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The Effects of Homogenization Conditions on the Hot Ductility Behaviour of AA2024 Aluminum Alloys

A. Saeed-Akbari[1], A. Zarei-Hanzaki[1], R. Rahmanian[1], Gh.R.Ebrahimi[2]

[1] Department of Metallurgy and Materials Engineering, University of Tehran, Tehran, Iran.
[2] Tarbiat Modarres University, Tehran, Iran.

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Abstract

The AA2024 aluminum alloys are known as high strength but low ductility-workability materials. In the present study, different homogenization treatments were performed on AA2024 aluminum alloy in the temperature range of 460°C to 500°C to change the second phase particle characteristics. This was followed by applying the hot tension tests to study the hot ductility behaviour of the homogenized alloy. Differential scanning calorimetry (DSC) and optical microscopy were used to investigate the role of second phase particles characteristics on the hot deformation behaviour of the experimental alloy. The results indicate that the maximum ductility would be achieved through homogenization treatment at 460°C for 16 hours followed by deformation at 400°C with strain rate of $0.1s^{-1}$.

1. Introduction

The AA2024 aluminum alloys are extensively utilized in aerospace industries due to their high strength, good fracture toughness, and high resistance to corrosion and fatigue failures [1]. These alloys are conventionally composed of copper, magnesium, manganese, and some minor alloying elements. The corresponding cast structures consist of cored dendrites of an aluminum solid solution with a variety of constituents in the interdendritic regions. The high amount of second phase precipitates results in the reduction of ductility and workability in these alloys. To improve the hot workability of the cast structure, a homogenization treatment is normally applied on these alloys [2]. During the homogenization process, the soluble precipitates are dissolved in the matrix and enhance the effects of solid solution hardening [2]. In addition, the precipitate volume fraction, morphology and distribution can be changed during homogenization processes. Accordingly the ductility of the AA2024 aluminum alloys may be increased if the latter would be intelligently programmed. The effects of homogenization treatments on the hot deformation behaviour of aluminum alloys have been broadly investigated [2-6]. However a study of the corresponding results has indicated that the effects of homogenization and deformation parameters (i.e., temperature-time-cooling rate and temperature-strain rate, respectively) on the hot deformation behaviour have not been exactly defined and interrelated. This is mainly attributed to the effects of microstructural state of the alloys once the experiment starts. In the present study, the effects of homogenization time and temperature on the hot deformation behaviour of a commercial hot extruded AA2024 aluminum alloy have been examined through the hot tension testing method.

To evaluate the effects of homogenization treatment on the microstructure and precipitation behaviour of the experimental alloy, optical microscopy and thermal analysis (DSC) routes were practiced.

2. Experimental Procedure

The experimental material is a commercial AA2024 aluminum alloy and its composition is given in Table 1. The alloy initial microstructure is shown in Figure 1. A dendritic structure with two types of precipitates located at the interdendritic spaces may be realized. In this micrograph the small dark areas are non-soluble precipitates, which mainly include the Fe-Mn-Si compounds, and the light precipitates are the soluble precipitates of θ ($CuAl_2$) and S ($CuAl_2Mg$) types.

Table 1: The chemical composition of the experimental alloy.

Zn	Pb	Ti	Cr (Max)	Si	Fe	Mn	Mg	Cu	Element
0.09	0.03	0.01	0.01	0.58	0.37	0.26	1.17	3.92	Amount wt%

Figure 1: The initial microstructure of the AA2024 alloy.

The hot tension specimens were taken from the longitudinal direction of the as-received extruded billet, and machined according to the ASTM-E8 standard. The specimens were homogenized at 460°C and 500°C for 12, 16 and 20 hours followed by quenching in cold water. These were then reheated to the tension test temperature and held for 7 minutes. The hot tension tests were carried out at 350°C and 400°C with strain rates of 0.1 and 0.001 sec^{-1} using a properly calibrated Instron universal testing machine. The specimens were quenched in water immediately after the fracture. In order to study the microstructural variations during the hot deformation process, the fractured specimens were cut through the longitudinal direction and the gage length microstructures were examined. Differential scanning calorimetry (DSC) was utilized to evaluate the effects of homogenization treatment on the consequent precipitation phenomena. To perform the DSC tests the proper specimens with 5mm diameter and the approximate thickness of 2mm were prepared and then subjected to the same heat-treating cycles of the hot tension tests. The heat-treated specimens were kept in a reservoir containing the ice and alcohol in order to avoid any precipitation to take place before the beginning of the DSC tests. The DSC tests were carried out under an argon inert atmosphere with the heating rate of

20°C/min to minimize the oxidation effects. The aluminum oxide was used as the reference in the DSC test and the system software corrected any heat capacity differences between the specimen and the reference in the resulting curves.

