THE EFFECT OF THE INITIAL STATE AND THE CYCLIC STRAIN AMPLITUDE ON THE WORK HARDENING OF BRASS SHEETS

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Abstract. *The work hardening characteristics presented by a material after a given mechanical processing route are influenced by several variables, such as the initial state of the material. The susceptibility to occurrence of phenomena detected in complex loading sequences, such as work hardening stagnation depends, for example, on the initial conditions of the material.The present article analyzes the influence of the initial hardness of the material (annealed or work hardened) and of the effective cyclic strain amplitude (0.10 and 0.25) on the work hardening of brass CuZn34 sheets. The results indicate that the work hardening evolution after cyclic loading depends on the initial state of the brass sheets, but this difference in the behaviour is lower for larger cyclic strain amplitude, probably due to substructure evolution.*

Keywords*: cyclic test, shear test, strain path, brass, work hardening.*

1. INTRODUCTION

The deformation mode is one of the main variables in the work hardening of metals (Rauch 2000). Considering, the same deformation mode, other variables are also important, such as the initial conditions of the material with regard to its crystalline structure, level of pre-strain and anisotropy. However, the effects of these variables, considering complex modes of plastic deformation, are not fully understood, (Hughes, 1992).

Considering loading sequences involving a reversion in the deformation direction (Bauschinger or cyclic loading), the work hardening of the material is affected by the evolution of the dislocation sub-structure, from both its spatial distribution and density aspects (Rauch *et al*. 2002 and Rauch *et al*. 2007).

Figure 1 (Rauch *et al*. 2007) illustrates the influence of anisotropy (loading direction) on the work hardening of the AA1050-O aluminum alloy, which was submitted to a Bauschinger type test involving a direct and a reverse loading in two directions: 0° or 45° to the rolling direction (henceforth referred to as RD). Figure 1a shows that the test at 0ºRD led to initial stress stagnation and low hardening rates, whereas testing at 45° involved similar results, but at more intense and at a substantially lower stress levels than at 0°RD (see Fig. 1b). This difference in the material behavior when tested in two directions is associated with its crystallographic texture evolution, associated with the reduction in the Taylor factor upon load reversal.

The initial state of the materials is frequently changed through heat treatments in order to adjust their properties for specific applications, and profoundly affect the subsequent hardening behavior of the material. The present paper analyzes the effect of the initial conditions of initially annealed or pre-strained CuZn34 brass sheets and the plastic strain amplitude on its hardening behavior caused by simple planar cyclic shearing.

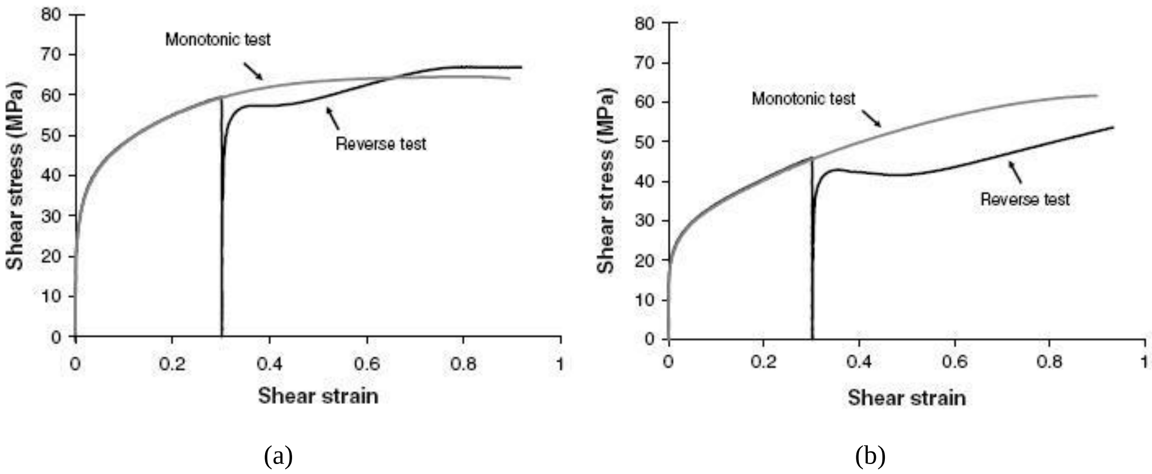


Figure 1. Shear stress versus shear strain curves for AA1050-O aluminum alloy under Bauschinger test: a) reverse shear along the rolling direction (0°RD) and b) reverse shear at 45° to the rolling direction (45°RD), Rauch *et al*. (2007).

