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EFFECT OF THE THERMO-MECHANICAL PROCESSING CHARACTERISTICS ON THE RECRYSTALLIZATION OF THE CuZn34 BRASS[1]

Wellington Lopes[2]
Elaine Carballo Siqueira Corrêa[3]
Haroldo Béria Campos[4]
Maria Teresa Paulino Aguilar[5]
Paulo Roberto Cetlin[6]

Abstract

The effect of the temperature and the time annealing on the characteristics recrystallization of metals have been widely researched. However, the influence of the history deformation, involving changes in the strain path on the recrystallization results of the metals is still fewer studied. Considering this, o aim of this paper was to investigate the effect of the loading sequence (Bauschinger tests), the pre-strain amount under forward shearing (effective strain of 0.10, 0.20 and 0.30) and the initial state (as-received and annealed) on the recrystallization process of the CuZn34 brass sheets. The results obtained from shearing and hardness tests and optical microscopy indicated that the softening presented by the brass tends to reduce with the amount of the reverse strain and pre-strain values, for the same conditions of thermo-mechanical processing. These data also revealed that the initial state and the amount of the reverse strain were the main variables on the recrystallization kinetics of the CuZn34 brass.

Keywords: Brass; Recrystallization; Shearing test; Strain path.

EFEITO DAS CARACTERÍSTICAS DO PROCESSAMENTO TERMO-MECÂNICO NA RECRISTALIZAÇÃO DO LATÃO CuZn34

Resumo

O efeito da temperatura e do tempo de recozimento nas características de recristalização dos metais tem sido pesquisado intensamente. No entanto, a influência da história de deformação, envolvendo mudanças na trajetória de deformação, na recristalização dos metais ainda é pouco estudada. Considerando isso, o objetivo deste trabalho foi investigar o efeito da sequência de carregamento (testes Bauschinger), da quantidade de pré-deformação sob cisalhamento direto (deformação efetiva de 0,10, 0,20 e 0,30) e do estado inicial (como recebido e recozido) no processo de recristalização do latão CuZn34. Os resultados obtidos a partir de ensaios de cisalhamento e de dureza e microscopia óptica indciaram que o amaciamento apresentado pelo latão tende a reduzir com o aumento dos valores de pré-deformação e de deformação reversa, para as mesmas condições de processamento termo-mecânico. Esses dados também revelaram que o estado inicial e a quantidade de deformação são as principais variáveis na cinética de recristalização do latão CuZn34.

Palavras-chave: Latão; Recristalização; Ensaio de cisalhamento; Trajetória de deformação.

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2 *Professor, Federal Center of Technological Education of Minas Gerais – CEFET-MG, Campus VII, Timóteo/MG, Departament of Metallurgy, wellingtonlopes@deii.cefetmg.br.*

3 *Professor, Departament of Materials Engineering, Federal Center of Technological Education of Minas Gerais – CEFET-MG, Campus I.*

4 *Professor, UFMG, Departament of Mechanical Engineering.*

5 *Professor, UFMG, Departament of Materials and Construction Engineering.*

6 *Professor, UFMG, Departament of Metallurgical and Materials Engineering.*

1 INTRODUCTION

The relationship between the microstructure, the process, the properties and the performance of the materials is known and largely used by the industries for the development of new materials and applications. The grain non-oriented silicon steels (GNO steels), for example, present high magnetic properties in all directions. In this case, the addition of silicon and aluminum atoms and thermo-mechanical processes increases the magnetic permeability of this material that is commonly used in electrical motors.

In this situation, the annealing treatment conditions should be carefully adjusted to obtain the required properties. The heat treatment changes the crystallographic texture and the microstructure of the GNO steel and consequently, the magnetic property.[1] This manner, the magnetic properties of these materials depend on the heat treatments, specially, the annealing.

The recrystallization, one of the three stages of the annealing, is characterized by the absorption of the point and linear (dislocations) defects by grain boundaries that migrate through the material.[2] The main feature of this process is the presence of new grains free of the initial conditions of mechanical and thermal operations. This stage of the annealing is commonly observed and measured by optical and transmission electron microscopy, hardness tests and electron back scatter diffraction (EBSD).[2]

The volume fraction transformed (R_v) from the initial state (such as deformed) to the recrystallized state is an important data for the study of the recrystallization phenomenon. The amount of the new grains formed during the recrystallization is normally measured using the Avrami equation[3] for different time of annealing. Others methods include analysis by optical microscopy and/or transmission electron microscopy (TEM), supported by image analysis sofwares.[4]

The R_v value is influenced by some variables, such as the chemical composition, the amount of strain, the temperature, the impurities present in the material, the annealing time and the stress field. The effect of the temperature and the annealing time on recrystallization kinetics is known and considered the most important, among the others variables. However, Winning and Schäfer[5] demonstrated the influence of the mechanical loads (shear stress) applied during the annealing on the recrystallization kinetics of an Al-Mg alloy.

These authors observed that for the same temperature, the specimens annealed without stress were recrystallized after 20 minutes. The samples annealed under stress of 0.035MPa were recrystallized after 240 minutes, whereas the samples annealed under stress of 10MPa presented only 15% of recrystallized fraction for the same time (240 minutes).

The reduction of the recrystallized fraction with the shearing stresses was explained by the increase of the misorientation of the initial angle grain boundaries, hindering the formation of mobile high angle grain boundaries necessary to the recrystallization.

