



Thermal stability evaluation of nanostructured Al6061 alloy produced by cryorolling

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Abstract: Grain growth of nanostructured Al6061 produced by cryorolling and aging process was investigated during isothermal heat treatment in 100–500 °C temperature range. Transmission electron microscopy (TEM) observations demonstrate that after cryorolling and aging at 130 °C for 30 h, the microstructure contains 61 nm grains with dispersed 50–150 nm precipitates and 0.248% lattice strain. In addition, an increase in tensile strength up to 362 MPa because of formation of fine strengthening precipitation and nano-sized grains was observed. Thermal stability investigation within 100–500 °C temperature range showed release of lattice strain, dissolution of precipitates and grain growth. According to the X-ray diffraction (XRD) analysis, Mg₂Si precipitates disappeared after annealing at temperatures higher than 300 °C. According to the results, due to the limited grain growth up to 200 °C, there would be little decrease in mechanical properties, but within 300–500 °C range, the grain growth, dissolution of strengthening precipitates and decrease in mechanical properties are remarkable. The activation energies for grain growth were calculated to be 203.3 kJ/mol for annealing at 100–200 °C and 166.34 kJ/mol for annealing at 300–500 °C. The effect of precipitation dissolution on Al lattice parameter, displacement of Al6061 (111) XRD peak and Portevin–LeChatelier (PLC) effect on stress–strain curves is also discussed.

Key words: mechanical characterization; X-ray diffraction; aluminium alloy; bulk deformation; grain growth; grain refinement

1 Introduction

In recent years, ultra-fine grained/nanostructured (UFG/NS) materials have received a great attention due to their superb mechanical properties [1–4]. However, structural changes, including grain growth and phase transformations as a result of increasing in working temperature will affect attractive properties of the mentioned materials. Generally, severe plastic deformation (SPD) processes are used to produce bulk UFG/NS materials. Recently, UFG/NS materials developed by equal channel angular pressing (ECAP), accumulative roll bonding (ARB), friction stir processing (FSP), high pressure torsion (HPT) and cryorolling (CR) have shown high strength and hardness as compared to coarse-grained structures [5]. Highly unstable microstructure containing non-equilibrium grains and high dislocation density are the main characteristics of severe plastic deformed materials. During recent years, for aluminum alloys cryorolling process followed by optimum heat treatment is introduced as an effective

process to develop bulk UFG/NS Al alloys. The excellent mechanical properties during cryorolling is obtained from suppression of dynamic recovery due to deformation at cryorolling temperature, which follows by optimal heat treatment and hence stable UFG/NS materials would be produced, which are suitable for structural and thermomechanical applications. DAS et al [6] have reported the improved tensile strength and impact toughness of the cryorolled Al7075 alloy due to grain refinement, and ultra-fine grain formation by multiple cryorolling passes. According to their results, the yield strength and impact toughness of the cryorolled Al7075 alloy up to 70% thickness reduction have increased by 108% and 60% respectively compared to the starting material. CHENG et al [7] have reported simultaneous increases in strength, work-hardening ability and ductility of cryorolled Al2024 alloy. The effect of deformation at the cryogenic temperatures during rolling of Al6061 and Al6063 was investigated by RAO et al [8,9]. According to the results, the pre-CR solid solution treatment combined with post-CR aging treatment for Al6061 alloy results in enhancing

mechanical properties and 360 MPa tensile strength along with 10% elongation were reported. Furthermore, HUANG et al [10] reported that cryorolling process of Al6061 alloy changes the precipitation sequence of strengthening phases and cryorolled samples followed by peak aging treatment shows a significant increase in mechanical properties.

However, as mentioned before, high working temperature results in microstructural changes and affects the UFG/NS materials properties. According to the literature, the thermal stability of UFG/NS materials depends on grain growth kinetics, which is influenced by grain boundary segregation [11], second phase drag and solute drag [12]. The grain growth kinetics of different UFG/NS materials developed by SPD processes have been studied [13–18]. According to the results, two different activation energies for grain growth of SPDed Al alloys were reported, i.e., the low temperature activation energy for grain growth at temperature below 300 °C which is within 5–30 kJ/mol range and the high temperature grain growth activation energy in 300–500 °C which is in 90–163 kJ/mol range. It is reported that the former is the activation energy required to obtain a fully recrystallized UFG/NS microstructure, and the latter is the activation energy required for grain growth from UFG/NS to coarse microstructure. However, no work has been reported until today on the study of the grain growth kinetics on cryorolled Al6061 alloy followed by optimal aging heat treatment. In this study, the thermal stability of nanostructured Al6061 alloy developed by cryorolling and optimal aging process was investigated.

2 Experimental

The chemical composition of the commercial Al6061 alloy used in this study is presented in Table 1. Before cryorolling process, the Al6061 alloy was solution treated at 530 °C for 3 h followed by water cooling down to room temperature by water quenching. Then the cryorolling process was carried out under conditions listed in Table 2. Finally, the cryorolled samples were aged at 130 °C for 30 h.

