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Effects of strain rate and temperature on hot tensile deformation of severe plastic deformed 6061 aluminum alloy

A.A. Khamei [a], K. Dehghani [a,b,*]

[a] Mining and Metallurgical Engineering Department, Amirkabir University of Technology, Tehran 15914, Iran
[b] Center of Excellence in Smart Structures and Dynamical Systems, Iran

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ABSTRACT

The hot ductility of severe plastic deformed AA6061 was studied at different temperatures and strain rates. The large processed by ECAP specimens with the dimensions of about 100 mm × 100 mm × 14 mm were then subjected to cold rolling (CR) in order to fabricate the long Ultra-fine grained sheets. According to microscopic observations and hot tensile tests, the combination of two severe plastic deformations (i.e. ECAP+CR) can affect significantly the refinement of grain/subgrain and the ductility of the studied alloy. The results were then compared with those of as-received and CRed cases. In case of ECAP followed by the cold rolling process, the effect of temperature on the ductility, strain rate sensitivity, activation energy and Zener–Hollomon parameter was higher than strain rate. It can be suggested that the possible mechanism dominated the hot tensile deformation during tensile testing is dynamic recovery and dislocation creep. Although the maximum hot ductility was obtained at 500 °C, an increase in the volume fraction of cavities and their distribution led to a decrease in hot ductility and superplasticity of AA6061 alloy processed by SPD .

1. Introduction

Generally speaking, superplastic flow refers to the ability of a polycrystalline material to extend to a very high tensile elongation prior to failure [1]. The fundamental requirements needed to achieve superplastic elongations are now well established [2]. The foremost of these are (i) the microstructural characteristics such as small grain size typically smaller than 10 μm [1,3], high stability and uniformity of the grain structure, low dislocation density in grain interiors, large percent of high-angle grain boundaries [4], second phases [5]; (ii) testing parameters such as a temperature above 0.5 T_m (T_m is the absolute melting temperature of the material) [6], low strain rate [7]; and (iii) chemical composition, e.g. the addition of zirconium and scandium to Al alloys [8]. The effect of different parameters on the superplastic behavior in 6 × × × alloys studied by many researchers is summarized in Table 1. According to Table 1, it seems that alloying elements exhibit the greatest effect on the superplasticity behavior of this alloy. Study of the effect of alloying elements on the hot ductility of AA6061 alloy showed that addition of Zr provided high stability of the formed fine grains by precipitation of Al_3Zr which led to its superplasticity at high temperature. Also, the increased amount of liquid phase, e.g. caused by copper addition, can enhance the superplastic behavior of the AA6061 alloy [9,10]. In terms of the ductility of hot AA6061 processed by SPD, it is shown [11] that Ultra-fine grained AA6061 alloys with higher grain boundary angles exhibit easier grain boundary sliding. According to their results, the precipitates formed during aging do not play an important role in improving tensile ductility, probably because the particles are stable enough at high temperatures to suppress grain growth effectively [11]. Regarding the effect of initial structure (Furnace/Water cooling) before SPD, it is shown that a solute-supersaturated material has higher ductility than fully annealed material at warm temperatures. This can be attributed to the smaller grain size and higher fraction of high-angle boundaries [12]. Although there are limited reports on the hot deformation behavior of AA6061 alloy processed by SPD, there is no detailed report regarding the effect of different parameters on the hot ductility of this alloy. Therefore, the aim of present work was to study the combined effects of two SPD processes (ECAP+cold rolling) and the thermomechanical parameters (strain, strain rate and temperature) on the hot tensile behavior of AA6061 alloy.

2. Materials and methods

The composition of studied alloy is summarized in Table 2. The large ECAP specimens had the dimensions of about 100 mm × 100 mm × 14 mm. They were solid solution treated at 803 K for 4 h followed by rapid quenching into ice water (WQ sample). The

* Corresponding author at: Mining and Metallurgical Engineering Department, Amirkabir University of Technology, Tehran 15914, Iran. Tel.: +98 21 64542900; fax: +98 21 66405846.
E-mail address: dehghani@aut.ac.ir (K. Dehghani).

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Table 1
Main parameters on superplastic behavior of 6000 Al alloys.

Alloy	The main parameters on superplastic behavior	Max. elongation, temperature, strain rate
6061 [9,10]	Alloying elements additions (Cu, Zr)	1300%, 590 °C, $2.8\times10^{-4}\,s^{-1}$
6061 [11]	Grain refinement (ECAP) Second phase (peak aging)	280%, 540 °C, $3\times10^{-4}\,s^{-1}$
6061 [12]	Initial structure (furnace/water cooling) Grain refinement (high-ratio differential speed rolling)	185%, 250 °C, $9.15\times10^{-4}\,s^{-1}$
6061 [13]	Grain refinement (ECAP)	150%, 300 °C, $1\times10^{-4}\,s^{-1}$
6061 [13]	Alloying elements additions (Mg, Zr) Grain refinement (HPT)	600%, 300 °C, $1\times10^{-2}\,s^{-1}$
6013 [14]	Alloying elements additions (Cu) Grain refinement (thermomechanical processing) Second phase (over aging)	375%, 540 °C, $5\times10^{-4}\,s^{-1}$
6082 [15]	Grain refinement (ECAP)	135%, 350 °C, $1\times10^{-3}\,s^{-1}$
6061 [16]	Grain refinement (ECAP)	100%, 250 °C, $1\times10^{-3}\,s^{-1}$
6061 [17]	Grain refinement (multi-axial compressions/forging)	115%, 300 °C, $1\times10^{-4}\,s^{-1}$

