Ageing condition of tensile specimens: fracture behavior of notched Al2024 sheet under tensile loading

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Abstract
The effect of different (T6 and T8) heat treatments on tensile properties and fracture behavior of Al2024 in presence and absence of notch by means of microhardness, tensile tests and scanning electron microscopy were investigated. Tensile and hardness specimens were subjected to two different artificial ageing (T6 and T8 heat treatment) for various times. These included under ageing (UA), peak ageing (PA) and over ageing (OA). T8 heat treatment, which has a cold rolling between solutionizing and ageing in its steps, showed a higher value of hardness and yield strength in comparison with common artificial ageing of T6 heat treatment. In notched-tensile specimens, yield stress was found to increase up to the peak ageing condition with a simultaneously decrease in elongation at fracture. This behavior was converse at OA condition. Although introducing of notch increase the yield stress of samples under T6 and T8 conditions in comparison with un-notched samples, the notch strengthening phenomenon was observed only under T8 treatment. Despite of an enhancement in strengthening by applying notch on tensile samples, the elongation to failure was notably lessen in both notched-heat treated samples in comparison with un-notches ones. Also, it was confirmed that the toughness of notched samples of both heat treatments at PA condition were significantly lower than un-notched ones. Consequently, toughness decrement was considerably dominated by the role of deformability compared to strengthening factor, however, the presence of cold rolling in the process of heat treatment (T8) could reduce the harmful effects of notch by increasing the stress bearing capacity in contrary with T6 heat treatment. Moreover, inserting the mechanical properties of peak aged samples from the un-notched tensile test in Abaqus finite element software; the V-shaped notch tensile test was simulated and confirmed the experimental results. It was shown in SEM results that the presence of notch enhanced the contribution of cracked particles, compared to particle/matrix deboining and matrix deformation, therefore, the non-homogeneous distribution of fracture features confirmed the harmful effect of notch. In the following, the distribution of three fracture micro-mechanisms were homogeneous in un-notched samples, which demonstrated the superior values of toughness in smooth samples. The present finding sheds light on development of processing techniques to optimize the mechanical properties of Al 2024 alloy.

Introduction
Al 2024 alloy has wide applications in numerous industries because of its excellent mechanical properties. Having high strength and adequate deformability make Al-2024 the best nominee for airframe structures [1]. In order to enhance the mechanical properties of this alloy, microstructural design is introduced as an effective strategy [2, 3]. One of the most effective strategy is heat treatments, which have notable effects on the nature, size and distribution of small particles which are demonstrated as precipitations [4, 5].

The most important prerequisite for the hardening process in an alloy is the limited solubility of the precipitate or the hard secondary phase in the alloy and the reduction of this solid solubility with decreasing
temperature [4]. Aluminum alloy 2024 is a high strength alloy with a heterogeneous structure that have intermetallic particles and dispersoids [5]. The most common intermetallic particles in the microstructure of Al2024 are the S-phase (Al2CuMg) particles. Strakeet et al [6] suggested that, in addition to S-phase and Ω-phase (Al2Cu) particles, the intermetallic particles included AlCuFe and AlFeMnSi. Bagaryatsky [7] proposed the following precipitation sequence:

$$\text{SSS} \rightarrow \text{GPBzone} \rightarrow S'' \rightarrow S' \rightarrow S$$

In this sequence, the SSS represents supersaturated solid solution and GPB is considered to be a short range ordering of Cu and Mg solute atoms. Also, S' are very small precipitates fully coherent with the Al matrix, while S-phase is considered as an incoherent phase. According to Ringer et al [8, 9], GPB zones and other precipitate-structures prior to the S-phase formation are considered as the dominant precipitates at the strengthening regime of the ageing curve, while the S-phase particles appears in the over-ageing (OA) regime.

Indeed, the values of hardness among different ageing time are controlled by the type, size and distribution of precipitates [6]. In the other words, the values and widths of this hardness-time curves depend on the heat treatments’ condition, such as: natural or artificial ageing [7–9]. For instance, Huang et al [10] found that by increasing the ageing temperature of Al2024, the peak value of hardness increases, however, the time to reach the maximum hardness value increases as well. Also, they found that the strength of Al2024 increased in artificial aging compared to natural one because of discrepancy in the size and types of precipitation. Moreover, Alexopoulos et al [11] found that lower ageing temperature enables higher peak strength to be achieved due to the well-balanced formation of S', S'' and S precipitates.

