

Combined effect of deformation and artificial aging on mechanical properties of Al–Mg–Si Alloy

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Abstract: The effect of pre-deformation followed by or together with artificial aging on the mechanical properties as strength and ductility of an AA6060 aluminium alloy was studied. AA6060 was initially cast, homogenized and extruded according to standard industrial practice. The extruded material was then subjected to a solution heat treatment and subsequently artificial aging after (sequential mode) and during (simultaneous mode) various combinations of deformation (0–10%) and heat treatments. The aging behaviour and mechanical properties were characterized in terms of Vickers hardness and tensile testing. It is found that precipitation kinetics and associated mechanical response, in terms of hardness and tensile properties are strongly affected by pre-deformations. In terms of aging behaviour, kinetics is accelerated and the peak strength generally increases. Comparing sequential mode and simultaneous mode, the latter seems to give overall better mechanical properties and after considerably shorter aging times. The results of the two modes of pre-deformation are compared and discussed in view of differences in processing conditions and microstructure characteristics.

Key words: Al–Mg–Si alloys; artificial aging; pre-deformation; tensile properties

1 Introduction

Al–Mg–Si-alloys (i.e. 6xxx series alloys) are widely used in the automotive sector, for packaging and in the building industry. 6xxx alloys are chosen whenever heat-treatable alloys combining medium strength with good corrosion resistance, reasonable weldability and moderate cost are required. Aluminium products made of 6xxx aluminium alloys are often first extruded, then formed, and finally artificially aged, i.e. heat treated at elevated temperatures, to obtain the desired mechanical strength. Even without forming, extruded profiles commonly have to be stretched to straighten out a certain degree of buckling and bending of the profiles as they leave the extrusion die. In both cases precipitation takes place in a material which is deformed to various degrees, which may strongly affect the precipitation behaviour and associated aging response. For many years there has been an extensive activity to characterise precipitation and aging behaviour

in Al–Mg–Si alloys, and the structural characteristics and associated mechanical response during aging as a function of alloy chemistry and heat treatment procedures are now well established [1–9]. However, the complex interplay between deformation and precipitation and their combined effect on the aging behaviour and associated mechanical properties are generally less characterized and quantified.

In order to investigate more systematically the effect of pre-deformation and artificial aging on the mechanical properties of an Al–Mg–Si alloy, a series of tensile tests have been designed and carried out on the commercial aluminium alloy AA6060. For the first set of experiments, a conventional way was used in order to pre-deform the material, where the pre-deformation is introduced after solution heat treatment, and prior to any aging at elevated temperatures, i.e. by sequential mode of aging treatment. Although this way of pre-deforming material is widely used in industry in order to improve the artificial aging response in Al–Mg–Si alloys [10–15], systematic investigations and a detailed documentation

of the effects are lacking. The same, and even more so, applies for the effect of simultaneous deformation and aging in Al–Mg–Si alloys. Some attempts to compare the two modes (sequential and simultaneous) of aging in Al–Mg–Si alloys have been done by CAI et al [16]. They observed an increase in the ultimate tensile strength for both an AA6061 and an AA6069 alloy treated via simultaneous mode as compared to a conventional sequential treatment at the same temperature. They also demonstrated that the size of the precipitates in simultaneously aged alloys is amendable by the temperature and strain rate of deformation, and that the growth of precipitates during simultaneous treatment is governed by dislocation-assisted diffusion mechanisms. However, the pre-deformation in their experiments was introduced by using the equal channel angular pressing (ECAP) technique providing much higher effective strains and resulting in higher dislocation densities than in the present work where the pre-deformation is kept within a range between 0 and 10%.