2. MATERIALS AND METHODS

2.1 Material

The chemical composition (weight percent) of CuZn34 (yellow brass, C-268 alloy) brass sheets 0.5mm thick is shown in Table 1. This material was used at initially work hardened or annealed conditions, with initial hardness of 130 ± 2HV and 90 ± 3HV, respectively. The material was received in the work hardened condition, and the annealing was performed at a temperature of 540°C for 5400s.

Table 1. Chemical composition (weight percent) of CuZn34 brass.

CuZn34 brass	
Cu	65.75
Zn	34.19
Pb	0.010
Fe	0.025

2.2 Cyclic shear loading

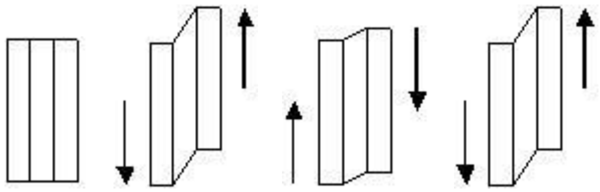
Planar cyclic shearing was performed with a specially built shearing device, coupled to a 5582 INSTRON universal tester. The shearing strain (γ) was calculated dividing the vertical grip displacement (ΔY) by the width of the sheared region (b). The shearing stress (τ) was evaluated dividing the shearing load (P) by the area being sheared, i.e., specimen length, (L), x specimen thickness (t).

The conversion of the shearing strains and stresses into effective strains (ε_e) and effective stresses (σ_e), respectively, was performed utilizing equations (1) and (2), where the conversion factor of 1.84 represents an average of the Taylor factors, as demonstrated by Rauch (1992).

$$\varepsilon_e = \gamma / 1.84 \tag{1}$$

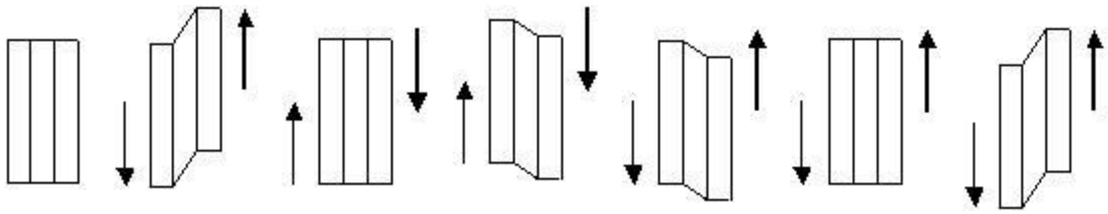
$$\sigma_e = \tau \,.\, 1.84 \tag{2}$$

The work hardened and the annealed specimens were initially submitted to an effective strain of 0.15 in the so-called forward shearing direction. In order to obtain two effective strain amplitude values, these specimens were then cyclically sheared following two sequences. The first one, $\Delta\varepsilon = 0.10$, is illustrated in Fig. 2, and included an initial forward shear with an effective strain of 0.15 (Fig. 2b), a partial back shearing with an effective strain of 0.10 (Fig. 2c) and a forward shearing with an effective strain of 0.10 (Fig 2d). These cycles were then repeated. The second sequence, $\Delta\varepsilon = 0.25$, is illustrated in Fig.3. This step involved an initial forward shearing also with an effective strain of 0.15 (Fig. 3b), followed by a reverse shearing with the same level of strain (Fig 3c), which was continued for a further effective strain of 0.10 (Fig 3d, involving a total effective strain of 0.25), followed by a full forward shearing (Figs 3e, 3e, 3f). These cycles were then repeated.



(a) (b) (c) (d)

Figure 2. Specimen shearing during the cyclic test with $\Delta\varepsilon$ = 0.10: (a) non-deformed, (b) prestraining up to 0.15 under forward shear, (c) reverse shear up to 0.10 and (d) last step of cyclic route: forward shear up to 0.10.