3. Results and Discussion

3.1. The Effects of Homogenization Treatment on the Microstructure

As is seen in Figure 2a, the soluble precipitates (θ and S) were partly dissolved in the matrix by heat-treating at 460°C for 12 hours and the rest were changed to a semi-spherical shape. As the homogenization time was increased the solubility of the precipitates in the matrix and their volume fraction decreased. In addition, the particle distribution became more homogeneous and also much coarser (Figs. 2b and 2c). Increasing the homogenization temperature from 460°C to 500°C reduced the precipitate volume fraction. The same effect would be observed by increasing the homogenization time at 500°C (Figure 2-d, e and f). Therefore, due to the solubility increase, the degree of matrix supersaturation was increased with the homogenization time and temperature.

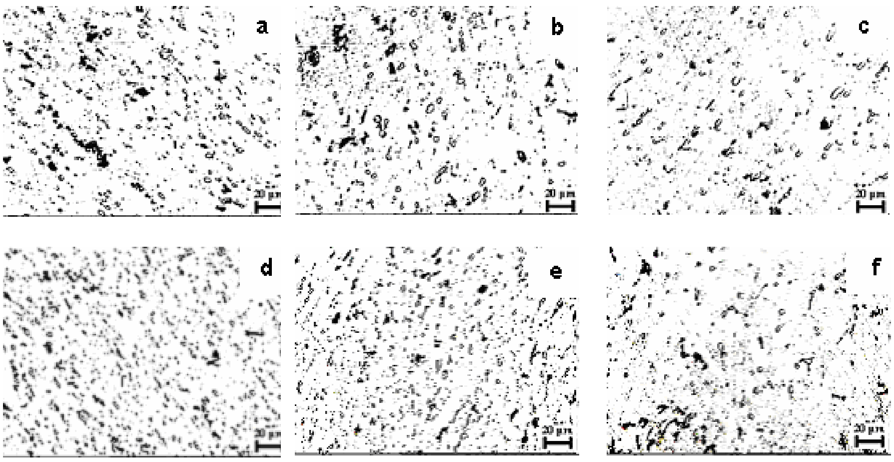

Figure 2: The microstructure of the homogenized specimens at 460°C for, a) 12hr, b) 16hr, and c) 20hr, and at 500°C for, d) 12hr, e) 16hr, and f) 20hr.

3.2. The Study of the Hot Deformation Behaviour

3.2.1. The UTS Variations

The engineering stress–strain curves of the specimens homogenized at 460°C for 12, 16 and 20 hours are shown in Figure 3. As is seen after a short strain hardening the material appears to start softening and this is followed by necking and final fracture. In addition, the flow stress in all specimens decreases with increasing the deformation temperature from 350°C to 400°C. The same effect is observed by decreasing the strain rate from 0.1 to 0.001 sec^{-1}. These may be related to the ease of the dislocation motions and increasing the rate of the dynamic recovery. The latter may soften the material under loading thereby decreasing the flow stress. The evacuation of the solute elements from the matrix due to the occurrence of dynamic precipitation may also assist the observed flow softening behaviour [2]. As is realized, the effect of homogenization time on the tensile strength in different deformation conditions was not the same. Depending on the deformation conditions (i.e., temperature and strain rate), the increase of homogenization time might lead to the decrease or increase of the tensile strength. For those specimens which were homogenized at 460°C and deformed at 350°C with a strain rate of 0.1 sec^{-1}, the maximum amount of tensile strength was obtained after 20 hours homogenization (Figure3a).