2 Experimental

An AA6060 aluminium alloy was obtained from Hydro, Norway. The received extrusion billets were industrially direct chill (DC) cast in logs, 203 mm in diameter, and then split and machined to billets, 95 mm in diameter and 200 mm in length. The billets were homogenized at 585 °C (± 10 °C) for 2 h (± 15 min) and extruded into 20 mm rods using an 800 t instrumented laboratory press at SINTEF in Trondheim, Norway. Prior to extrusion the billets were heated to 545 °C in an induction furnace, cooled by forced air to 430 °C and stabilized at this temperature. The profiles were extruded into a water tank and were thus rapidly quenched to room temperature (RT). This procedure of pre-heating the extrusion billets was referred to as “overheating” [17] and was used in order to ensure that all (Mg, Si) particles

were dissolved in the profile as it left the extrusion die [7]. The chemical composition of the alloy is given in Table 1.

Table 1 Chemical composition of AA6060 alloy investigated (mass fraction, %)

Al	Mg	Si	Mn	Fe
Bal.	0.47	0.41	0.02	0.2
Ti	Cu	Zn	Cr	
0.008	0.003	0.009	0.002	

All test samples were solution heat treated (SHT) for 5 min in a salt bath at 545 °C, water quenched, and then either only artificially aged at 190 °C for different aging time (10, 100, and 300 min), pre-deformed (amount of deformation is 2%, 5% and 10%) prior to artificial aging, i.e. in sequential mode, or pre-deformed (2%, 5% and 10%) together with artificial aging, i.e. in simultaneous mode.

In the latter case (simultaneous mode), pre-deformations were introduced into the specimens (with a gauge diameter of 6 mm) simultaneously with artificial aging treatments using a hydraulic MTS 880 testing machine equipped with an MTS 651 environmental chamber at various crosshead speeds ranging from 5.7×10^{-3} to 0.345 mm/min, corresponding to an average strain rate from 2.78×10^{-6} to $1.67 \times 10^{-4} \text{ s}^{-1}$, respectively. Strain was measured in the reduced section of the specimens using a longitudinal clip-on extensometer (MTS 633.11C–10) with 25 mm gauge length. Tensile tests were conducted at RT using a hydraulic MTS 810 testing machine at a constant crosshead speed of 2 mm/min, corresponding to an initial strain rate of $1.3 \times 10^{-3} \text{ s}^{-1}$.

The experimental setup for tensile testing of the pre-deformed and simultaneously artificially aged AA6060 alloy is schematically shown in Fig. 1. Tensile

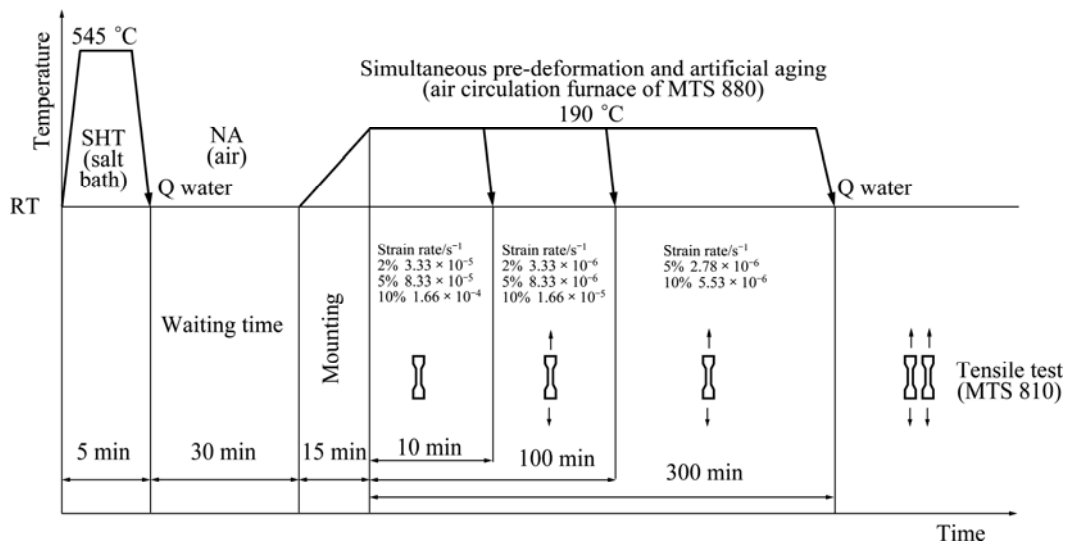


Fig. 1 Experimental setup for tensile testing of simultaneously deformed and artificially aged AA6060 with indicated time-frame