The study of the influence of the mechanical loads on the amount of the recrystallized microstructure is still little studied, when compared with the effect of the other variables, as the annealing time, for example. The occurrence of strain path changes during the loading sequence is other condition that can be to influence the amount of recrystallized grains in a metal.[5]

Considering this, the aim of this work is to study the influence of deformation history on the recrystallization of CuZn34 brass sheets under a loading sequence composed by monotonic and Bauschinger shearing tests (forward and reverse shearing) with different values of pre-strain and amount of reverse strain.

2 MATERIAL AND METHODOLOGY

Brass sheets CuZn34 (yellow brass, C-268 alloy), state O82, as received and annealed states were used in this research. The initial grain size of this material was 19.79μm (as-received state) and 135.41μm (annealed state).

The chemical composition of the brass is shown in Table 1. The specimens were submitted to a mechanical loading sequence, involving shearing efforts and different conditions of annealed treatments to promote the recrystallization of the brass sheets.

Table 1. Chemical composition [weight %] of brass CuZn34

Cu	65.75
Zn	34.19
Pb	0.010
Fe	0.025

Shearing specimens with 0.5mm thickness (t), 50mm length (L), 15mm total width (w) and 3.5mm effective width (b) were used for the shearing tests.

The stress and the strain shears (τ and γ, respectively) were converted into stress and strain effectives (σ_e and ε_e, respectively) using the parameter 1.84, presented by Rauch[6] and exhibited in Eq. (1) and Eq. (2), respectively:

$$\sigma_e = 1.84 \,.\, \tau \qquad (1)$$

$$\varepsilon_e = \gamma / 1.84 \qquad (2)$$

Figure 1 shows the experimental procedure executed in this research. The first step of the loading sequence (Figure 1a) involved a monotonic shearing test with a device designed for shear testing that was mounted in an INSTRON 5582 test machine. This test was conducted at the rolling direction (0ºRD) up 0.25 effective strain (ε_e) and 0.001s^{-1} of strain rate.

The second step (Figure 1b) comprehended a heat treatment (annealing) at 800ºC for 1200s and furnace cooled to room temperature of the all samples pre-deformed by monotonic shearing. After the annealing, the CuZn34 brass samples were submitted to the Bauschinger shear sequences (Figure 1c). These loading sequences were composed by forward and reverse shears with three different values of effective pre-strain: 0.10, 0.20 and 0.30.

The last step of this work involved the annealing conducted at 450°C and 650°C, during 1800s (Figure 1d). The annealing time increases (1200s to 1800s) because the brass sheets were imposed to strain path changes before this last heat treatment.

Vickers hardness tests and optical microscopy were executed after each step described in Figure 1. The optical microscopy analyzes were carried out by standard metallographic techniques and etching performed with the use of Di Copper solution (sulfuric acid, potassium dichromate, sodium chloride and distilled water).

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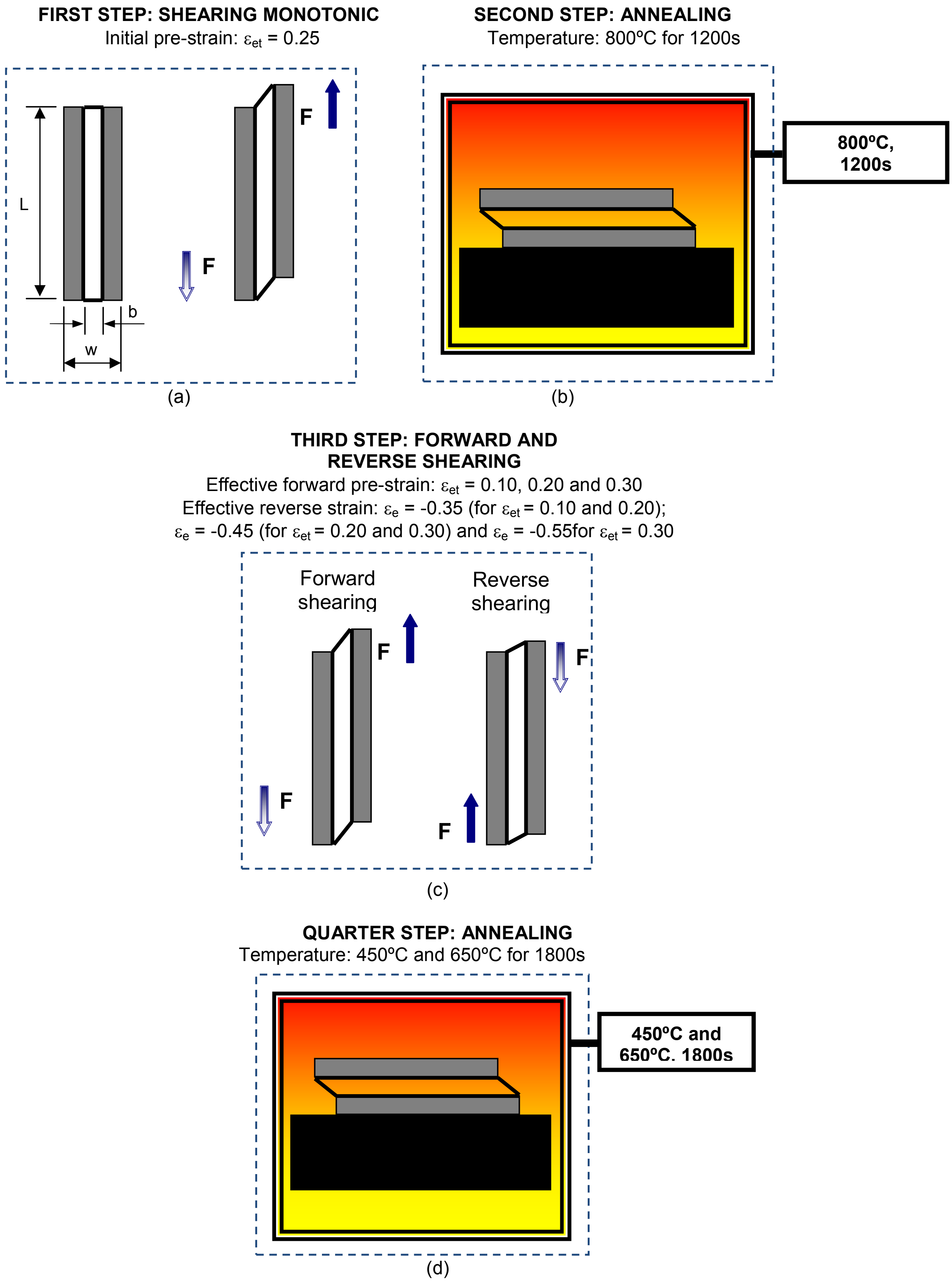