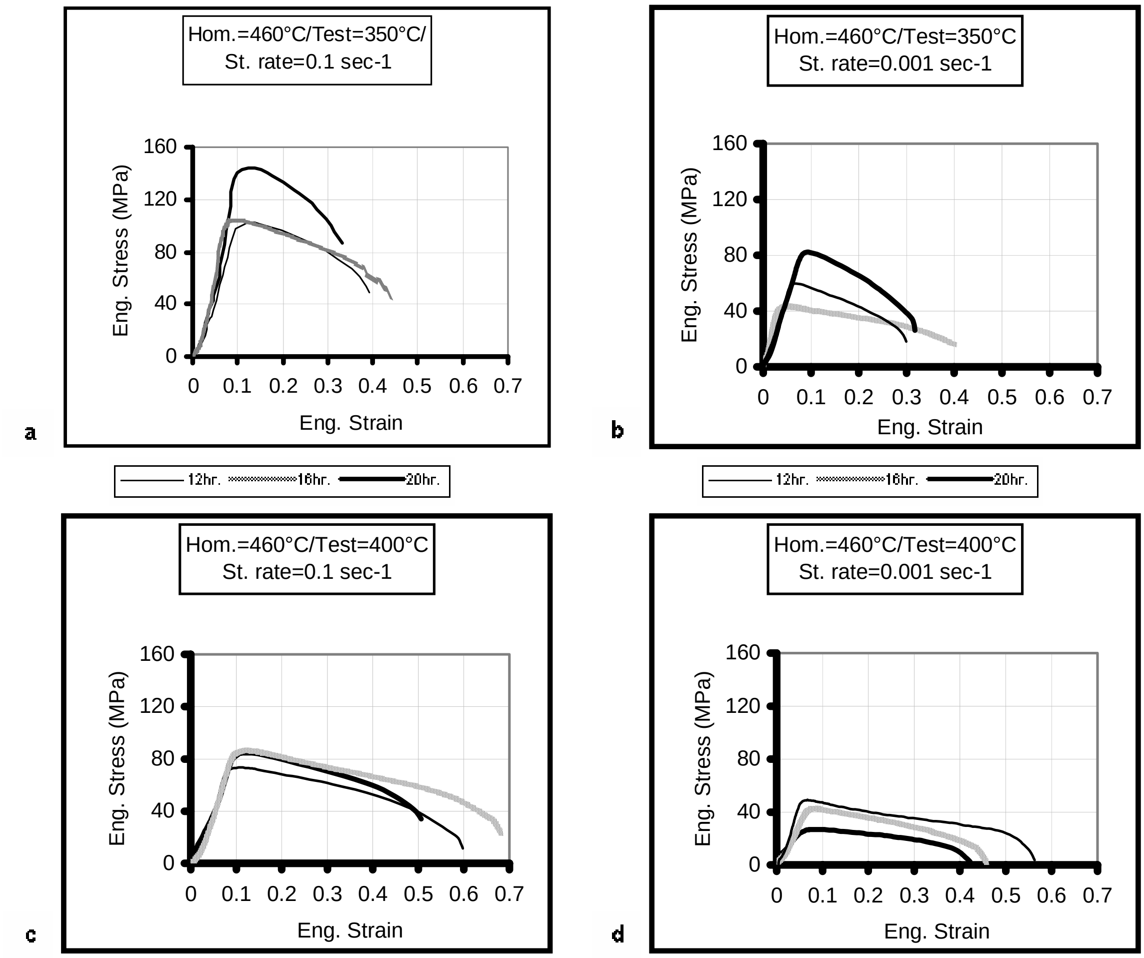

Figure 3: The engineering stress–strain curves of the homogenized specimens at 460°C for 12, 16 and 20 hours: a) tension temperature 350°C with strain rate of 0.1 sec^{-1}, b) tension temperature 350°C with strain rate of 0.001 sec^{-1}, c) tension temperature 400°C with strain rate of 0.1 sec^{-1} and d) tension temperature 400°C with strain rate of 0.001 sec^{-1}.