To study the thermal stability, mechanical and

Table 1 Chemical composition of Al6061 alloy (mass fraction, %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.462	0.339	0.196	0.039	0.923	0.068	0.159	Bal.

Table 2 Process parameters of cryorolling and following aging process

Sample	Reduction/%	Reduction per pass/%	Rolling speed/(r·min ⁻¹)	Liquid N ₂ time/min	Aging time/h	Aging temperature/°C
CR+PA	85	5	8	5	30	130

microstructural changes of cryorolling and peak aging (CR+PA) samples, they were annealed at different temperatures in the range of 100–500 °C for 1, 2 and 3 h followed by water quenching. The microstructural features of the Al6061 CR+PA sample were examined by TEM with mechanical polishing up to 0.1 mm followed by electrojet polishing. Philips CM120 FEG TEM with an accelerating voltage of 120 kV was used for microstructural analysis. Also the microstructures were analysed by using scanning electron microscope (SEM, JEOL 7001F)/electron backscatter diffraction (EBSD) analysis. In order to investigate the structural changes as a result of cryorolling process, aging treatment and isothermal heat treatment, X-ray diffractometry (XRD) was used. A Philips diffractometer (40 kV) with Cu K_α radiation was used for XRD measurements. The grain size and lattice strain were estimated from broadening of XRD peaks using Williamson–Hall formula [19]. The optical microscopy is also used for structural evaluations. The dislocation density (ρ) was estimated by the following formula [20]:

$$\rho = \frac{2\sqrt{3} \langle \varepsilon^2 \rangle^{\frac{1}{2}}}{Db} \quad (1)$$

where b is the Burgers vector of dislocations, ε is the lattice strain and D is the subgrain size estimated by Williamson–Hall method. In order to evaluate the hardness of the material, Vickers microhardness tests were conducted on samples with a load of 50 g and dwell time of 10 s. At least 5 different readings for each sample were obtained to ensure repeatability of the results. For the tensile tests, samples were machined into the ASTM subsized specimens with 25 mm gage length. Uniaxial tensile tests were conducted with an Instron machine operated at constant 2.5 mm/min cross head speed. Also the mechanical properties were investigated in the cross-section of samples using a nano-indenter NHTX S/N:01-03119 produced by CSM Inc.

3 Results and discussion

3.1 Characterization of cryorolled peak aged Al6061 samples

The microstructural evaluation of Al6061 alloy after cryorolling and optimum aging process, was investigated by TEM and EBSD and the results are shown in Fig. 1. The starting material in solid solution treated (ST) condition exhibits coarse grains with an average grain size of 227.4 μm . Figure 1(a) shows the TEM image of

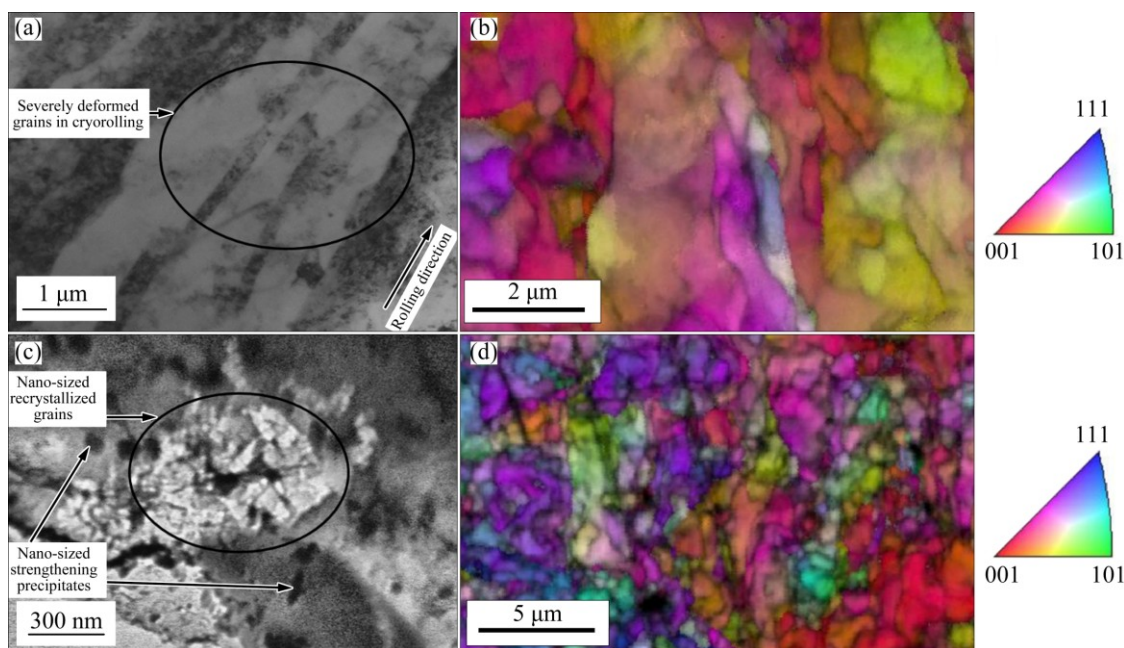


Fig. 1 TEM image (a) and EBSD image of as-cryorolled Al6061 alloy (b), TEM image (c) and EBSD image (d) of of Al6061 alloy after cryorolling and aging heat treatment

cryorolled sample including elongated grains while the microstructure of cryorolled and peak aged sample (Fig. 1(c)) contains equiaxed grains with size of 61 nm.