test specimens machined from the extruded rod were solution heat treated (SHT) at 545 °C for 5 min and immediately quenched into water (WQ) at room temperature (RT). Then, after 30 min storage at RT, specimens were mounted in the grips of the MTS 880 testing machine within 15 min. Pre-deformation was introduced by stretching the specimens at different strain rates up to the desired degrees. These well-defined values of strain rates and pre-deformations resulted in the corresponding times of simultaneously ongoing artificial aging. Artificially aged specimens were then cooled to RT in water and tensile tested to fracture.

3 Results and discussion

3.1 Sequential mode

The effect of pre-deformation in the range of 0–10% in sequential mode on the hardness response and the associated tensile properties has been reported elsewhere [18,19], and only the main results and conclusions are recapped here, as a basis for a comparison with the simultaneously deformed and aged conditions reported below. For pre-deformation followed by artificial aging at 190 °C, it was found that there is a distinct increase in the peak hardness at the same time as the peak condition is reached after a shorter time. Without pre-deformation the peak condition is reached after about 300 min, while for the condition with 10% pre-deformation peak strength is reached within 200 min. In general, the peak hardness for the artificially aged pre-deformed material is significantly higher compared to that of the material with no pre-deformation. This is a combined effect of strength additions from strain hardening (dislocations) and precipitate hardening, whose relative contributions change with pre-deformation and aging time [19].

Key parameters characterising the stress—strain tensile behaviour, after different degrees of pre-deformation and different aging times, i.e. 10, 100, and 300 min, are summarised in Table 2. As shown in the table, the uniform strain decreases with increasing pre-deformation and increasing aging time. The yield strength (YS) and ultimate tensile strength (UTS), on the other hand, generally increase with increasing pre-deformation. However, after artificial aging at 190 °C for 300 min, the stress—strain curves level out regardless of the introduced pre-deformation [19], resulting in almost the same yield and ultimate tensile strength for all pre-deformations. In this latter case the increase in the dislocation strength contribution with pre-deformation is counter-balanced by a decrease in the precipitate hardening contribution, which can be understood by changes in the precipitation kinetics and behaviour. Still, the sequentially deformed and aged

material that reaches the highest yield and ultimate tensile strength at given heat treatment parameters is 10% deformed and subsequently artificially aged for 300 min. However, it is also observed that with only 2% of pre-deformation prior to 300 min aging, only slightly lower mechanical properties (UTS=223 MPa) compared to the 10% deformed one are obtained.

Table 2 Mechanical properties in terms of yield stress, ultimate tensile strength and uniform strain of AA6060 after different degrees of pre-deformation and aging time in sequential mode

Pre-deformation/ %	Aging time/ min	Yield stress/ MPa	Tensile strength/ MPa	Uniform strain
0	10	40	145	0.165
	100	112	180	0.088
	300	185	223	0.063
2	10	69	148	0.136
	100	141	188	0.065
	300	192	223	0.051
5	10	97	166	0.130
	100	174	212	0.063
	300	195	226	0.056
10	10	123	180	0.086
	100	193	224	0.057
	300	202	231	0.053