The latter is attributed to the higher level of supersaturation and hence the higher degree of solid solution strengthening [2,3]. However, the rate of flow softening beyond the peak stress in this condition is higher than that of the two others. The substantial flow softening in this case is related to the higher rate of dynamic precipitation and thereby faster evacuation of the solute elements from the matrix. By decreasing the strain rate from 0.1 to 0.001 sec^{-1}, the level of flow stresses decreases in all three conditions. But the 16 hours homogenized specimen shows the lowest level of strength in this case. Nevertheless the rate of flow softening for 20 and 12 hours homogenization is higher than that of 16 hours (Figure 3b). The level of flow stress decreases in all three homogenization conditions with increasing the deformation temperature from 350°C to 400°C (Figure 3c and 3d). As is seen, straining the specimens at a rate of 0.1 sec^{-1}at 400°C resulted in the same trend as at the lower temperature. Moreover, the flow curves became more or less identical (Figure 3c). By decreasing the strain rate from 0.1 to 0.001 sec^{-1}, the flow-softening behaviour continues but the samples given 20 hours homogenization show the lowest levels of flow stress (Figure 3d). Generally, the softening phenomena in precipitation-hardened alloys is related to three factors: *i)* dynamic recovery, *ii)* reduction of the fine-particle strengthening effects due to particle coarsening, and the variation of their interface structure from coherent to incoherent, and *iii)* decreasing the solid solution strengthening effects due to the precipitation and the consequent evacuation of the matrix from the solute elements [2,5]. As is well established the presence of fine dispersed particles and solid solution effects may hinder dislocation motion thereby increasing the dislocation density and stored strain energy in the matrix. The latter in turn promotes the dynamic precipitation and coarsening phenomena through strain-assisted mechanisms. However, the occurrence of dynamic recovery may retard dynamic precipitation and precipitate coarsening processes due to the consumption of stored strain energy [5]. The effect of fine particle strengthening is not noticeable at the high temperatures applied in the present research; therefore, it is not strongly participating in observed flow softening behaviour [3]. Based on the above results and discussion, it can be concluded that the precipitation and the evacuation from the matrix of solute elements occur at a higher rate in the specimens homogenized for longer times. It is worth classifying two different effects here as follows: *i)* the process of dynamic precipitation results in a sharper drop of the flow stress, and *ii)* the possibility of any static precipitation during preheating the specimens at the deformation temperature leads to a higher reduction of the overall level of tensile flow stress after longer homogenization time. This is strongly supported by considering the fact that the higher degree of matrix supersaturation resulted in an increase of diffusion driving force and hence of precipitation rate [5]. The latter is clearly confirmed by DSC results (Figure 4). It is observed that the longer the homogenization time, the lower the temperature (time) of the precipitation exothermic peak.

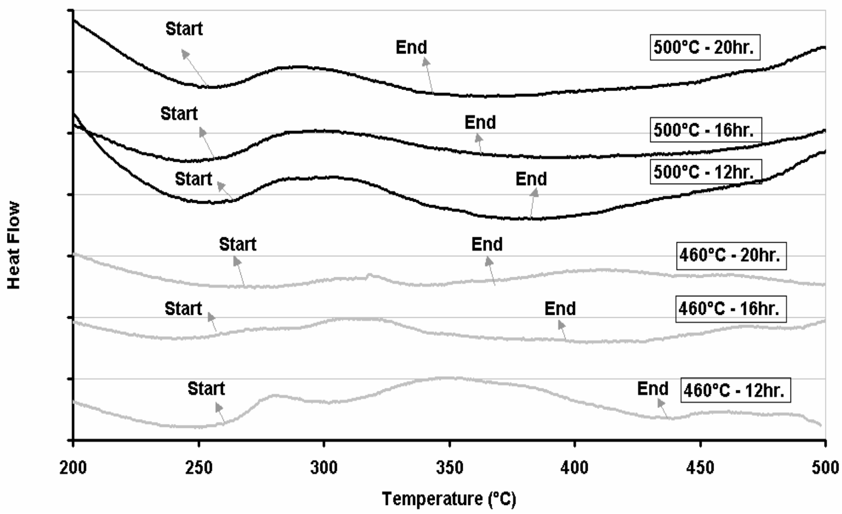

Figure 4: DSC curves of the homogenized specimens at 460°C and 500°C for 12, 16 and 20 hours.