Figure 1. Experimental procedure: (a) monotonic shearing, (b) first annealing, (c) forward and reverse shearing and (d) second annealing.

3 RESULTS AND DISCUSSION

Figure 2 exhibits the effective stress – effective strain curves for the as-received and the annealed brass before the mechanical loading and heat treatments. The flow curves reveal the initial differences between the brass sheets, as the higher initial flow stress (indicated by arrows) and the work-hardening (indicated by the slope of the curves) for the as-received brass.

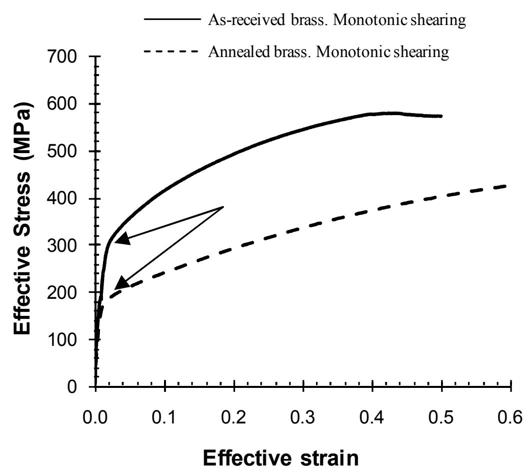
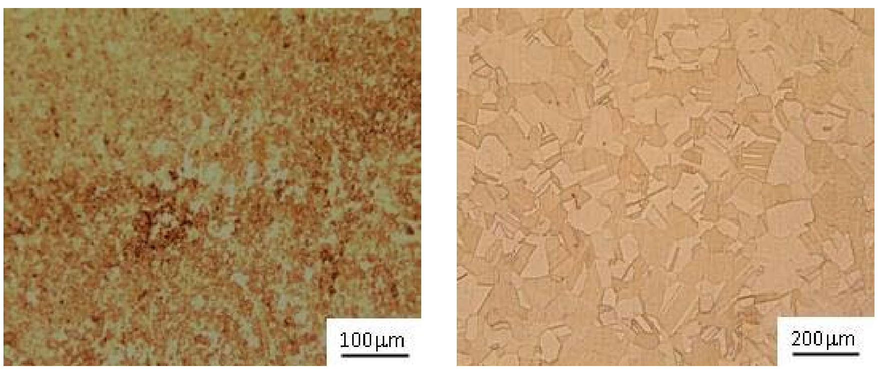


Figure 2. Effective stress – effective strain curves for the brass in as-received and annealed states before the recrystallization process.

Figure 3 shows the initial microstructure of the brass in as - received (Figure 3a) and annealed (Figure 3b) states. The initial hardness of the brass sheets in these conditions was of 130HV for the as-received brass and of 90HV for the annealed brass.



(a) (b)

Figure 3. Optical micrographs of the brass sheets at initial states: (a) as-received and (b) annealed conditions.

Figure 4 displays the effective stress – effective strain curves of the as-received (Figure 4a) and the annealed brass (Figure 4b) obtained after the Bauschinger tests conducted in the specimens pre-strained up ε_{et} = 0.25 and annealed at 800°C for 1200s.

The initial flow stress of the forward shearing (Figure 4, point A) reduced after the first annealing, when compared with the effective stress value of the monotonic test for the same amount of effective strain (ε_e = 0.25). This softening was higher for the as-received brass. This result can be associated with the higher grain size of the as-received brass after the route 0.25/800°C, when compared with the grain size of the annealed brass, as exhibited in Figures 5a and 5b, respectively.