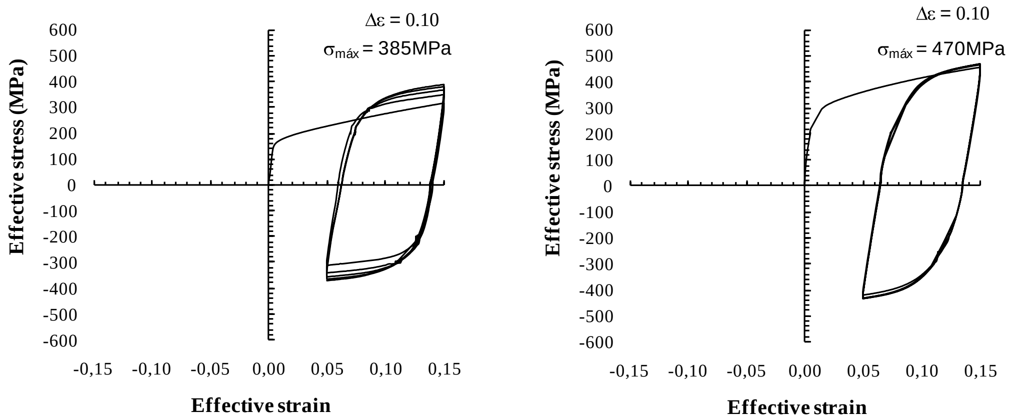


(a) (b) (c) (d) (e) (f) (g)

Figure 3. Models of the shear specimen during the cyclic test with $\Delta\varepsilon$ = 0.25: (a) non-deformed, (b) prestraining up to 0.15 under forward shear, (c) reverse shear of 0.15 (d) additional reverse shear of 0.10 (e) start of forward shear (f) forward shear up to 0.15 and (g) additional forward shear up to 0.25.

3. RESULTS and DISCUSSION

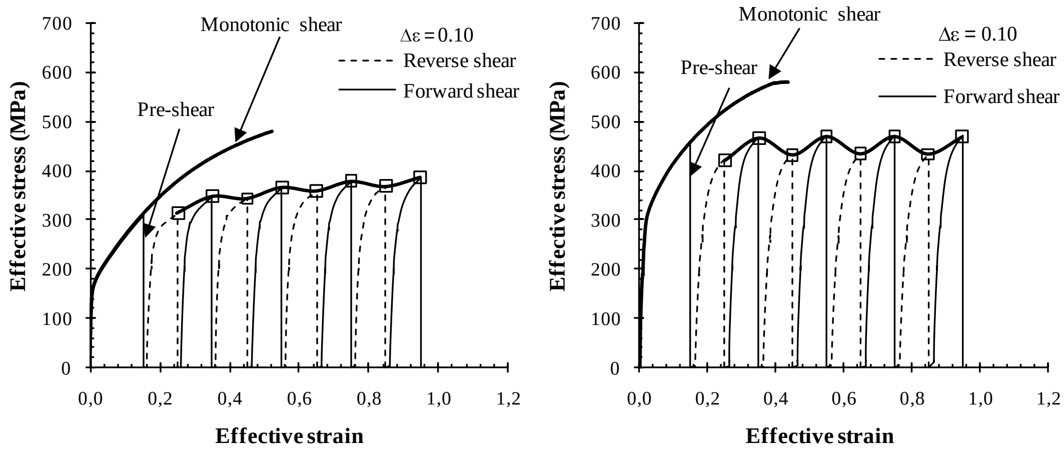
Figure 4 exhibits the cyclic effective stress-effective strain curves (henceforth called cyclic SS curves) for the strain amplitude of 0.10 and the initially annealed (Fig. 4a) or work hardened (Fig. 4b) material. The maximum stress ($\sigma_{máx}$) reached by the annealed samples was approximately 18% lower than the same stress for the initially work hardened materials. On the other hand, the difference between the monotonic shearing and the cyclic one is, in both cases about the same, and about 20%.



(a) (b)

Figure 4. Effective stress versus effective strain curves obtained after the cyclic test with $\Delta\varepsilon$ = 0.10: (a) annealed brass and (b) work hardened brass.

