the two values of deformation, 10% and 14%, is compared through the Fig. 7 (10% prestrain) and 8 (14% prestrain). Fig. 7(a) shows the effective stress-effective strain curves of the AISI 430 prestrained by rolling and tension up to 10% and Fig. 7(b) presents the normalized hardening rate-effective strain curves. Both the prestrain modes lead to an initial flow stress higher than the stress reached on the monotonic curve. For the material prestrained in rolling the increase of the yield stress on reloading is higher than for tension, although the severity of the strain path change is the same (α = 0), Fig. 7(a). For the material prestrained in rolling, the hardening rate transient is more pronounced than for tension.

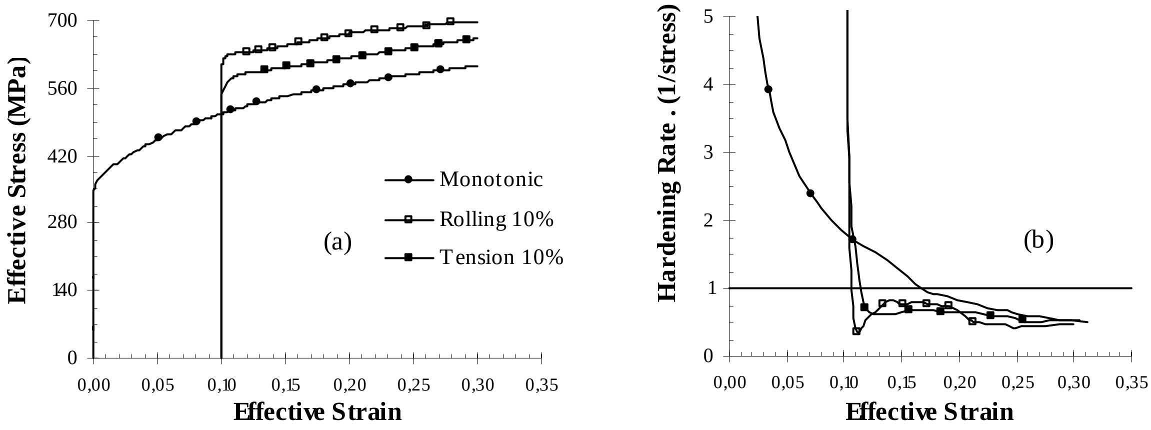


Figure 7 Rolling/shear and tension/shear sequences with prestrain up to 10% (a) effective stress-strain curves; (b) normalized strain-hardening rate versus strain curves.

For the prestrain value of 14%, the yield stress value on reloading is higher than for 10% for both loading sequences. Figure 8 reveals that the reloading yield stress after rolling is higher than after tension. The specimen prestrained in rolling presents an abrupt fall in the hardening rate followed by a short process of recovery and then a decrease in the hardening. The material prestrained in tension has a similar behavior, but the decrease in the hardening rate is less pronounced and followed by an almost constant hardening rate.

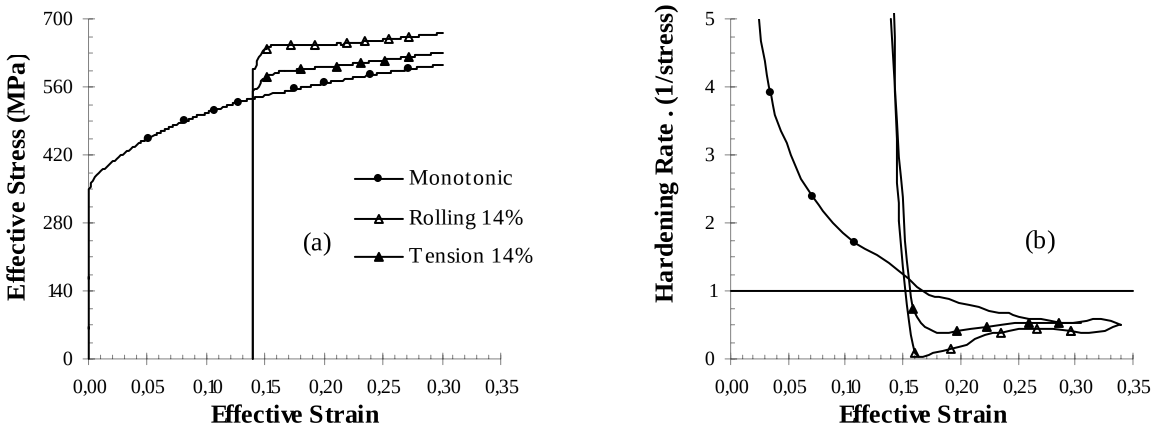


Figure 8. Rolling/shear and tension/shear sequences with prestrain up to 14% (a) effective stress-strain curves; (b) normalized strain-hardening rate versus strain curves.