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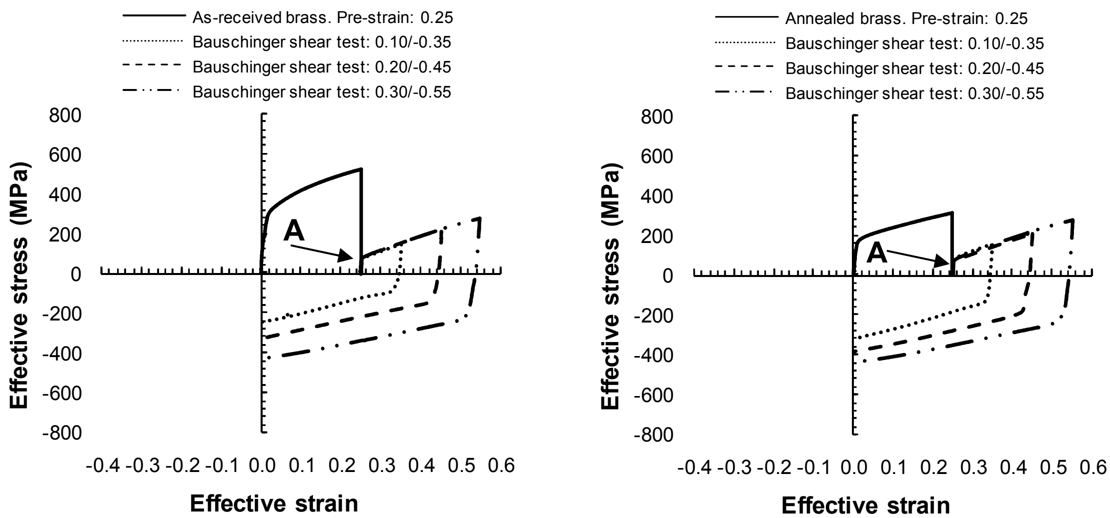

(a) (b)

Figure 4. Effective stress – effective strain curves under Bauschinger for different effective pre-strain values of the brass sheets: (a) as-received and (b) annealed conditions.

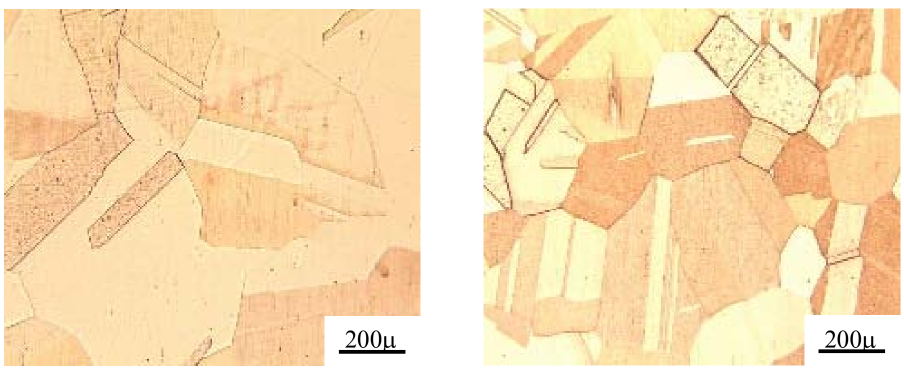

Figure 5. Optical micrographs of the brass sheets for the 0.25/800°C route: (a) as-received and (b) annealed conditions.

Figure 6 exhibits, as example, the effective stress – accumulated effective strain curves of the as-received (Figure 6a) and the annealed brass (Figure 6b) for the route 0.25/800ºC/0.30/-0.25. In these figures are presented only the absolute values of the effective stress and strain.

The Bauschinger effect (indicated in Figure 6 by the ratio of the flow stress for the reverse and the monotonic loading, $\Delta\sigma$, for the same value of the effective strain, $\varepsilon_e = 0.55$) is higher in the as-received brass (Figure 5a, $\Delta\sigma = 0.75$). This softening higher detected in the as-received brass is related with the initial condition of the material (pre-worked). The mechanical process applied to the as-received before the experimental tests used in this work supported the recrystallization, as previously stated.

Figure 6 displays the $\Delta\sigma$ value only for the pre-strain of 0.30 for the two initial states of the brass. The other pre-strain values (ε_{et} = 0.10 and 0.20) presented results similar, as the reduction of the Bauschinger effect with the pre-strain amount. This behavior is typical of metals submitted to reversal tests at room temperature and is related to the opposition of the dislocations substructure generated in the pre-strain and the newly substructure formed during the reverse shearing.[7]

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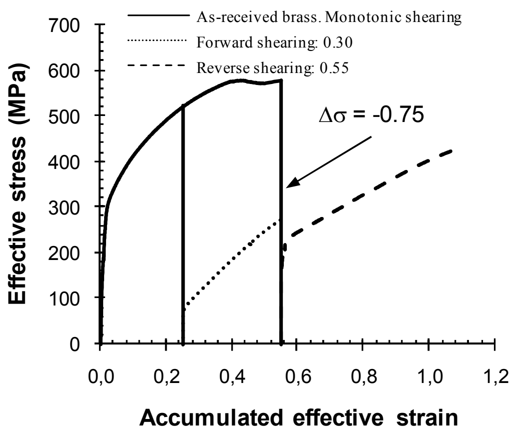

(a) (b)

Figure 6. Effective stress – accumulative effective strain curves obtained after the Bauschinger tests (forward and reverse shearing) for the route 0.25/800°C/0.30/-0.55: (a) as-received and (b) annealed brass states.