In addition to precipitation hardening as a strengthening mechanism, strain working can be effective for producing fine-grained materials which increases the strength of material [12]. By applying cold working, the strength of material is enhanced due to the growth of dislocation density [13]. Considering this issue, it was found that applying cold rolling between solutionizing and age-hardening in heat treatments steps (T8 heat treatment) make a significant increase in hardness. In addition, the time that is required to achieve peak hardness is rather short in contrast to the typical age-hardening, i.e. heat treatments without cold working [14]. In another research, Zhao et al [15] found that, in addition to the effect of cold-working itself, the amount of this metal forming process has notable effect on the value of hardness and strengthening as well. For example, as it was represented by Zhao et al [15], Al-2024 alloy’s strength is increased by increasing the rate of cold working up to 30% then decreased after this amount, due to the higher number of Ω participates with smaller diameters that nucleate on dislocations at 30%. It is notable that Ω participates have a lower number and bigger diameter at rates higher and lower than 30%.

In addition to different types of heat treatments, the geometry of specimens can influence the strength of materials [16, 17]. For instance, in the presence of notch, as a stress concentration factor, the risk of crack initiation from the notch borders enhance as a result of high stress gradient at the notch neighborhood, and then the final fracture occurs owing to the propagation of the created crack [18]. For notched engineering components which are made of ductile materials, crack initiation and propagation normally proceed by plastic region around the notch, which absorbs energy till fracture happens. It is notable that, due to negligible deformability in brittle materials, the plastic energy absorption mechanism is not highlighted in these kinds of materials [19]. It was proved that with the present of notch, materials with limited plastic deformation become weaker and materials with higher plasticity begin to be stronger [20]. Regardless of strengthening or weakening behavior of materials in present of notches, the introduction of tri-axial stress field in the vicinity of notch, reduces plastic deformability considerably [21]. The tendency for reducing ductility simultaneous with severe stress gradient in the presence of a tri-axial zone is often termed as ‘notch sensitivity’, which is equated as the ratio of tensile strength of notched tensile samples to smooth ones, if this amount is upper than one, the material is not sensitive to notches and if this ratio is lesser than one, it can be concluded that the material is sensitive to notches [22]. For instance, Westerman et al [16] found that, although the yield stress of Al6060-T8 notably increases by applying notch, there is no obvious alteration in the magnitude of ultimate strength, so Al 6060 becomes weaker in the present of notch due to its high notch sensitivity to notch. In another research [23], the notch sensitivity of K418 (Ni based super alloy) as a ductile and TiAl alloy as a brittle material were studied. It was shown that, the value of tensile strength of notched samples is higher than smooth ones in ductile alloy, which demonstrated no notch sensitivity also, the final fracture of K418 alloy is controlled by strain. Despite the results of Ni-supper alloy, the final fracture of TiAl is controlled by stress, and specimens do exhibit small notch sensitivity. Considering, the geometry of notch can have effect on both tensile behavior and notch sensitivity [24, 25], e.g. Majzoobi et al [21] investigated theoretical and simulated analysis of notch geometry’s role on the point of damage. They realized that, the deformability and tensile strengthening increase and decrease respectively by increasing curvature radius of notch. It is notable that, the micromechanics of fracture can be varied by precipitation characteristics and notch nature [26].
Micro-voids coalescence, particle cracking accompanied with particle/matrix dehoming are three dominated micro-mechanisms of fracture in precipitation hardenable alloys, which the contribution of each fracture feature depends on both intrinsic nature of materials and loading conditions [27, 28]. For instance, doing any process or treatment which have results in precipitation refinement and/or homogeneous distribution of second phases can lead to an increment in the level of deformability via increasing the contribution of void coalescence [29]. In addition, the contribution of different fracture features depends on notch ratio, which was investigated by Derpenski et al [18] on Al 2024-T351 having circumferential notches.

Different shapes of notch, which act as stress concentration factor, is inevitable in mechanical structures joining and designing. Now, it is noteworthy to demonstrate that it is possible to decrease the effect of stress concentration on notched samples by modification of heat treatment conditions.

Up to our literature review, there are some researches which were concentrating on T6 heat treatment, as a routine treatment, and its effects on microstructure and mechanical properties of smooth or notched samples [4, 5, 11, 18]. The aim of this research was to investigating the tensile behavior and fracture mechanisms of smooth and notched samples under T8 and T6 heat treatments in three different conditions of UA, PA, OA. Also, notch sensitivity of Al 2024 alloys under these two heat treatments conditions were compared. It is notable that, up to our literature review [19, 30, 31], the effect of V-notch, which has the most stress concentration on alteration the micro mechanisms of fracture were not studied in detail. Thus it is interesting to demonstrate the consequence of stress concentration factor on fracture behavior under different types of artificial age hardening as T6 and T8 treatments. In addition to experimental tests, the simulation of notched samples were carried out to reach the better comprehension.