As mentioned earlier, the crystallite size (d), and approximate upper limit of the lattice strain (ϵ) can be evaluated by XRD peak analysis according to Williamson–Hall relation [19]:

$$\beta \cos \theta = \frac{0.9\lambda}{D} + 2\epsilon \sin \theta \quad (2)$$

where β is the peak width at half the maximum intensity, θ is the position of peak maximum and λ is the X-ray wave length ($\lambda_{\text{Cu}}=1.54056$ nm). Using this method, the grain size of Al6061 CR+PA sample was measured to be 48 nm which is in good agreement with the grain size calculated from TEM images. Also the EBSD images of grain orientation distribution of Al6061 alloy subjected to cryorolling and following peaked age heat treatment are illustrated in Figs. 1(b) and (d), respectively. According to the EBSD results, the cryorolled samples showed fragmented and elongated ultrafine grains along rolling direction, while, nano equiaxed grains are depicted in microstructure of the peak aged sample.

Figure 2 shows the engineering stress–strain curves of Al6061 alloy in different conditions, including solution treated (ST), T6 heat treated (T6), cryorolled (CR) and peak aged after cryroll (CR+PA) samples. The strength of the CR sample ($\sigma_y=(271\pm16)$ MPa and $\sigma_{\text{UTS}}=(297\pm18)$ MPa) was much higher than that of ST sample ($\sigma_y=(50\pm6)$ MPa and $\sigma_{\text{UTS}}=(134\pm10)$ MPa). This is due to the high density of dislocation accumulated as a

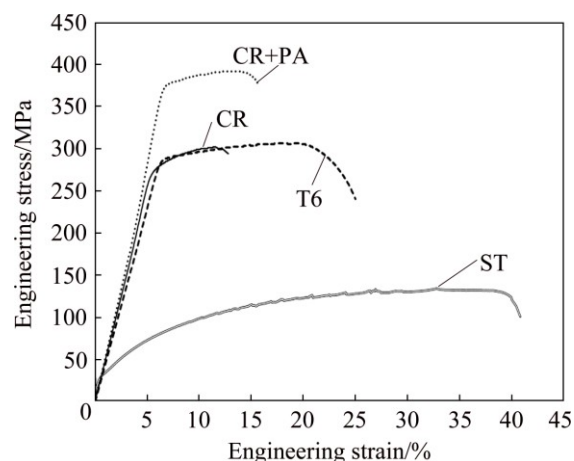


Fig. 2 Engineering stress–strain curves of Al6061 alloy in different conditions

result of plastic deformation at -196 °C temperature in deformation at cryogenic temperatures. Effective suppression of dynamic recovery resulted in a high density of dislocation in CR samples [21]. According to the results, cryorolling process followed by aging heat treatment caused a further increase in strength ($\sigma_y=(362\pm15)$ MPa and $\sigma_{\text{UTS}}=(388\pm17)$ MPa for CR+PA sample). Formation of fine strengthening precipitation and nano-sized grains plays an important role in enhancement of mechanical properties (Fig. 1(b)). For better evaluation of mechanical properties, nano indentation test was performed on Al6061-T6, CR and CR+PA samples. A comparison of hardness, HV (39 ± 3.4), HV (118 ± 3) and HV (137 ± 2.5) in ST, CR and CR+PA samples respectively, showed that the cryorolling process

followed by aging heat treatment has a great effect on enhancing mechanical properties of the Al6061 alloy. Also, elastic modulus of Al6061-T6, CR and CR+PA samples were measured to be 70.089, 75.707 and 73.558 GPa, respectively, by nano indentation tests.

The follow stress of material in uniform plastic deformation region is presented by the Holloman relationship [22–25]:

$$\sigma = k\epsilon^n \quad (3)$$

where n is the strain hardening exponent, k is the strength coefficient, σ is true stress and ϵ is true strain.

Also the hardening capacity (H_c) of a material can be presented by the following normalized equation by considering σ_{UTS} and σ_y [26]:

$$H_c = \frac{\sigma_{UTS} - \sigma_y}{\sigma_y} = \frac{\sigma_{UTS}}{\sigma_y} - 1 \quad (4)$$

The calculated strain hardening exponents and hardening capacities of Al6061-T6, CR and CR+PA samples are presented in Table 3.