initial grain size of the sample was about 70 μm, as shown in Fig. 1. The severe plastic deformations were performed by 2 passes of ECAP followed by 90% reduction in cold rolling (CR). Both the ECAP and CR were performed at room temperature. The inner and outer angles are 100° and 60° respectively. As for the pressing speed during ECAP, it was 10 mm/s. The effective strain applied by ECAP and rolling was about 1.6 and 2.2, respectively. The ECAP-die configurations and the effective strains applied by ECAP and rolling are shown in Fig. 2 and Table 3, respectively. After applying the ECAP+CR, a long sheet (about 50 cm in length) with ultra-fine grain was fabricated. The thickness and width of ultra-fine grained sheet were respectively about 1.5 mm and 10cm, as shown in Fig. 3. The hot tensile tests were performed at temperatures of 300 °C, 400 °C and 500 °C with the strain rates ranged between 1.0×10^{-2} and $5.0\times10^{-4}\,s^{-1}$. The tensile samples were prepared by an ECAP+CR direction process with 31 mm gauge length, 6 mm width and 1.5 mm thickness. The microstructural evolutions were characterized using the X-Ray diffraction (XRD) technique, optical microscopy (OM) and transmission electron microscopy (TEM) operating at 200 kv.

3. Results and discussion

3.1. Microstructure evolutions and metallurgical interpretation

3.1.1. Microstructures after severe plastic deformation

Fig. 4 shows the microstructures of the CRed and the 2P-processed by ECAP plus CRed samples. Fig. 4a and b presents a heterogeneous structure having high dislocation density after CR. As observed in Fig. 4c, the combination of ECAP and CR led to the formation of more homogeneous grains comparing to that of CRed only. Comparing Fig. 4b and c, the grain/subgrain sizes formed in the ECAP plus CRed sample are much smaller than in case of CRed sample, presumably due to application of higher plastic strain.

X-ray diffraction (XRD) technique can be used to characterize the microstructural evolutions in terms of studying the maximum peak intensity/changes, broadening and the shifting in peaks as well as the variation in lattice parameters. These are necessary to study the effect of two SPDs methods on the deformed structure. The X-ray diffraction (XRD) patterns of the non-deformed and deformed samples are shown in Fig. 5. According to Fig. 5a, the variations in the peak intensity of the samples processed in different conditions are obvious. It is of interest that for a given condition, the maximum intensities of XRD patterns are pertaining to different planes. For example, although the highest peak for as-received sample is regarding the (111), the (200) is the dominant one for WQ+CRed and WQ+ECAP+CRed conditions. Another interesting point is a

Table 2
The composition of studied AA6061 (wt%).

Sample	Si	Fe	Cu	Mn	Mg	Cr	Al
Studied alloy	0.73	0.37	0.2	0.07	0.9	0.19	Bal.
Standard [18]	0.4–0.8	≥0.7	0.15–0.4	≥0.15	0.8–1.2	0.04–0.35	Bal.

significant reduction of the peak intensity for CRed and ECAP+CRed samples when compared to initial condition. It should be noted that the peak intensities of (111) and (200) planes are surprisingly identical for WQ+CRed and WQ+ECAP+CRed specimens. It may be concluded that the rolling process exhibits more significant effect on the microstructural development than ECAP. These results can be attributed to the formation of different textures, the more homogeneity in the dislocation densities and the formation of ultra-fine grains (UFGs) [19]. Fig. 5b and c compares the shifting and broadening of XRD peaks obtained at three different conditions, i.e. as-received, cold rolled and combination of ECAP plus CR. All the peaks corresponding to the two planes ((111) and (200)) regarding the CRed and ECAP+CRed samples are shifting to left when compared to those of as-received case. Referring to Fig. 5b, the deviation of the peaks from initial state (as-received sample) rises with increasing the plastic strain especially in case of CRed specimen. The shifts in XRD peaks are attributed to the enhanced strain [20] and consequently residual stresses in the structure [21]. It is found that decrease of 2θ due to application of high plastic strain causes an increase in the lattice parameter as shown Fig. 5d. It is reported in Ref. [22], that the high density of dislocations and point defects can explain the increment of lattice parameter. The variations in the full width of half-maximum of X-ray peaks (FWHM) from the samples processed in different conditions are illustrated in Fig. 5c. It can be seen that an increase in the widths of X-ray peaks was observed which indicates the enhancement of internal/lattice strain [23], the dislocation densities [24] and/or residual stresses [25], the development of fine subgrains [26], the grain refinement [27], and increase in the defect density and higher lattice distortion [28]. According to Fig. 5c and d, both the FWHM and lattice parameter of WQ+CRed sample are higher than WQ+ECAP+CRed sample. The results show that when the samples are deformed up to a strain of 3.8 at room temperature, the dislocations are annihilated due to dynamic recovery.

3.1.2. Microstructures after hot tensile deformation

Hot formability is often limited by cavitation during forming, making cavity formation, growth and coalescence [29]. The variation in size and volume fraction of cavities as a function of the