An increase of the homogenization time at 500°C results in the same flow stress and flow softening behaviour (Figure 5).

Generally, an increase of homogenization temperature resulted in an overall decrease in the tensile strength. This is related to the higher degree of supersaturation in these specimens, which in turn led to the higher precipitation rate during the preheating and a reduction in the matrix supersaturation before starting the deformation. A comparison of the DSC curves (Figure 5) shows that the precipitation exothermic peaks shift to lower temperatures (times) as the homogenization temperature increases.

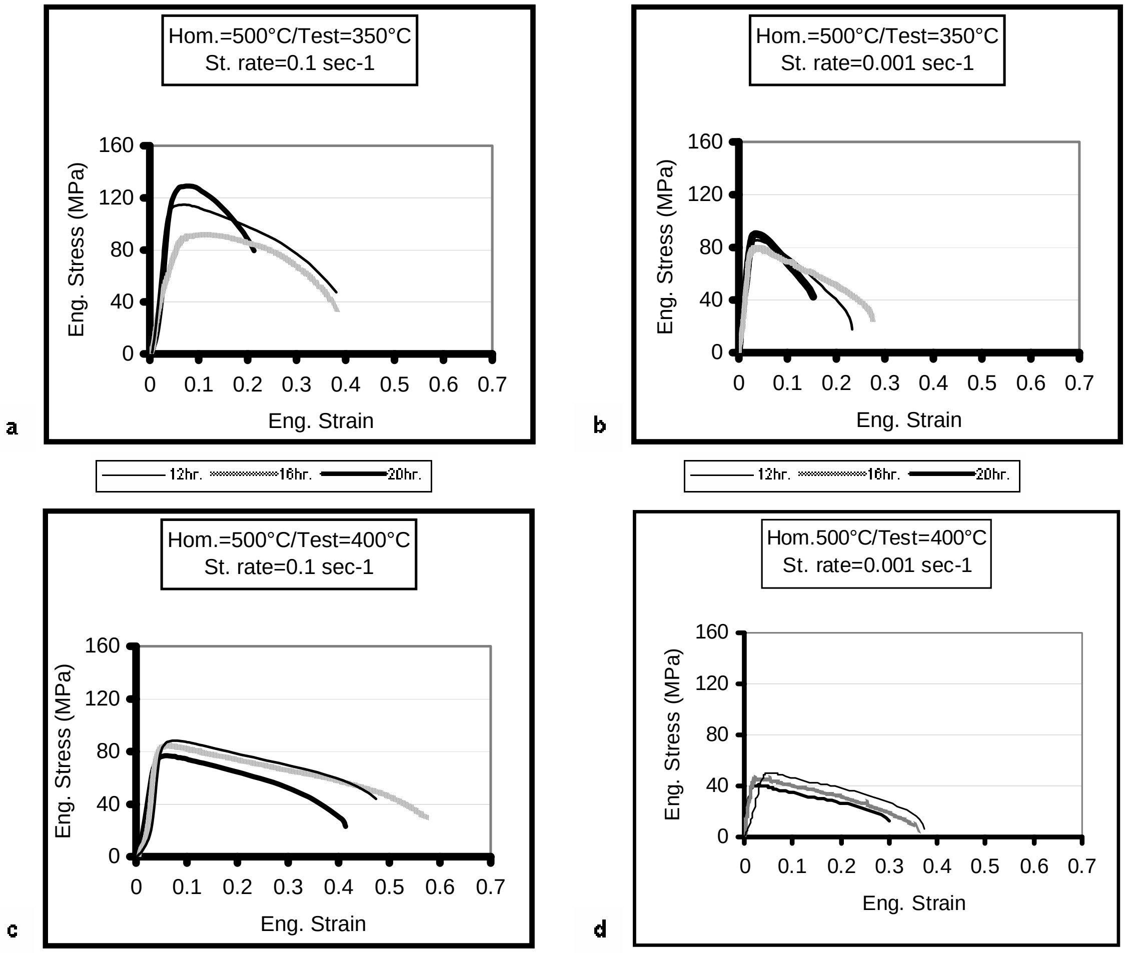

Figure 5: The engineering stress–strain curves of homogenized specimens at 500°C for 12, 16 and 20 hours: a) tension temperature 350°C with strain rate of 0.1 sec^{-1}, b) tension temperature 350°C with strain rate of 0.001 sec^{-1}, c) tension temperature 400°C with strain rate of 0.1 sec^{-1} and d) tension temperature 400°C with strain rate of 0.001 sec^{-1}.