3.2 Simultaneous mode

A record of engineering stress—strain curve of material with pre-deformation can serve as a substitute to commonly used hardness measurements in order to characterize the mechanical response during artificial aging in simultaneous mode. Figure 2(a) shows the record of engineering stress versus time (referred to as an “aging curve”) of the materials deformed to various degrees during simultaneous artificial aging at 190 °C. The samples pre-deformed by 2%, 5% and 10% in 10 min, respectively, seem all to be in an under-aged condition since there is no sign of flattening at the end of the “aging curves”. On the other hand, the samples pre-deformed by 5% and 10% in 300 min are strongly over-aged as the “aging curves” gradually decrease in stress after reaching the “peak” stress between 100 and 150 min of aging. After simultaneous deformation and aging for 100 min the specimens pre-deformed by 2% and 5% seem to be close to their peak-aged conditions. However, the specimen pre-deformed by 10% seems to be still slightly over-aged after aging for 100 min, and its peak-aged condition is probably reached in even a shorter time (between 10 and 100 min).

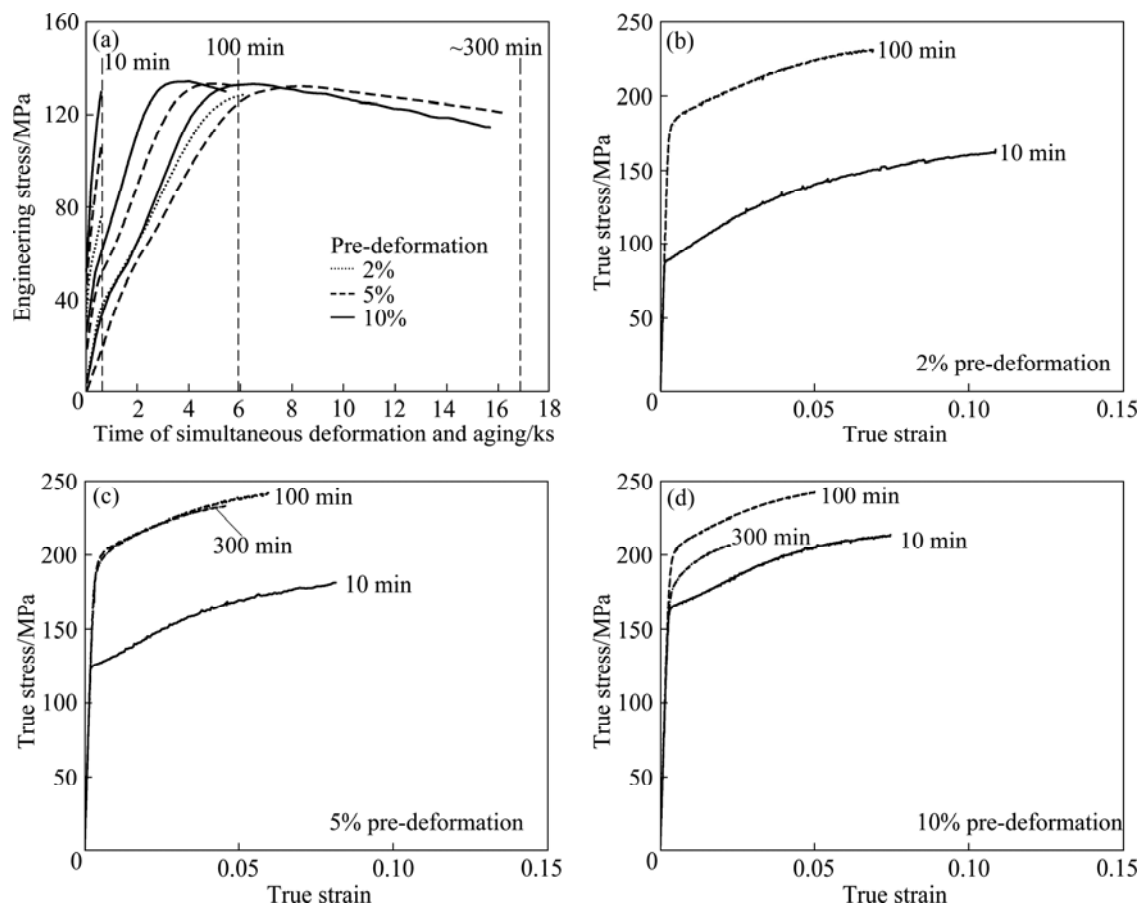


Fig. 2 Aging curves for materials simultaneously deformed and aged at 190 °C (a) and corresponding true stress—strain curves for 2% (b), 5% (c) and 10% (d) pre-deformation