Table 3 Strain hardening exponents and hardening capacity of Al6061-T6, CR and CR+PA samples

Sample	Hardening capacity	Strain hardening exponent
Al6061	0.075	0.06
CR	0.096	0.11
CR+PA	0.072	0.09

The strain hardening of the material after yielding is related to the dislocation strain field interactions. An increase in the number of dislocations during the cryorolling as a result of suppression in dynamic recovery, decreases the spacing among dislocations and their interaction becomes repulsive. By increasing the number of dislocations, the resistance to the dislocation movement increases and the stress required to deform the materials becomes higher with increasing deformation or cold work [27]. Based on the above discussion and calculated strain hardening exponent for Al6061-T6, CR and CR+PA samples, the highest value was obtained for CR sample which has the highest dislocation density, then CR+PA (the nanostructured sample) and finally Al6061-T6 sample. According to the literature, hardening capacity of the material is associated with its grain size affecting yield strength [22,27,28].

In explaining strain hardening behaviors, grain size and dislocation strengthening is considered. In this regard, the following equation was introduced in recent strain hardening model [25,29]:

$$\sigma = \sigma_0 + \sigma_{HP} + \sigma_d \quad (5)$$

where σ_0 is the frictional contribution, $\sigma_{HP} = kd^{-1/2}$ is the Hall–Petch contribution and $\sigma_d = MaGb\rho^{1/2}$ is the Taylor

dislocation contribution (ρ is dislocation density, a is a constant, M is Taylor factor, G is the shear modulus, and b is the Burgers vector). The applied stress necessary to deform a material after yielding is proportional to the dislocation density inside the material. Due to an increase in the number of dislocations during deformation, the resistance to the dislocation movement increases and the stress required to deform the material becomes higher with increasing deformation [27]. So, it can be concluded that the high initial dislocation density and dislocation tangles in the CR sample as a result of cryorolling process (Fig. 3) act like barriers against the dislocation movement. Moreover, according to Fig. 1(a), the CR sample contains long ultra-fine grained microstructure. On the other hand, in CR+PA sample despite of the fact that aging process results in decreasing dislocation density, but ultra-fine grains and nanometric strengthening precipitates, act as barriers for dislocation movement. So, for CR and CR+PA samples, the strain hardening behavior appeared to be large with varying slope in the plastic domain.

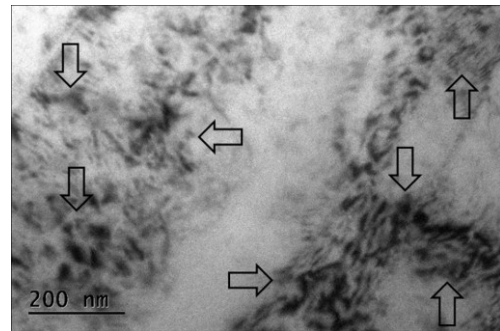


Fig. 3 TEM image of as-cryorolled Al6061 alloy after 85% thickness reduction, containing dislocation tangling zones (areas which are shown by black arrows)

3.2 Structural changes of nanostructured Al6061 alloy during annealing

As illustrated in previous section, cryorolling of Al6061 alloy followed by aging heat treatment led to the formation of stable nanostructured Al6061 alloy with grain size of 61 nm and fine 50–150 nm precipitates.

Thermal stability of Al6061 alloy after the cryorolling process and aging was investigated by heat treating the samples in 100–500 °C temperature range for 1 to 3 h. Changes of the dislocations density and crystallite size (obtained by using Williamson–Hall method) versus temperature are presented in Fig. 4. According to the results, dislocations annealing seriously started at 300 °C and continues to 500 °C. On the other hand, nanostructured Al6061 alloy would be kept up to 200 °C. According to the literature in Al6061 alloy with increasing temperature from 300 °C, β' and β'' precipitates are dissolved in the structure. By increasing the annealing temperature, the driving force for the grain

boundaries migration would increase [30]. During the annealing up to 300 °C, due to the presence of nanometric precipitates in the structure of CR+PA sample and due to the grain boundaries pinning by precipitates, migration of grain boundaries would be prevented, and thus the microstructure of material would not be changed even at 200 °C. The effect of precipitates on preventing the grain boundaries migration depends on the size and distribution volume of the precipitates which are expressed according to the following equation [29]:

$$F_Z = k \left(\frac{f\lambda}{r} \right) \quad (6)$$

where k is the coherency coefficient, λ is interface energy between grain boundary and precipitate, f is the volume fraction of precipitates, r is the mean radius of precipitates and F_Z is Zener drag force. According to Eq. (6), the finer the dispersed precipitates, the higher the Zener drag force is. Therefore, it can be concluded that by increasing the annealing temperature and time, due to the growth of precipitates, the value of grain boundaries pinning force would decrease due to the decrease in (f/r) ratio and subsequently, grain growth occurs.