3.2.2. Ductility Variations

As is observed from Figure 3 and Figure 5, the tensile strain at fracture in all the specimens was reduced by increasing the deformation temperature from 350°C to 400°C. This is attributed to the acceleration of the dynamic precipitation at higher temperatures, which in turn may soften the internal areas of the grains. The latter results in reducing the formability difference of the grain boundary areas and the internal parts of the grains, thereby decreasing the stress concentration in the vicinity of grain boundaries and triple points. This retards the crack nucleation and propagation in these areas and consequently leads to higher levels of ductility [2,5]. Relying on the same mechanism, a similar variation in ductility due to the strain rate reduction can be justified [2]. However, the results of the present study demonstrate a different behaviour. The ductility decreases in all the specimens as the strain rate is reduced from 0.1 to 0.001 sec^{-1}. Nevertheless the latter is consistent with the results reported by a number of investigators [5,6,8], although their findings were not clearly justified. The present authors, however, believe that these results may be explained through dynamic precipitation process as follows. When the strain rate decreases the second phase precipitates receive more opportunity to grow. As is well-established, the latter may assist the formation of precipitation free zones (PFZ) in the vicinity of grain boundaries, thereby reducing the ductility. This justification is confirmed by microstructural studies of the deformed specimens as is illustrated in Figure 6.

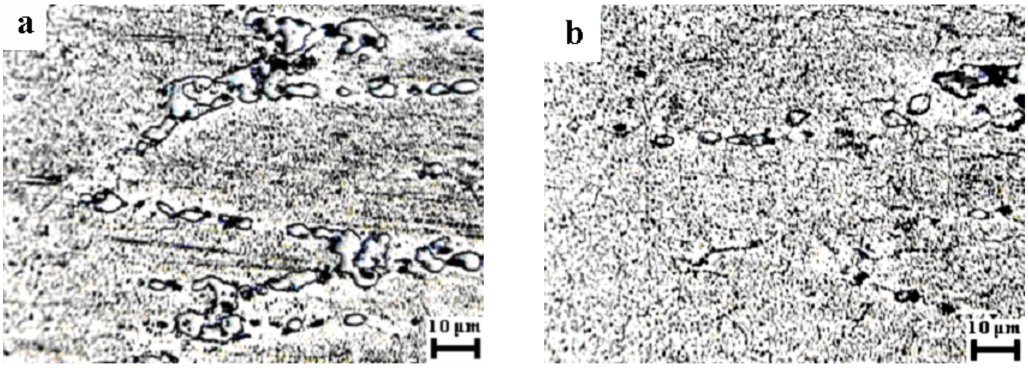

Figure 6: The optical microstructures of the deformed specimens: a) homogenization at 460°C for 16 hours, and deformed at 400°C with strain rate of 0.001 sec^{-1} , b) homogenization at 460°C for 16 hours, and deformed at 400°C with strain rate of 0.1 sec^{-1} .