The same mechanical properties behaviour as observed and concluded from the “aging curves” in Fig. 2(a) can be verified by investigating the true stress—strain curves in Figs. 2(b), (c) and (d). Samples after 100 min aging, i.e. in peak-aged or close to peak-aged condition, display increased yield and ultimate tensile strengths compared to both under-aged samples after 10 min and over-aged samples after 300 min. As can be seen in Figs. 2(c) and (d), samples deformed by 5% and 10% and aged for 300 min reach very low values of uniform strain and their plastic region of the stress—strain curve is very limited. This can most probably be attributed to a heavily over-aged microstructure.

Key parameters characterising the stress—strain tensile behaviour, after different degrees of pre-deformations and different aging times, i.e. 10, 100, and 300 min, in simultaneous mode are listed in Table 3.

A direct comparison of the tensile properties following the two modes of deformation and aging are shown in Fig. 3. From Fig. 3 and Tables 2 and 3, the following observations can be made. Simultaneous mode of pre-deformation results in higher yield stress (YS) and ultimate tensile strength (UTS) for 10 and 100 min of artificial aging as compared to sequential mode, while

Table 3 Mechanical properties in terms of yield stress, ultimate tensile strength and uniform strain of AA6060 after different degrees of pre-deformation and aging time in simultaneous mode

Pre-deformation/ %	Aging time/ min	Yield stress/ MPa	Tensile strength/ MPa	Uniform strain
2	10	87	161	0.108
	100	180	231	0.068
	300			
5	10	123	167	0.081
	100	200	241	0.059
	300	193	231	0.045
10	10	164	213	0.074
	100	202	242	0.050
	300	176	206	0.023

after 300 min of artificial aging the mechanical properties of simultaneous mode degrade as compared to sequential mode. With 2% pre-deformation and 10 min of artificial aging (AA) in simultaneous mode, an increase of ~20 MPa in YS as compared to sequential