Figure 5 shows changes in hardness and tensile properties of CR+PA sample, after annealing at 100 °C

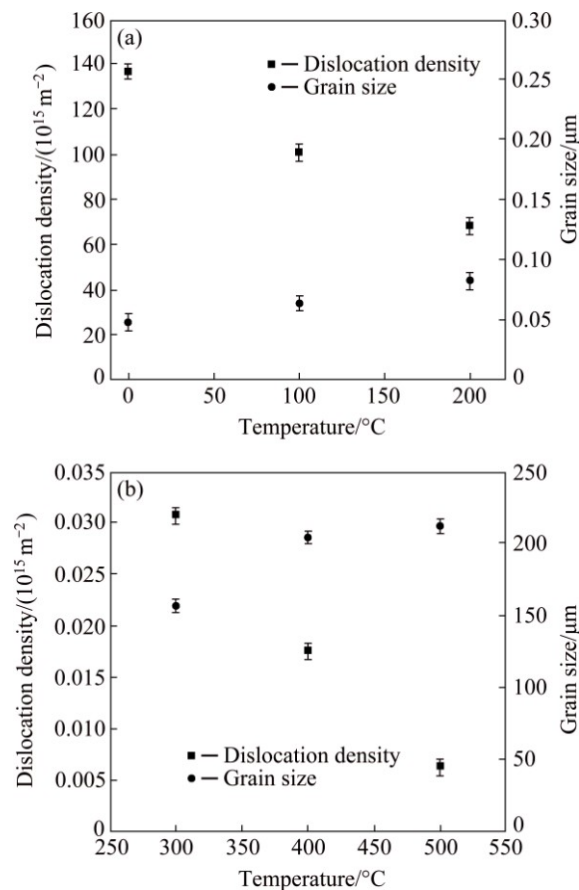


Fig. 4 Changes in density of dislocations and crystallite size as function of temperature in CR+PA sample

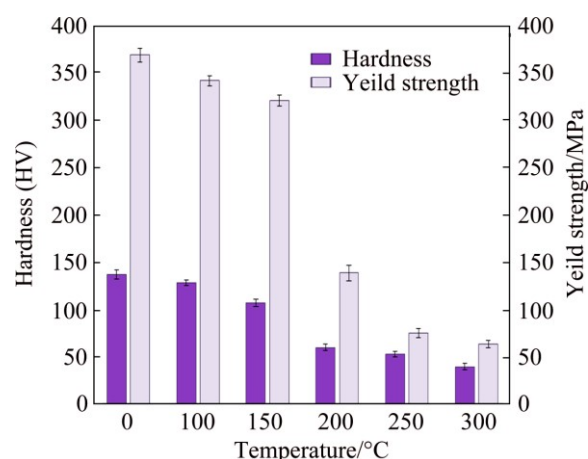


Fig. 5 Changes in hardness and tensile properties of CR+PA sample, after annealing at 100 °C to 500 °C for 1 to 3 h

to 500 °C for 1 to 3 h. The general trend is the reduction of mechanical properties by increasing the temperature and the time of annealing heat treatment which is due to the grain growth and dissolution of the strengthening precipitates.

X-ray diffraction patterns of CR+PA sample after annealing at 100–500 °C for 1 to 3 h are illustrated in Fig. 6. The dissolution of precipitates in the samples annealed at temperatures higher than 300 °C is remarkable. Furthermore, according to Fig. 7(a) by heat treating the CR+PA sample, the (111) peak position did not change significantly. In addition, as it is presented in Fig. 7(c), lattice parameter of Al is almost constant after heat treatment of up to 200 °C. The main reason is the resistance of stable structure of CR+PA sample, which is due to applying optimum aging treatment after cryorolling process, in which grain growth and significant dissolution of the precipitates do not occur up to 200 °C even after 3 h. As mentioned for X-ray

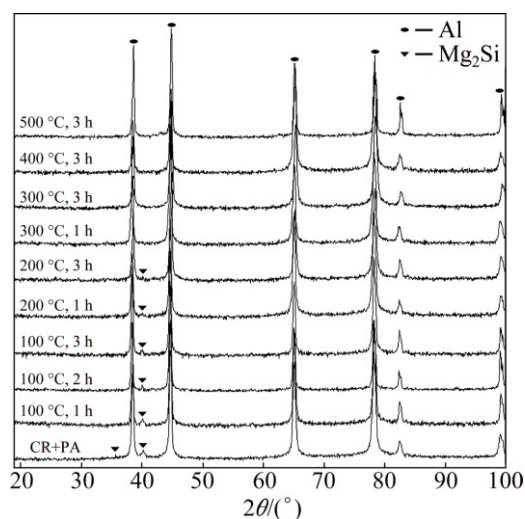


Fig. 6 X-ray diffraction patterns of CR+PA sample after annealing at 100–500 °C for 1 to 3 h