Figure 5 shows the cyclic effective stress-effective strain curves displayed in Fig.4, but the effective stresses and strains are considered always positive, and the effective strains are thus considered cumulatively. The curves joining the stress maxima in the cyclic loading show an oscillating character, and the curve for the initially work hardened material displays higher amplitude of oscillation than that for the initially annealed material. This suggests that the dislocation structure in the initially work hardened material is less stable than that in the initially annealed material, undergoing a higher degree of cyclic re-organization Rauch *et al*. (2002).



(a) (b)

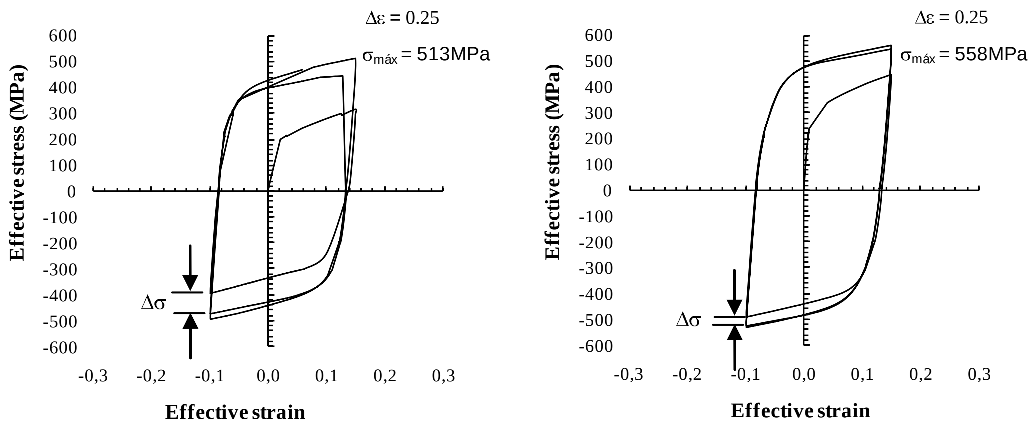
Figure 5. Effective stress versus accumulated effective strain curves after cyclic test with $\Delta\varepsilon = 0.10$: (a) annealed brass and (b) work hardened brass.

Brass presents a FCC structure with low stacking fault energy (SFE), where monotonic straining leads to planar and regular dislocation arrays (Chung and Lee 1993). For the same pre-strain, higher cyclic plastic strain amplitudes and the initial state of the material (annealed or work hardened) affect the stability of this structure during cyclic shearing re-loading. Higher back stresses in the work hardened material would be responsible for a higher degree of disorganization during the cyclic shearing of the initially work hardened material, (Rauch *et al*. 2002).

Figure 6, similarly to Fig. 4, exhibits the cyclic SS curves for the initially annealed or work hardened brass for effective strain amplitude of 0.25. Both materials display similar levels for the maximum annealed stress, which differed by only 8% (513MPa for the initially annealed material and 558MPa for the initially work hardened material). On the other hand, the ratio of the flow stress at the end of the reverse shearing in the first and in the second cycles ($\Delta\sigma$), is 1.20 for the initially annealed material but only 1.07 for the initially work hardened material. The difference between these flow stresses decrease as the number of cycles increase, indicating a stabilization of a new dislocation structure. Figure 7, similarly to Fig. 5, shows the cyclic SS curves for the material cycled with a strain amplitude of 0.25, but now considering both the effective stresses and the effective strains as positive. Once again, the curve connecting the flow stress maxima for the direct and reverse cycles display an oscillating character, but now the oscillation amplitude is similar for both initially annealed and initially work hardened material. The cyclic strain amplitude of 0.25 thus seems to be sufficient to eliminate the effect of the different initial states of the material. This was not observed for the cyclic strain amplitude of 0.10.