4. DISCUSSION

This paper analyses the influences of the amount of prestrain (ε_{eff} = 10% e 14%) and of this initial deformation mode (rolling or tension) on mechanical behavior of AISI 430 stainless steel after strain path changes under two loading sequences: rolling/shear and tension /shear at 0ºRD (Rolling Direction). These loading sequences are classified as orthogonal sequences, i.e., the cross product of the two strain rate tensors describing the imposed strain path change is equal to zero, Schmitt *et al.* (1985).

The orthogonal sequence involves the activation of previously latent slip systems that were generated during the prestrain, Rauch (1992). Moreover, two phenomena are associated with this loading sequence: an increase of the flow stress at the beginning of the second stage of the deformation followed by a macroscopic work-softening. The latter is connected to the appearance of microbands that shear the preformed dislocations walls and cause a decrease in the stress, Bouvier *et al.* (2005). Transmission Electron Microscopy (TEM) investigations show that these macroscopic effects are due to the development and evolution of dislocation structures (Rauch and Thuillier, 1993; Nesterova *et al.* 2001).

The common characteristic for both loading sequences used in this study is the existence of a high initial flow stress followed by a lower hardening rate when compared with the monotonic deformation at the same accumulated strain.

The intensity of these phenomena, however, was different for the two types of the prestrain, although the material (AISI 430), the state of the material (as received) and the severity of the strain path change, (α=0) were kept constant.

Wilson and Bate (1994) concluded that the magnitude of the increase in reloading yield stress and the amplitude of the subsequent reduction in work-hardening depend on the strength of dislocations walls generated in the prestrain rather than the grain size, for tests in sheets of interstitial-free steel prestrained in rolling followed by uniaxial tension tests at 90ºRD (α=0). The dislocation walls preformed in the prestrain can act as strong barriers to dislocation glide of the dislocations in the slip systems, which intersect the walls. However, the effective strength of these barriers depends on the local dislocation density, the strain path mode and the amount of the prestrain. Fig. 5 and 6 show that larger amounts of prestrain increase the effective strength of these barriers for both sequences, as pointed out by Li e Bate (1991) through experiments with cube textured aluminum sheet prestrained in tension at 0ºRD followed by tension at 45º (α=0,5) and 90ºRD (α=0). This means that it is more difficult to disintegrate the preformed microstructure for larger prestrain value. Therefore, the reduction in hardening rate is higher for 14% prestrain.

Fernandes and Vieira (1997) also verified the effect of the prestrain value on the hardening rate transient with copper prestrained in rolling followed by tension at 90ºRD (α=0). At a given stress, the hardening rate is lower after reloading than for a monotonic test; this effect is greater for large prestrain values.

The strain path change leads to a transient behavior in the hardening rate. The primary cause of the subsequent reduction in hardening rate is the disruption and partial dissolution of the original dislocation substructure, Li e Bate (1991). After strain-path changes, reinforcement, dissolution or rearrangement of the previously formed dislocation walls seem to be responsible for (or at least associated with) the transient work-hardening regime observed at the earlier stages of subsequent loading (e.g. stagnation, softening), Rauch and Schmitt (1989).

In the present study, the hardening rate decreases to a value that depends on the initial deformation mode. For the rolling/shear sequence the minimum value of the hardening rate is higher than for the tension/shear sequence, as shown in Fig. 7 and 8. This situation is more noticeable with the largest prestrain value, 14%. After the rapid decrease in the hardening rate, there is a hardening recovery towards the levels typical of monotonic deformation. The rate of this recovery, however, is higher for the rolling/shear sequence. The length of the hardening rate transient in rolling/shear sequence is higher than under tension/shear. This indicates that in the tension/shear sequence the preformed microstructure is more easily destabilized by the subsequent loading (shear) than for the rolling/shear sequence, Haddadi *et al.* (2006). The final recovery in the hardening rate is caused by the generation of a new substructure compatible with the new deformation mode and varies widely in different materials, Wilson and Bate (1994). For materials such as a low-carbon ferritic steel and CP aluminum alloys with high stacking fault energy, SFE, ($\approx$200 $mJmP^2$) the rate of recovery is more rapid than for an austenitic stainless steel as 304 with low SFE ($\approx$20 $mJmP^2$), Zandrahimi *et al.* (1989).

5. CONCLUSIONS

Strain path changes in AISI 430 stainless steel under rolling/shear or tension/shear loading orthogonal sequences indicate that:

a) There is an increase of yield stress and a transient behavior in the hardening rate after these strain path changes;
b) The mechanical behavior of the material after the strain path changes depends on the amount of prestrain and on the initial deformation mode;
c) Larger prestrains lead to larger increases of the yield stress on reloading and to longer hardening rate transient;
d) The effects of the strain path changes were more pronounced for the rolling/shear loading sequence than for the tension/shear one.

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