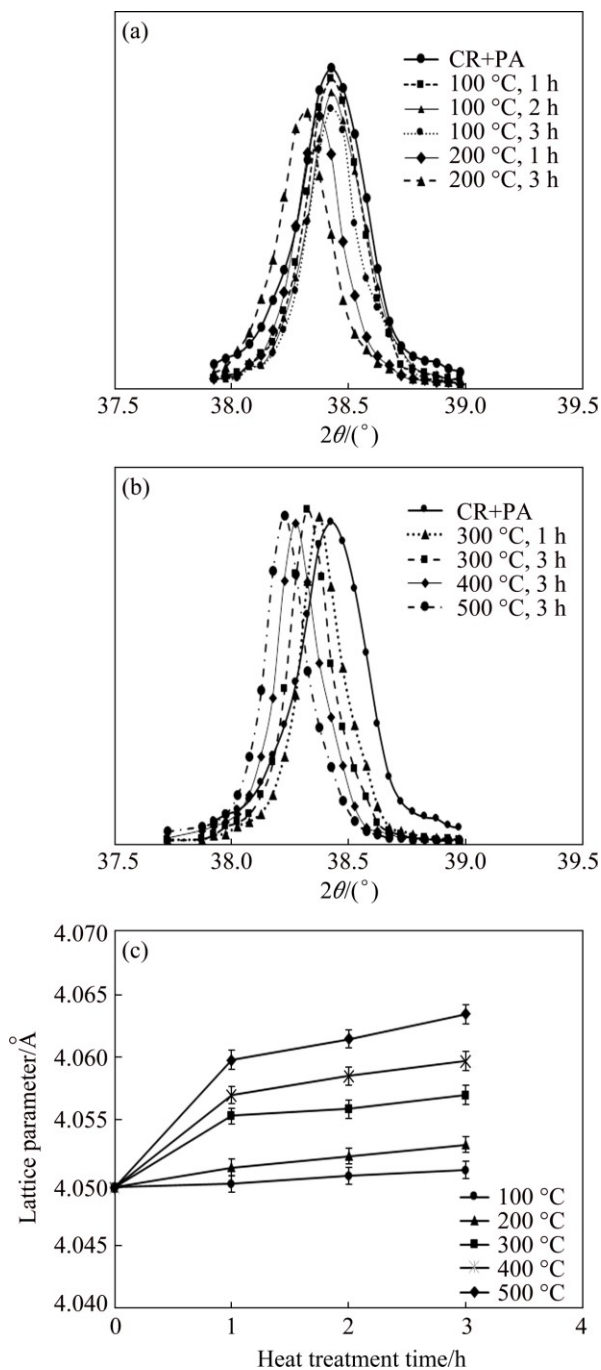


Fig. 7 Displacement of (111) aluminum peak after heat treatment at 100–200 °C (a), at 300–500 °C (b) and changes in lattice parameter of Al as function of heat treatment time and temperature (c)

diffraction patterns of heat-treated samples, dissolution of the Mg_2Si precipitates and the significant strength reduction are the main changes during heat treatment at temperatures higher than 200 °C. This is accompanied by displacement of (111) aluminum X-ray peak to lower angles (Fig. 7(b)) and also increasing the lattice parameter of Al (Fig. 7(c)), which represents the dissolution of intermetallic compounds at temperatures higher than 300 °C.

3.3 Grain growth kinetics

Based on Fig. 5, with increasing annealing temperature and time, the loss of properties would be increased and grain growth plays an important role in decreasing mechanical properties. Grain growth in an exothermic process is inherent because it reduces the energy of the system. However, in any case, this process requires a driving force which is provided from microstructural changes or absorbed heat by the environment. Generally, grain growth kinetics is based on an empirical relation according to the following equation [17]:

$$d^n - d_0^n = kt \quad (7)$$

where d is grain size at time t , d_0 is the initial grain size, t is annealing time, n is grain growth exponent and k is a parameter corresponding to the migration of grain boundaries at the interface. Equation (7) indicates isothermal growth in ideal condition and is based on two assumptions. First, there is a direct correlation between the rate of grain growth and interfacial free energy per unit volume [13]. And second, there is an inverse relationship between the rate of grain boundaries migration and grain boundary curvature [14]. Based on these assumptions for ideal grain growth, the amount of grain growth exponent (n) has an approximate value of 2 [16]. In Fig. 8, the values of the isothermal grain growth exponent (n) are plotted versus annealing temperature. The value of n was obtained by fitting the isothermal grain growth data mathematically using a nonlinear general curve fitting to Eq. (7). According to the results, the amount of n decreases by increasing the temperature. However, it indicates two different behaviors in the temperature range of 100–200 °C and 300–500 °C, which may be due to the effect of dispersed nanometer precipitations on pinning of grain boundaries [31]. According to the results, the value of n is equal to 7.5 and 2 in the temperature ranges of 100–200 °C and 300–500 °C, respectively.