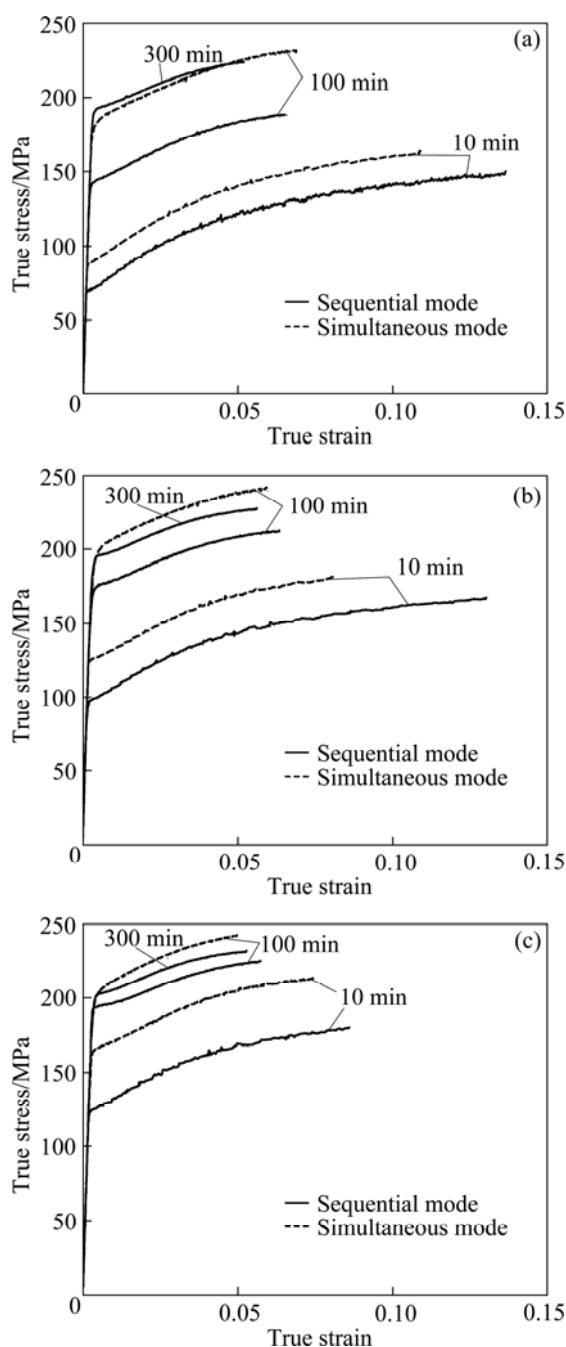


Fig. 3 Comparison of stress—strain curves for the two modes of deformation after different aging time with different amounts of predeformation: (a) 2%; (b) 5%; (c) 10%

mode is obtained, a difference which increases to about 40 MPa for 10% deformation and AA of 10 min. After the 100 min of AA the surplus of the simultaneous mode decreases with increasing degree of deformation. Almost the same values of mechanical properties are obtained for 2% pre-deformation in simultaneous mode, as 5% in sequential mode (as well as 5% simultaneous mode and 10% sequential mode). Moreover, for 100 min of artificial aging, 2% simultaneous deformation reaches the same mechanical properties as 10% pre-deformation in sequential mode.

Comparing the same amount of pre-deformation, it is seen that 2% pre-deformation in simultaneous mode results in very similar values of yield and ultimate tensile strengths after 100 min of aging as compared to the sequentially treated material aged for 300 min. However, in the former case the uniform strain is increased by 0.02. For both 5% and 10% deformation in simultaneous mode 100 min of aging displays the best overall properties, as compared with those of the sequential mode and simultaneous mode aged for 300 min. Artificial aging for 300 min in general levels all the stress—strain curves out regardless of the mode of pre-deformation (sequential vs simultaneous), and for the simultaneously treated material the mechanical properties are already considerably degraded including very small fracture strains (Table 3).

4 Discussion and conclusions

In sequential mode, we introduce the pre-deformation at room temperature after solution heat treatment prior to any artificial aging. The tensile test sample is pre-deformed at a relatively high average strain rate of $1.3 \times 10^{-3} \text{ s}^{-1}$. During such pre-deformations, dislocations are introduced into the material with a microstructure corresponding to the solution heat treated condition with a majority of elements in solid solution. Dislocation sources are then limited to line defects (dislocations produced as a result of solidification and processing which are left after SHT) and point defects (isolated solute atoms, clusters of atoms and vacancies). New dislocations are then generated or multiplied as proposed by the Frank-Read mechanism [20], and they further frequently pile up on slip planes at grain boundaries. The pre-deformed tensile test sample is then subjected to an artificial aging treatment. During artificial aging, precipitation takes place in the material where the precipitates form predominantly on dislocations which serve as nucleation sites [20–23].

In the undeformed material, precipitates form homogeneously during artificial aging [20,23]. The main hardening precipitates are expected to be β'' , which contribute significantly to the final mechanical properties due to their small size and homogeneous distribution. In the case of pre-deformed material, the precipitates of mainly post- β'' type form heterogeneously on dislocations [20,23]. The governing factor for such a case is the dislocation density. When increasing the amount of introduced dislocations, the number of nucleation sites for precipitates is increased and faster dislocation-assisted diffusion replaces slower bulk diffusion. However, the drawback of pre-deformation can be seen in faster coarsening of the precipitating phases [20,23]. This coarser size, together with a heterogeneous

distribution of post- β'' precipitates, causes less pronounced effect on final mechanical properties compared to that of β'' precipitates in the undeformed material. However, this is counter-balanced by the strain hardening contribution from pre-deformation to the final mechanical properties. These observations are in good agreement with the findings of a number of research groups [10,21,22,24,25].