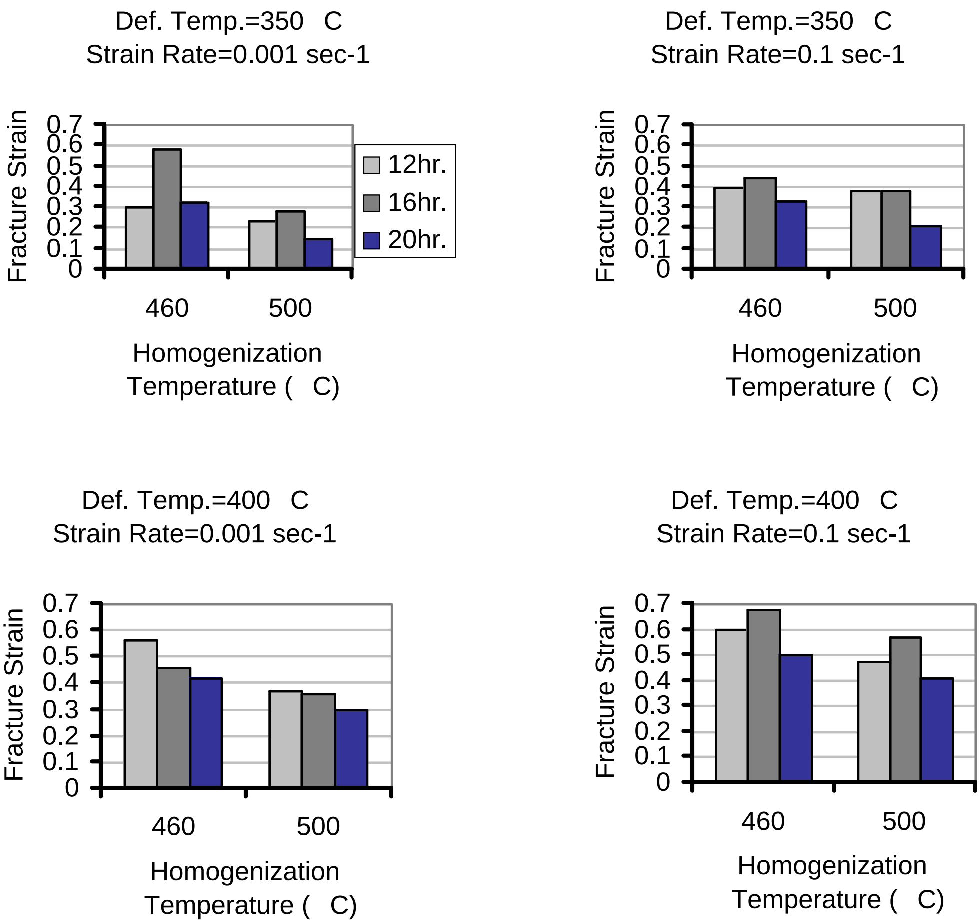

Figure 7: The effect of homogenization time and temperature on the fracture strain: a, b) deformed at 350°C, c, d) deformed at 400°C, at different strain rates.

The effect of homogenization temperature on the fracture strain is shown in Figure 7. As is seen, the ductility is decreased as the homogenization temperature increases. This may be attributed to the higher rate of the precipitation in the specimens homogenized at 500°C. As was mentioned, the latter in turn is related to the higher precipitation driving force due to the higher degree of matrix supersaturation in this condition. Accordingly the static precipitation is promoted during the preheating procedure. In addition, it is expected that the precipitate coarsening occurs faster than at 460°C and this indeed results in lower ductility properties during hot tension testing. The variation of the fracture strain with homogenization time is also shown in Figure 7. As is observed, the lowest ductility occurred in the 20 hours homogenized specimen. This may be explained through the higher coarsening rate of the precipitates in this specimen which leads to easier crack nucleation and propagation. It is worth mentioning that the maximum ductility in most of the applied conditions was realized for 16 hours homogenization specimens. Therefore, it appears that a kind of balance has been achieved between the initial amount of the precipitates, which decreases with increasing homogenization time, and the amount and size of the new precipitates (which increases with increasing homogenization time, because of the acceleration of the precipitation process during preheating procedure). Nevertheless, wherever the precipitate coarsening in 16 hours homogenized specimen resulted in overaging, the ductility was decreased.

4. Conclusion

- The solubility of the precipitates in the matrix increases with increasing homogenization time and temperature, thereby increasing the degree of matrix supersaturation.
- Increasing the hot deformation temperature resulted in lower tensile strength but higher ductility. This was related to the higher rate of the dynamic recovery process.
- Reducing the strain rate led to lower tensile strength and ductility. The latter was related to the PFZ formation in the vicinity of grain boundaries.
- The precipitation driving force increases with increasing degree of matrix supersaturation. This in turn may increase the rate of static precipitation and coarsening.
- Increasing the homogenization time and temperature may lead to higher workability, only if the state of matrix supersaturation varies during the hot deformation. Any precipitation and coarsening during the preheating process may lead to lower ductility through the generation of preferred sites for crack initiation and propagation.

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