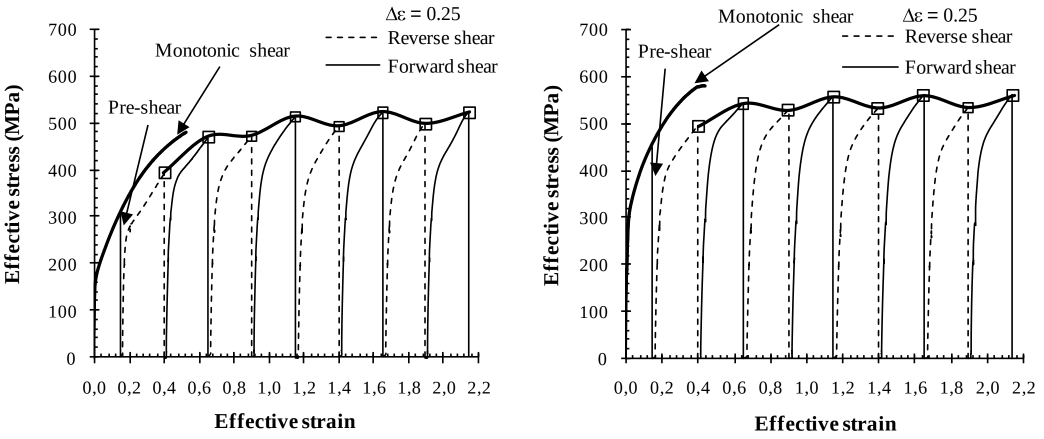
Figure 8 displays the average flow stress amplitude for each step of the cycle (reverse and forward shear), for both cyclic strain amplitudes analyzed in the present paper. Figure 8a indicates that the difference between the average stresses for the forward and the reverse shears, for the strain amplitude of $\Delta\varepsilon = 0.10$ decreases with the number of cycles for both initially annealed and initially work hardened material, probably due to the increasing back stress acting in the direction of favoring the destruction of the dislocation sub-structure establishes during the previous work hardening. On the other hand, the absolute value of the average stress for the initially annealed material is lower than that for the initially work hardened material. This is probably associated with the relatively low value of the strain amplitude (0.10). The increase in the deformation level connected to the rise of the strain amplitude from 0.10 to 0.25 leads to an increase in the average stresses in both the forward and reverse shearing of the initially annealed material. These stresses thus reach values close to those for the initially work hardened material. It can also be observed that the difference between the average stresses in the forward and in the reverse shearing increase with the cyclic strain amplitude; especially for the initially annealed material. On the other hand, it can be seen that for both initial conditions of the material, the average stresses tend to saturate for increasing cyclic deformation amplitude (see Fig. 8b).

According to Rauch *et al*. (2007), for the same level of pre-strain, the fraction of the dislocation density which is annihilated with the reversion of the direction of plastic deformation increases with the cyclic deformation amplitude. This leads to an increase in the difference between the average stress in the forward and in the reverse shearing. However, as the number of cycles (and thus the total strain) is increased, this difference decreases, especially for the initially work hardened brass, probably due to the establishment of a new dislocation sub-structure. As previously discussed, the increase in the difference between the forward and the reverse shearing in the initially annealed material is probably connected to the increased disorganization of the dislocation sub-structure, for the cyclic strain amplitude of 0.25.



(a) (b)

Figure 6. Effective stress versus accumulated effective strain curves after cyclic test with $\Delta\varepsilon = 0.25$: (a) annealed brass and (b) work hardened brass.



(a) (b)

Figure 7. Effective stress versus accumulated effective strain curves after cyclic test with $\Delta\varepsilon = 0.25$: (a) annealed brass and (b) work hardened brass.

One can thus conclude that in the present situation, for a pre-strain of 0.25, the effect of the strain path on the work hardening of the initially work hardened brass is small, and its behavior is similar to that for the initially annealed material. Figure 9 displays the curves for the normalized work hardening rate (θ . $1/\sigma$, where $\theta = d\sigma/d\varepsilon$) vs. effective strain for the same situations shown in Fig. 7. The analysis of this figure indicates that for a cyclic strain amplitude of 0.25, the material in both conditions (initially annealed or work hardened) displays work hardening transients, whose magnitude increases with the total amount of straining. A value of $\theta.1/\sigma$ below unity indicates the occurrence of plastic instability during tensile deformation (Zandrahimi *et al*. 1989). Figure 9 indicates that the initially annealed material undergoes such instability only after the reverse shearing in the 2nd cycle.