The reduction of the flow stress, when compared with the monotonic loading, occurred since the forward shearing. This situation is explained by the first annealing applied after the initial pre-strain (ε_{et} = 0.25). This heat treatment probably reduced the dislocations density of the brass sheets that was initially higher in the as-received brass, as previously stated during the discussion of the results displayed in Figure 4.

The softening detected in the brass sheets after the thermo-mechanical routes applied in this work was identified by the fractional softening. This parameter was measured using the ratio between the hardness after and before the thermo-mechanical processing of the brass sheets. The Table 2 shows these values of hardness for all conditions analyzed in this research.

Table 2. Fractional softening (ratio of the hardness before and after the thermo-mechanical processing) for the as-received and the annealed brass

Thermo-mechanical processing	Fractional softening: as-received brass	Fractional softening: annealed brass
0.25/800°C	-0.38	-0.20
0.25/800°C/0.10/-0.35/650°C	-0.44	-0.14
0.25/800°C/0.20/-0.35/450°C	-0.45	-0.11
0.25/800°C/0.20/-0.35/650°C	-0.42	-0.11
0.25/800°C/0.20/-0.45/450°C	-0.39	-0.09
0.25/800°C/0.20/-0.45/650°C	-0.41	-0.11
0.25/800°C/0.30/-0.45/450°C	-0.37	-0.07
0.25/800°C/0.30/-0.45/650°C	-0.41	-0.17
0.25/800°C/0.30/-0.55/450°C	-0.35	-0.03
0.25/800°C/0.30/-0.55/650°C	-0.41	-0.14

As previously stated, the softening was higher in the as-received than the annealed brass. This result reveals the influence of the initial state on the recrystallization of the brass sheets. The effect of other variables displayed at the Table 2 (the amount of the pre-strain and the reverse strain and the annealing temperature) will discussed in the next figures. A trend, however, is observed: the increase of the pre-strain (0.10 to 0.20 and 0.20 to 0.30) for the same reverse strain values (ε_e = 0.35 and 0.45) decreased the softening in the brass sheets (compare the hardness data for 0.25/800°C/0.10/-0.35/650°C and 0.25/800°C/0.20/-0.35/650°C routes and the 0.25/800°C/0.20/-0.45/450°C and 0.25/800°C/0.30/-0.45/450°C routes, for example). This behaviour is associated to the arrangement of the dislocations substructure during these loading sequences.[8]

The establishment of a new dislocations substructure after a Bauschinger test depends, among other variables, on the pre-strain value, on the amount of reverse strain and on the material characteristics. The transient stage in the work-hardening rate, indicated by the inflexion points in stress- strain curves presented in Figure 6 occurs due to the obstruction of the early dislocations substructure to the rearrangement that is commonly observed during the reverse strain. The obstruction of the dislocation movement detected during the reverse strain[9] hinders the nucleation of new grains and consequently, the recrystallization process.[8] This manner, for the same pre-strain value, the increase in the reverse strain tends to reduce the softening of the brass sheets, as notified in Table 2.

The Figure 7 displays the Vickers hardness versus accumulated effective strain for the routes described in Table 2, considering the second annealing conducted at 450°C (Figure 7a) and at 650°C (Figure 7b). A dashed reference line was drawn in Figures 7 to indicate the initial hardness for the as-received brass. The Figure 7 indicates that the heat treatments and shearing tests reduced the hardness of the brass sheets.

For the same amount of reverse strain (ε_e = 0.45, accumulated effective strain of 0.80) and temperature, the increase in the pre-strain value (ε_{et} = 0.20 to 0.30) also increased the hardness of the as-received brass, as indicated by the points displayed in Figure 7. This situation is more evident for the annealing conducted at 450°C.

The second annealing executed at 650°C (Figure 7b) registered the smaller oscillation of the hardness values. This indicates that the recrystallization method observed during the different routes is similar.

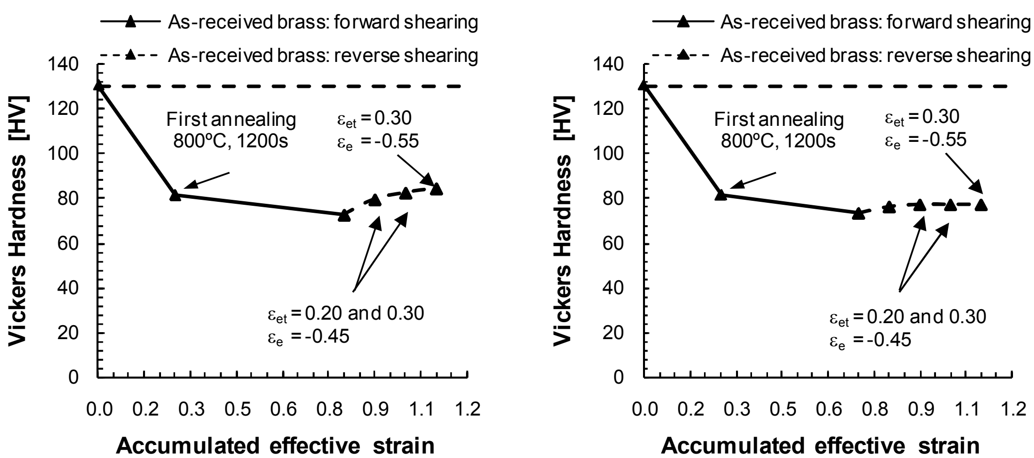

Figure 7. Vickers hardness – accumulated effective strain (forward and reverse shearing) of the as-received brass after annealing treatment conducted at: 450°C, 1800s and (b) 650°C, 1800s.