### Materials and methods

In this research, Al-Mg-Cu alloy was used in the form of sheet having 3 mm thickness. The composition of the alloy (table 1) indicated that the material is Al2024. Considering the potential of precipitation hardening of Al2024 alloy, different steps of heat treatments were applied according to T8 and T6 protocols. Following T8 treatment, solid solution treatment (SST) was carried out at 500 °C for various times for choosing the best solutionizing time, then the material immediately quenched into the water. Indeed according to [15], 500 °C is the temperature, which is above solubility line and in order to dissolve all hard precipitates, i.e. solutionizing, the specimen must keep until certain time to lessen the hardness value before grain growth taking place. After quenching, which results in super saturated solid solution, cold rolling with 30% thickness reduction was performed at room temperature. Then, all samples were heated to a temperature well below the dissolution temperature and allowed additional solute elements to penetrate into the germination sites which are the same lattice defects such as dislocation, vacancies and other lattice defects such as grain boundaries [15], so samples were heated at 200 °C (T8 heat treatment). Also, T6 heat treatment as a standard artificially aging (SST at 500 °C, water quenching and ageing at 200 °C) was carried out on a batch of samples. In order to evaluate the time of under aging (UA), peak aging (PA) and over aging (OA) conditions, T6 and T8 samples were heated at 200 °C up to 4 h. This high range artificially ageing time was chosen because of the reason that increasing the aging temperature causes the germination and sedimentation occur rapidly and hardness increases quickly, but due to high temperatures, it is possible to over-grow the sediments and thus reduce the hardness [14, 15].

Brinell hardness measurements with a load of 31.25 Kg was applied for a holding time of 10 s. At least 10 points were measured for each sample. The tensile tests according to ASTM E8 were performed to investigate the role of different heat treatments on mechanical properties of Al2024 samples. Tensile tests were carried out at 25 °C using an Instron 5500 type machine at strain rate of $2 \times 10^{-3}$ s$^{-1}$. In addition to smooth sample, notched tensile samples with 2 mm V-notched in both sides were tested. The schematic of smooth and notched tensile specimens were displayed in figure 1. Moreover, for the case of peak age condition, the Abaqus finite element method was employed to simulate the notch tensile tests. To this aim, the material properties of both T6 and T8 heat treatments were inserted in Abaqus from un-notched tensile tests. The mesh sizing of the 2D model is shown in figure 2. Besides, the dynamic explicit procedure was selected as a suitable solver for this problem. Finally, all fracture surfaces of specimens were analyzed by PhilipsXS30 scanning electron microscope.

As illustrated in figure 2 the model is x-symmetry in which the symmetry line shown by dotted yellow line. The mesh size decreased in the notch area to arrange a fine mesh.

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**Table 1. The Composition of 2024 Al alloy used in this study.**

| Element | Cu | Fe | Mn | Mg | Si | Al |
|---------|----|----|----|----|----|----|
| Weight% | 0.10 | 0.09 | 0.29 | 2.08 | 0.30 | 93.74 |
Results and discussion

Hardness

Figure 3 shows the hardness variations versus time for SST samples at 500 °C. After 60 minutes, the hardness of as-received samples decreased for about 36% immediately. This downward attitude became stable in from 1 to 3 h. Therefore, the solutionizing for 2 h was selected as SST time, in which, the precipitates was dissolved, as well as, any segregation was reduced [32].

In the following figure, the evolution of Brinell hardness as a function of ageing time for 2024 Al alloy samples subjected to different heat treatments is shown.

According to figure 4, in both heat treatments, rising the ageing time leads to an increment in hardness values until peak age. Afterwards, in over-aging states, the amount of hardness decreased. It is notable that, in the primary stage of hardening, the small precipitates nucleate and growth via diffusion, which is named as under-aging [10]. In utmost values of hardness, the distribution and size of precipitates are optimum [10]. Finally growth of hardening factor occurs after peak aging due to sacrificing small precipitates [15]. According to the mentioned figure, considering the value of as-received (0 hour) and maximum hardness (2 hours for T6 and 1 hour for T8) of both T6 and T8 heat treatments, it is seen that the hardness values were promoted at T8 condition.
compared to T6 heat treatment. In addition, the time required to achieve peak hardness in T8 heat treatment is found to be about 1 h, which is shorter than T6 heat treatment. One may claimed that, the significant increase in hardness values accompanied with accelerating peak aging time is accomplished by cold-rolling treatments. This could be attributed to the formation of high-density dislocation and vacancies introduced via cold rolling [33]. Accordingly, the chosen time for different aging conditions in T6 and T8 heat treatment were presented in table 2.

| Heat treatment | Under-aging time (min) | Peak-aging time (min) | Over-aging time (min) |
|----------------|------------------------|-----------------------|-----------------------|
| T6             | 30                     | 120                   | 240                   |
| T8             | 15                     | 60                    | 240                   |

compared to T6 heat treatment. In addition, the time required to achieve peak hardness in T8 heat treatment is found to be about 1 h, which is shorter than T6 heat treatment. One may claimed that, the significant increase in hardness values accompanied with accelerating peak aging time is accomplished by cold-rolling treatments. This could be attributed to the formation of high-density dislocation and vacancies introduced via cold rolling [33]. Accordingly, the chosen time for different aging conditions in T6 and T8 heat treatment were presented in table 2.