It should be remembered that each cycle includes a forward and a reverse shearing, and that such work hardening transients are probably connected to the repeated instability of the dislocation sub-structure developed in the previous cycle. It is possible that for a large number of cycles the material would eventually evolve into a stable dislocation structure, which would then display no such work hardening gradients. It is also believed that such a situation will depend on the cyclic plastic strain amplitude. On the other hand, Vincze *et al*. (2005), Rauch *et al*. (2007) and Shigesato and Rauch (2007) concluded that the dislocation distribution, by itself, does not control the work hardening rate during Bauschinger type strain paths. The controlling aspect would be linked only to the dislocation density. Their conclusion was based on the fact that different dislocation arrangements lead to similar work hardening transients upon strain reversals, in situations where the crystallographic texture has no influence. On the other hand, it is possible the dislocation structure re-arrangements are related to changes in the dislocation density.

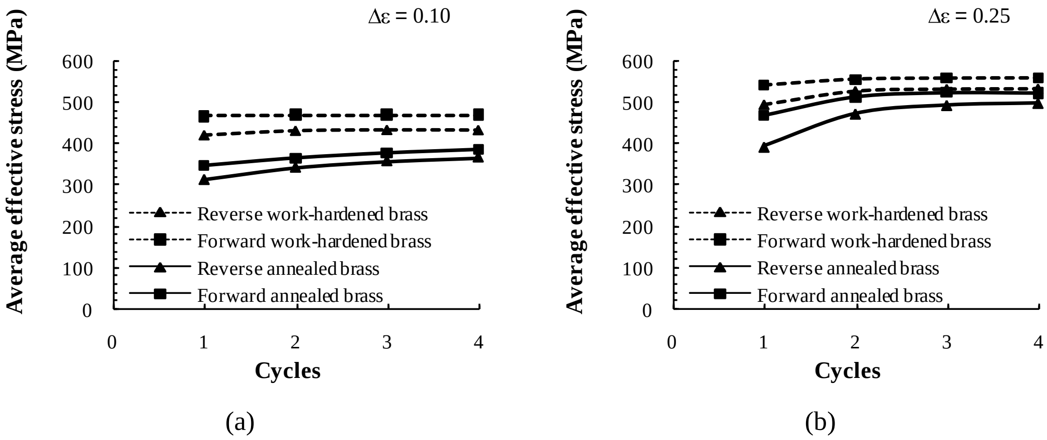


Figure 8. Average effective stress versus number of cycles for plastic strain amplitude of: (a) 0.10 and (b) 0.25.

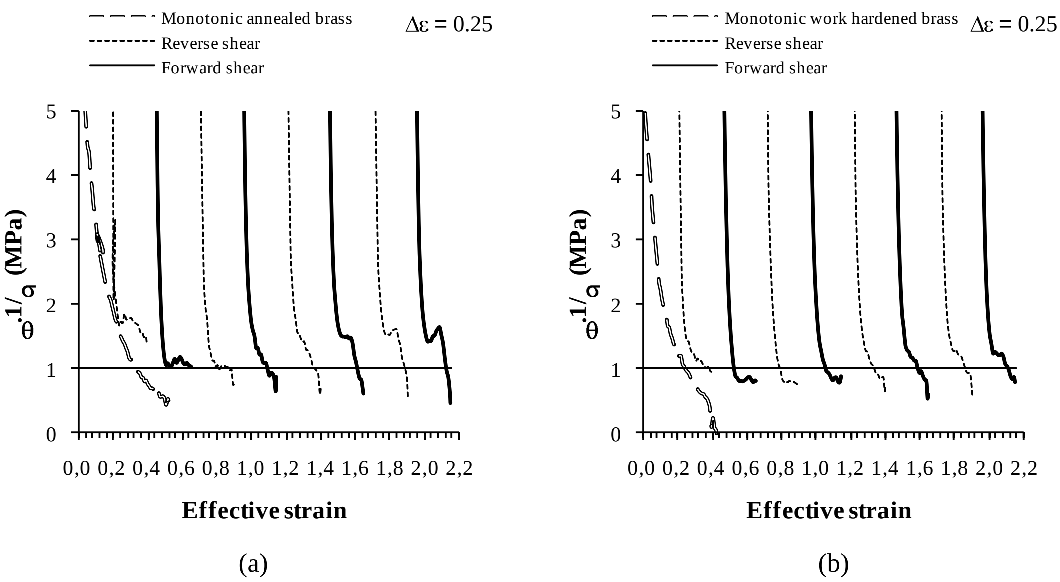


Figure 9. Normalized work hardening rate versus effective strain for cyclic strain amplitude of $\Delta\varepsilon = 0.25$: a) annealed brass and (b) work hardened brass.