The increase of reverse strain, ε_e = 0.35 to 0.45 (accumulated effective strain of 0.80 and 0.90, respectively) for ε_{et} = 0.20 and ε_e = 0.45 to 0.55 (accumulated effective strain of 1.00 and 1.10, respectively) for ε_{et} = 0.30 increased the hardness for both annealing temperatures. This behaviour also was notified for the aluminum under tension-compression tests.[8] Jorge-Badiola and Gutiérrez[8] identified the same situation for microalloyed steel under torsion tests. These authors show that for higher reverse strains, the dislocations substructure generated during the forward loading are substituted by another, typical of the last mechanical effort applied in the reverse loading. The continuous

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deformation in this condition anticipates the recrystallization, as observed for monotonic tests.

The deviations in the hardness values for the effective strains analyzed in Figure 7 indicate that the recrystallization process of the as-received brass was influenced by the strain path changes and by the conditions of the annealing. Considering this, the Figure 8 presents the photomicrographs of the as-received brass for the second annealing executed at 450°C for increasing pre-strain (ε_{et} = 0.20 to 0.30, Figures 8a and 8b) and two reverse strain values (ε_e = 0.45 to 0.55, Figures 8b and 8c). The photomicrography of the region outside the Bauschinger shear tests is presented in Figure 8d. The main difference from the region submitted to the complete thermo-mechanical routes (Figures 8a, 8b and 8c) and the area where the brass experimented only the initial pre-strain (ε_{et} = 0.25) and the first annealing (800°C during 1200s, Figure 8d) is the grain size, higher for this last condition (outside the Bauschinger test).

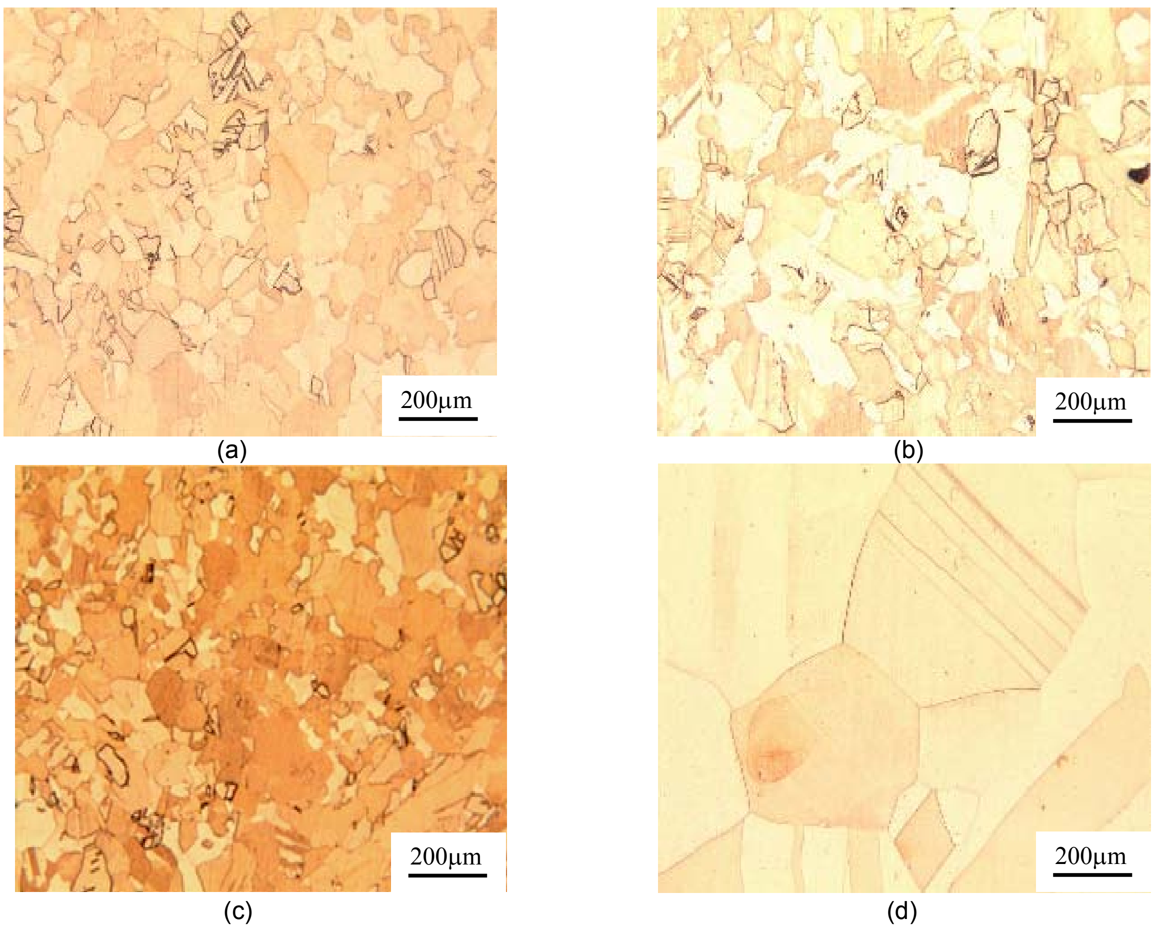

Figure 8. Optical micrographs of the as-received brass for different thermo-mechanical processes: (a) 0.25/800°C/0.20/-0.45/450°C, (b) 0.25/800°C/0.30/-0.45/450°C, (c) 0.25/800°C/0.30/-0.55/450°C and (d) 0.25/800°C/450°C, outside the shearing zone.