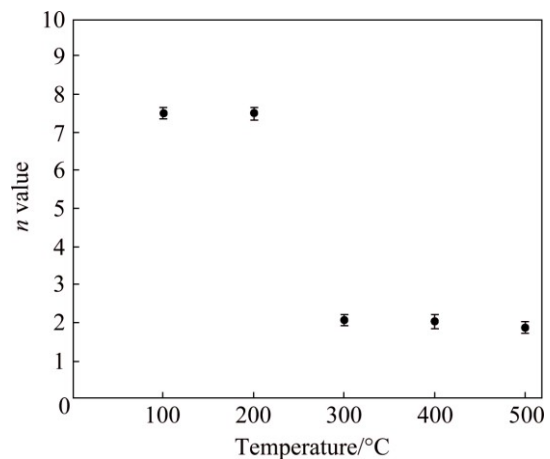


Fig. 8 Changes in n value of Eq. (7) versus temperature

Grain growth rate is dependent on the grain boundaries mobility factor (k) which is dependent on temperature according to Eq. (8) [31]:

$$k = k_0 \exp\left(\frac{Q}{RT}\right) \quad (8)$$

where k_0 is an independent factor of temperature and time, R is the gas constant, T is the temperature of the material, Q is the mobility activation energy of grain boundaries, which is related to the driving force for starting the grain growth. By combining Eqs. (7) and (8), Eq. (9) is obtained as follows:

$$\ln(d^n - d_0^n) = \ln k_0 + \ln t - \frac{Q}{R} \left(\frac{1}{T}\right) \quad (9)$$

Now, there is a linear relation between $\ln(d^n - d_0^n)$ and the slope of $(-Q/R)$, and hence it is possible to calculate activation energy needed for grain growth in the CR+PA Al6061 alloy. According to the changes in grain size with the temperature in Fig. 4, it was observed that until 200 °C, major changes did not occur in the crystallite size. However, the significant growth occurs at temperatures higher than 300 °C. In Fig. 9, grain growth kinetics for CR+PA sample with the activation energy values calculated from the slope of the curves are given. Also, in Table 4, a comparison on the thermal stability of aluminum alloys produced by different methods is performed and the reported activation energy can be observed. According to the results, obtained activation energy for grain growth of CR+PA sample at the low temperatures is equal to 203.3 kJ/mol, which is significantly more than aluminum samples produced by cryomilling (CM), equal channel angular pressing (ECAP) and accumulative roll bonding (ARB). The main reason of this difference is that, in the low-temperature range in the mentioned cases in the literatures [14,16,17,29,32,33] due to the presence of unstable structure, less driving force is needed for the grain growth. However, due to the optimized aging process in the CR+PA sample, non-equilibrium structures are lost after cryorolling process. On the other hand, the amount

of activation energy in the high temperature range (300–500 °C) is similar to that for nanostructured alloys produced by other processes and activation energy for self-diffusion of polycrystalline aluminum (143.4 kJ/mol [32]). Effective factors on activation energy are the presence of precipitates and their effect on pinning grain boundaries, which prevents the grain boundaries migration. However, by increasing the temperature due to the dissolution of strengthening precipitates and reduction in the effect of pinning the grain boundaries, the amount of activation energy is reduced.

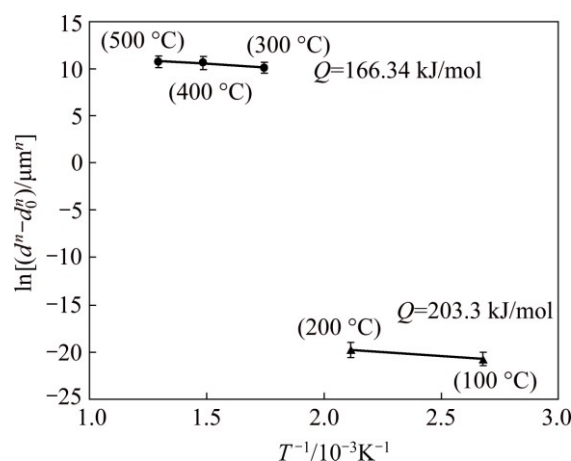


Fig. 9 Kinetics changes of grain growth for CR+PA sample

As it is presented in Fig. 10, the effect of Portevin–LeChatelier (PLC) or dynamic strain aging that causes appearance of indentation in the stress–strain curves, is one of the stress–strain characteristics of sample heat treated at 400–500 °C. This phenomenon appears when the solute atoms have good mobility. Under these conditions, the atoms can be placed below the dislocation line, so lock them and then by increasing the force this obstacle would be removed. According to the presented results in this field, for nanostructured Al–Mg–Si alloys, very fine precipitates dispersed in the structure act as a barrier to the movement of dislocations, and hence the PLC effect is not observed [34]. In other words, PLC