The comparison of Fig. 9a and 9b reveals that in the 1st deformation cycle the reverse deformation displays a work hardening transient that is much more pronounced in the initially annealed material than in the initially work hardened material. This fact can be easily seen in Fig. 10. It is thus clear that the initial forward straining of 0.15 in the annealed material is not able to establish a relatively stable initial dislocation sub-structure, which is strongly disorganized in the reverse cycle. This is not the situation for the initially work hardened material, where the pre-strain, added to the initial 0.15 strain in the forward direction, were able to establish a relatively stable dislocation sub-structure, displaying a mild work hardening transient upon reverse shearing.

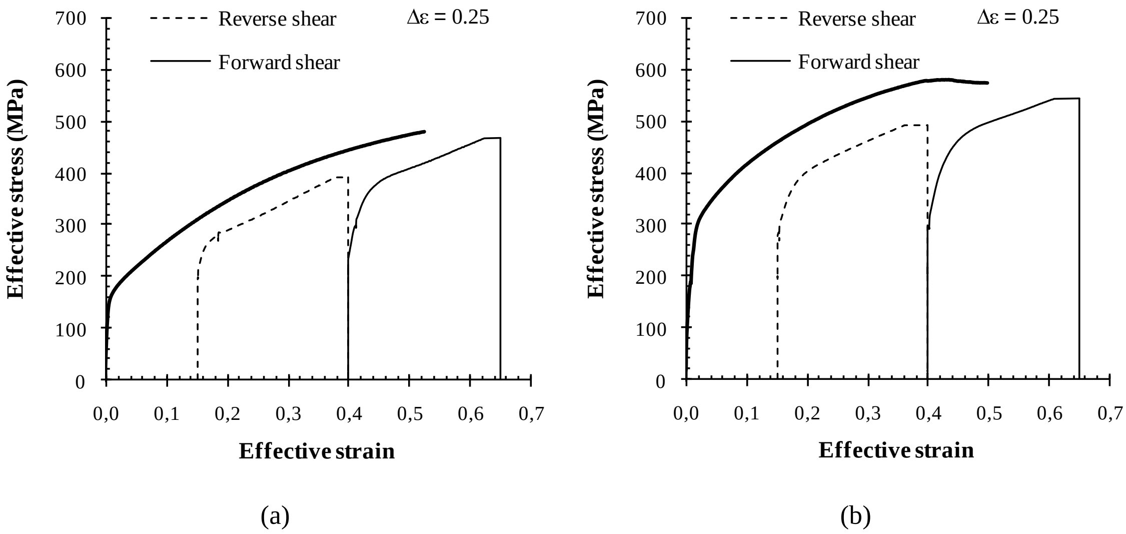


Figure 10. Effective stress versus effective strain for first cycle with $\Delta\varepsilon = 0.25$: a) annealed brass and b) work hardened brass.

4. CONCLUSIONS

The cyclic strain loading composed by five cycles and two strain amplitudes (0.10 and 0.25) applied to annealed and pre-worked CuZn34 brass indicate that:

a) A distinct mechanical behavior for the initially annealed or work hardened material, for a cyclic strain amplitude of 0.10;
b) The level of the maximum stresses reached at the end of the successive cycles depends on the initial state of the material (annealed or work hardened);
c) The differences between the average stresses in the forward and reverse shearing decreases with the number of cycles and with the cyclic strain amplitude;
d) The effect of the previous strain history of the material is erased by the cyclic shearing of the initially work hardened material with a cyclic strain amplitude of 0.25;

Both the initially annealed and initially work hardened material displayed work hardening transients followed by instabilities in tensile deformation for cyclic shearing with a strain amplitude of 0.25; this instability occurs at lower strains for the initially work hardened material than for initially annealed material.

5. ACKNOWLEDGEMENTS

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