The effect of the initial state on the softening and consequently, on the recrystallization phenomenon is exhibits in Figure 9. This figure shows the Vickers hardness versus accumulated effective strain for the annealed brass for both second annealing temperatures: 450°C (Figure 9a) and 650°C (Figure 9b) and for the same conditions presented in Figure 7. The reduction of the hardness for the annealed brass is smaller than observed in the as-received brass. Considering that the amount of the previous strain

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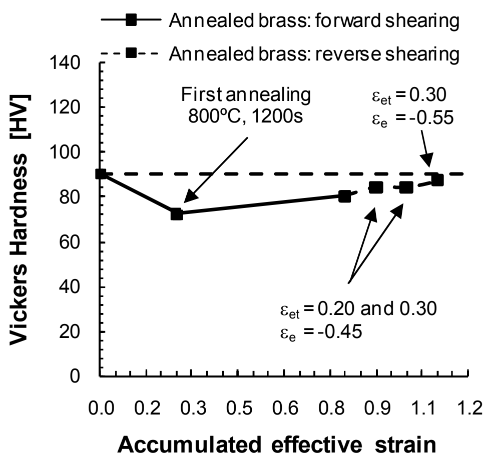
increases the recrystallization, this result explains the smaller hardness of the as-received brass.

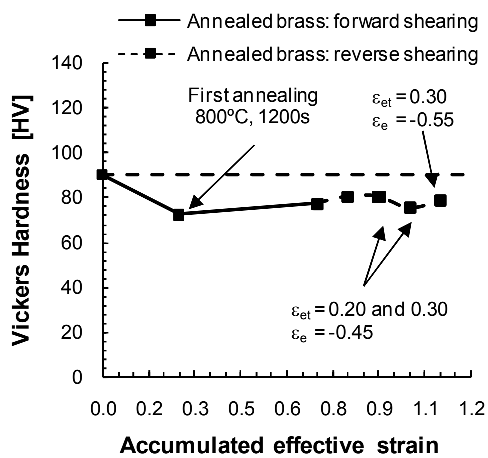
The influence of the strain path and the heat treatment on the softening of the annealed brass was sensibly smaller than observed in the as-received brass. The difference between the initial and the hardness values measured after the thermo-mechanical operations for the annealed brass is small, when compared to the as-received brass.

On the other hand, the phenomena observed in as-received brass also were notified in the annealed brass, as the reduction of the softening with the increasing in the pre-strain and reverse strain values for the both annealing temperatures (Figures 9a and 9b).

The recrystallization of a material depend on the amount stored energy and its local dislocation density. The region of the material that was deformed and, higher dislocation density, is the preferential local to start the recrystallization, reducing the stored energy.[10] Therefore, the difference in the dislocations density for as-received (higher) and for annealed (smaller) brass can to explain the deviations of the Vickers hardness – accumulated effective strain curves of these brass sheets.



(a)



(b)

Figure 9. Vickers hardness – accumulated effective strain (forward and reverse shearing) of the annealed brass after annealing treatment conducted at: 450°C, 1800s and (b) 650°C, 1800s.

In a similar manner as does in Figure 8, the Figure 10 exhibits the photomicrographs presented by the annealed brass for conditions of increasing pre-strain (Figures 10a and 10b) and reverse strain values (Figures 10b and 10c) for the second annealing temperature of 450°C.

The condition of higher hardness value (route 0.25/800°C/0.30/-0.55/450°C, Figure 10c) of the annealed brass presented a reduced microstructure grain refinement. This condition (grain refinement) is associated to the occurrence of recrystallization and indicated in Figure 10c by arrows. This indicates that the recrystallization process is smaller when compared with the other situations (Figures 10a and 10b).

The differences detected in the results presented by the as-received and the annealed brass confirms the influence of the initial state on the recrystallization of the brass sheets analyzed in this work.

The Figures 7b and 9b showed that the hardness values of the brass sheets were similar for the second annealing executed at 650°C. The hardness of the as-received and the annealed brass for the route 0.25/800°C/0.30/-0.55/650°C, for example, was 77HV and 78HV, respectively. These results suggest that the recrystallization operation of the brasses in this condition also was analogous, although the initial state of the brass is different.