Table 4 Comparison between activation energy of grain growth in aluminum alloys produced by different methods

Material	Process	Activation energy (kJ/mol)		Exponent (n)	Ref.
		Low temperature	High temperature		
Al 5083	CM	25 (75–200 °C)	124 (200–275 °C)		[30]
Al 5083	PM	5.6 (<381 °C)	142 (>381 °C)	2	[28]
Al–3%Mg	ECAP	30 (<275 °C)	90 (>290 °C)	2	[14]
Al	PM	79 (200–300 °C)	112 (>300 °C)	2	[16]
Al 2024	CR	20.72 (200–350 °C)	163.96 (350–400 °C)	2	[31]
Al 6061	ARB	13.3 (50–300 °C)	–	2	[17]
Al 6061	CR+PA	203.3 (100–200 °C)	166.34 (300–500 °C)	7.5 (Low)–2 (High)	Present work

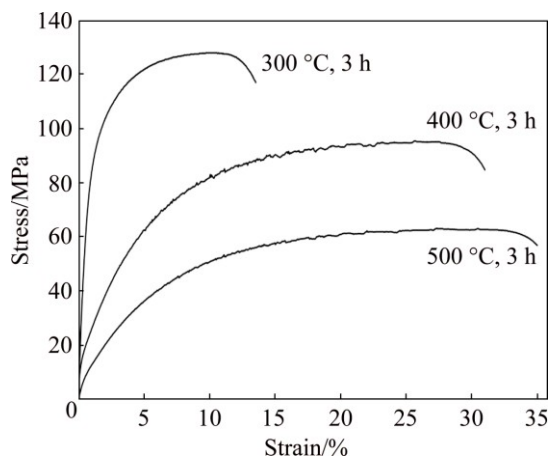


Fig. 10 Changes of stress–strain curves after aging in range of 400–500 °C for 3 h

effect arises when the stoppage time of dislocation behind obstacles (t_w) is in the level of solute atoms to the dislocation line (t_d). Therefore, in the presence of very finely dispersed precipitates, PLC effect is not observed.

4 Conclusions

1) A nanostructured Al6061 alloy with grain size of 61 nm and dispersed 50–150 nm sized strengthening precipitates was produced by cryorolling process followed by optimum aging heat treatment.

2) A significant increase was observed by applying cryorolling and aging process (CR+PA sample), such that yield strength, ultimate tensile strength and hardness of CR+PA sample were HV (118±3), 362 MPa and 388 MPa, respectively.

3) Evaluation of thermal stability of CR+PA sample within 100–500 °C temperature range, for 1 to 3 h showed that, up to 200 °C, the main structural characteristics of nanostructured Al6061 alloy including nanosized grains and dispersed fine Mg_2Si precipitates and kept even after annealing for 3 h.

4) By increasing the annealing temperature to more than 300 °C in thermal stability tests, according to XRD patterns, Mg_2Si dissolved and grain growth occurred which resulted in decreasing mechanical properties.

5) Little differences in position of Al (111) peak and lattice parameters in XRD patterns of cryorolled Al6061 alloy within 100–200 °C temperature range is a good evidence for stable structure of nanostructured Al6061 alloy.

6) The activation energies for grain growth of nanostructured Al6061 alloy were calculated to be 203.3 kJ/mol for annealing at 100–200 °C and 160.34 kJ/mol for annealing at 300–500 °C. Furthermore, the isothermal grain growth exponent (n) was calculated to be 7.5 at 100–200 °C and 2 at 300–500 °C.

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深冷轧制备纳米 6061 铝合金的热稳定性评估

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摘 要: 研究深冷轧时效态纳米 6061 铝合金在 100~500 °C 下等温热处理过程的晶粒生长。透射电子显微镜观察结果表明经深冷轧及在 130 °C 时效 30 h, 合金显微组织中含有 61 nm 的晶粒和 50~150 nm 的析出相, 以及 0.248% 的点阵畸变。此外, 由于形成细小的强化相和纳米晶粒, 合金的拉伸强度达到 362 MPa。在 100~500 °C 下进行热稳定研究, 结果表明, 点阵畸变得到减弱, 析出相溶解, 晶粒长大。X 射线衍射结果表明, 当退火温度高于 300 °C 时, Mg₂Si 相将消失。当退火温度低于 200 °C 时, 晶粒长大不明显, 力学性能下降也不明显。但在 300~500 °C 时, 晶粒长大, 析出相溶解和力学性能下降都比较明显。在 100~200 °C 时, 晶粒长大的活化能为 203.3 kJ/mol, 在 300~500 °C 时, 活化能为 166.34 kJ/mol。讨论了析出相溶解对铝点阵常数和 XRD(111)面峰位移的影响, 也讨论了 PLC 对应力应变曲线的影响。

关键词: 力学性能表征; X 射线衍射; 铝合金; 体变形; 晶粒生长; 晶粒细化

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