It can be assumed that all previously mentioned mechanisms are also acting at about the same time in simultaneous mode, but in contrast to sequential mode, these mechanisms act, in simplification, one after each other. This makes it difficult to separate the effects of concurrent introduction of dislocations, precipitation and their interaction during simultaneous pre-deformation and aging. In this mode, dislocations start to be introduced in the solution heat treated material at considerably slower rates as compared to that in sequential mode, i.e. with strain rates ranging from 2.78×10^{-5} to $1.67 \times 10^{-4} \text{ s}^{-1}$. However, the rate of dislocation introduction is then continuous throughout the whole aging process and affects both the nucleation and growth of precipitates. Due to this gradually developing formation of precipitates we have to consider, as well, their role as new obstacles for introduced dislocations. It can be concluded that the microstructure in the material develops as a result of complex interplay between dislocation and precipitate formation and interactions.

One of the most striking effects of simultaneous mode of aging treatment is a significantly decreased aging time to reach the peak-aged condition, with even better mechanical properties than in the sequential mode. It can be speculated whether this beneficial effect of simultaneous mode can be attributed to the fact that the nucleation of precipitates takes place in a dynamic situation where dislocations sweep through the material (most probably in a Jerky mode), providing a high density of heterogenous nucleation sites. Moreover, upon continued straining the dislocations unpin from the precipitates and coarsening of the already precipitated particles takes place in a undeformed matrix, i.e. slower than in the static situation above, ensuring a faster precipitation kinetics and higher density of small precipitates in the simultaneous mode, which is beneficial for the mechanical response. In addition, the interaction between introduced dislocations (by pre-deformation) and forming precipitates during the aging treatment, most probably results in a more effective strain hardening, compared to the strain hardening prior to artificial aging in sequential mode, which is dependent only on mutual interactions between dislocations.

To conclude, it has been shown that precipitation

kinetics during artificial aging of an Al–Mg–Si-alloy (AA6060) and associated mechanical response, in terms of hardness and tensile properties are strongly affected by pre-deformation (in the range of 0–10%). In terms of aging behaviour, kinetics is accelerated and peak strength generally increases. Comparing sequential pre-deformation and aging and simultaneous deformation and aging, the latter seems to give overall better mechanical properties and most importantly with shorter aging time to peak strength. The latter observation is most probably due to a unique synergy of concurrent deformation and precipitation, where moving dislocations provide fast precipitation of a high density of small precipitates, which gives the superior mechanical properties. However, further investigations, preferentially detailed quantitative transmission electron microscopy (TEM) studies are needed to understand and explain the mechanical results obtained in view of the underlying microstructural evolution. In addition, the effect of aging and deformation conditions on the ductility to fracture is to be taken into consideration.

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预变形结合人工时效对 Al–Mg–Si 合金力学性能的影响

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摘 要: 研究预变形结合人工时效处理对 AA6060 铝合金强度和韧性的影响。对经过均匀化热处理和挤压加工的 AA6060 铝合金进行固溶处理, 然后对材料实施 0–10% 的预变形并再进行时效处理或者在人工时效过程中进行同步变形。通过对不同时效处理后的合金的显微硬度和拉伸性能分析, 发现预变形对材料的时效行为和力学性能有显著影响, 它可以使合金的时效速度明显加快。比较预变形和同步变形对人工时效的影响发现, 同步变形结合人工时效可以使该合金在更短的时间内得到更好的力学性能。对两种变形对时效行为的影响机理进行了探讨。

关键词: Al–Mg–Si 合金; 人工时效; 预变形; 拉伸强度

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