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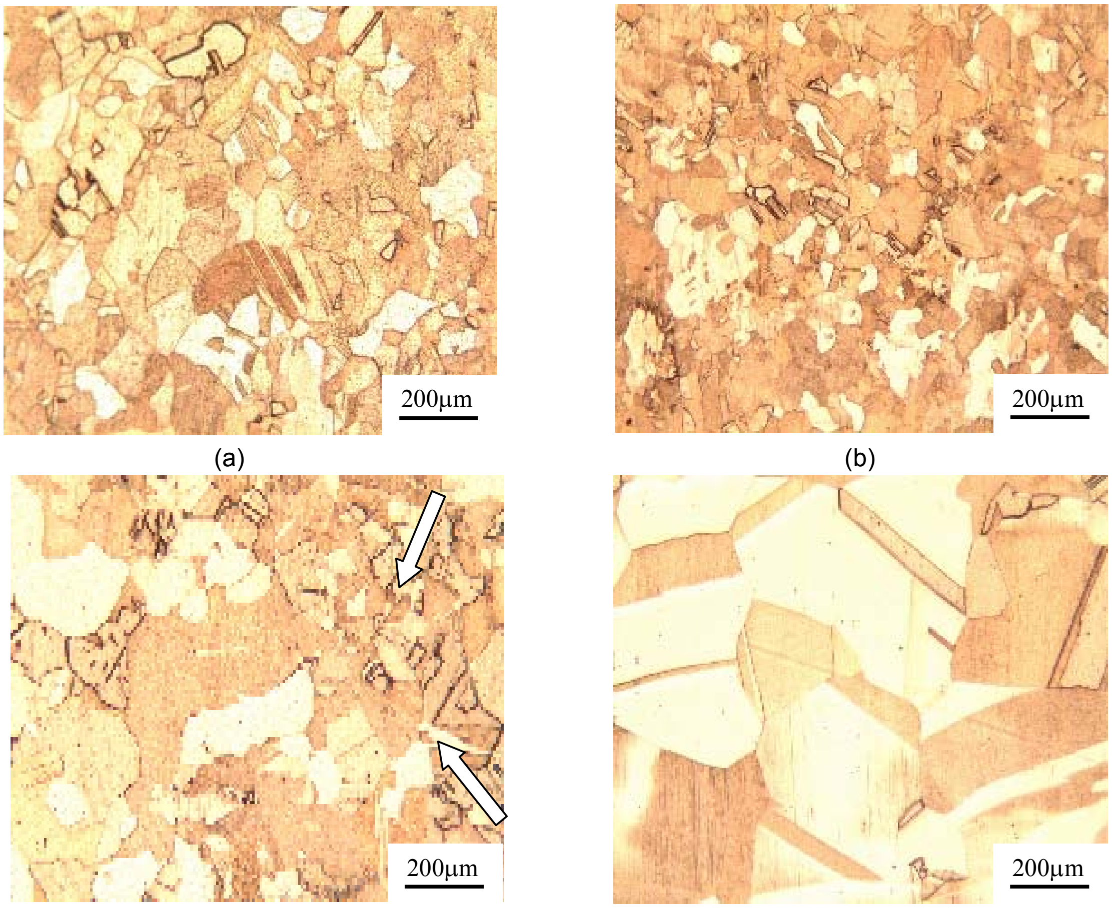
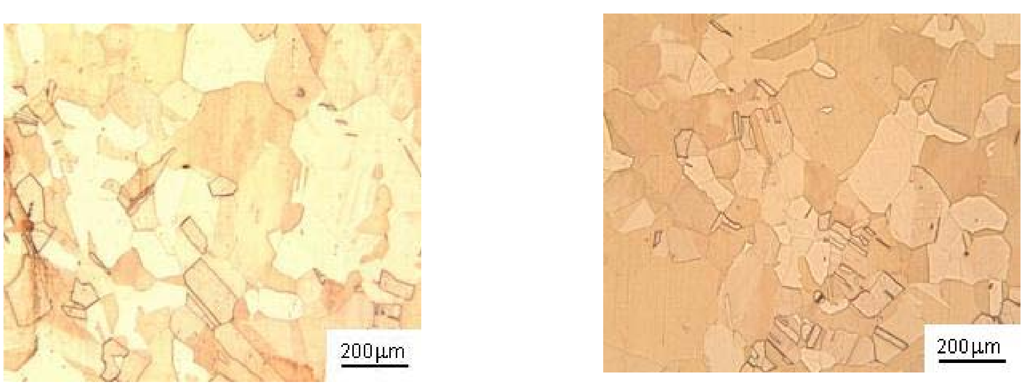


(a) (b) (c) (d)

Figure 10. Optical micrographs of the annealed brass for different thermo-mechanical processes: (a) 0.25/800°C/0.20/-0.45/450°C, (b) 0.25/800°C/0.30/-0.45/450°C, (c) 0.25/800°C/0.30/-0.55/450°C and (d) 0.25/800°C/450°C, outside the shearing zone.

The discrete difference between the hardness values of the as-received and annealed brass for the 0.25/800°C/0.30/-0.55/650°C route presented in Table 2 suggests that the microstructure characteristics (shape and grain size) of these materials in this condition were again similar, as shown in Figure 11.



(a) (b)

Figure 11. Optical micrographs of the brass sheets for the 0.25/800°C/0.30/-0.55/650°C route: (a) as-received and (b) annealed conditions.

4 CONCLUSIONS

Strain path changes (Bauschinger shear tests) and heat treatments (annealing) executed in brass sheets in two initial conditions (as-received and annealed) indicated that:

i) For the same conditions of thermo-mechanical processing, the softening presented by the as-received brass was higher than observed in annealed brass;
ii) The maximum softening of as-received brass was detected during the thermo-mechanical process, whereas for the annealed brass this condition was observed before the strain path changes (0.25/800°C route);
iii) The trend of reduction of softening with the increase in pre-strain and effective reverse strain values (-0.35, -0.45 and -0.55) for both brass sheets and annealing temperatures (450°C and 650°C);
iv) The effect of pre-strain, reverse strain and strain path changes on the recrystallization kinetics was reduced with the increase of the annealing temperature (450°C to 650°C).

Acknowledgments

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