**Table 2.** Selected time for under age, peak age and over age time under T6 and T8 heat treatments.

**Tensile test**
The stress-strain curves of PA-T6 and PA-T8 samples were displayed in figure 5. Considering the figure, although the type of treatment cannot change the deformability of Al2024, the stress bearing capacity of cold rolled sample was significantly higher than the routine PA-T6 sample. Since the dislocation generation enhances because of cold rolling process, the precipitation-nucleation sites become numerous. This increment results in
stress shift up owing to further precipitation contents [15]. It reveals that, the combination of both precipitate size \((r)\) and the volume fraction of these second phases \((f)\) control the strengthening behavior as \(\sigma \propto \frac{f}{r} [32]\).

Considering figure 5 and table 3, the amount of yield stress and ultimate tensile strength of T8 heat treated species were increased about 28% and 21% compared to T6 samples respectively. One may claim that, rising the dislocation density in T8 samples is accompanied with descending the deformability. It is notable that, in T8 treatment, some plate-shape precipitate nucleate and growth which accommodate the deformation in Al matrix and benefits the materials' ductility [34]. In addition, despite the relative uniformity of strain, the more stress-bearing capacity in T8 treatment, results in an increment of toughness, the area underneath the stress-strain curve, for about 20%.

As the yield stress increases in peak ageing condition, the elongation at fracture decreases simultaneously. Considering precipitation growth under OA condition, the plastic deformability of matrix increases. This up and down hill behavior of strength versus aging time is investigated in the smooth samples without any imperfection [35]. In order to study these variations on notched samples, the effect of different aging conditions were studied on tensile behavior of T6 and T8 notched samples (figure 6). The value of mechanical data, which was obtained from figure 6 were presented in table 4.

Table 3. Tensile properties of smooth samples in PA condition under T6 and T8 heat treatments.

| Materials | Yield stress (MPa) | Ultimate tensile strength (MPa) | Elongation to failure (%) | Toughness (MJ.m\(^{-3}\)) |
|-----------|-------------------|-------------------------------|--------------------------|---------------------------|
| PA-T6     | 156.40            | 372.78                        | 29.79                    | 94.73                     |
| PA-T8     | 184.26            | 427.21                        | 30.23                    | 112.88                    |

Table 4. Data extracted from tensile test in T6 and T8 notched tensile tests. N denotes notched specimen.

| Materials | Yield stress (MPa) | Ultimate tensile strength (MPa) | Elongation to failure (%) | Toughness (MJ.m\(^{-3}\)) |
|-----------|-------------------|-------------------------------|--------------------------|---------------------------|
| N-UA-T6   | 265.32            | 362.02                        | 2.44                     | 6.35                      |
| N-PA-T6   | 282.2             | 365.31                        | 2.23                     | 5.57                      |
| N-OA-T6   | 223.84            | 339.74                        | 2.80                     | 6.86                      |
| N-UA-T8   | 385.65            | 532.20                        | 2.19                     | 7.69                      |
| N-PA-T8   | 414.86            | 528.66                        | 2.05                     | 7.18                      |
| N-OA-T8   | 362.67            | 515.92                        | 2.19                     | 7.53                      |

Figure 6. The stress-strain curves of UA, PA, OA condition and Abaqus FM in notched samples in (a) T6 and (b) T8 heat treatments.

Table 4 shows that, the yield strength of both notched samples under T6 and T8 heat treatments are enhanced with increasing ageing time up to maximum value; this maximum value is evaluated to be 282.2 and 414.86 for T6 and T8 samples, respectively. According to the literature [35], the variation of strengths among time related to the type and size of different precipitates. In addition, as yield stress increases up to peak ageing condition, the elongation at fracture decreases simultaneously. After this peak ageing condition, the elongation at fracture is meliorating in OA state. Following
to the trend of deformability, the magnitude of toughness is minimized in PA condition under both types of heat treatments.

Comparing the tensile results of smooth and notch samples in PA condition (tables 3 and 4) under T6 and T8 heat treatments shows that significant increment of yield strength is manifest after applying notches. The yield strength of PA samples with notch is about 80% and 125% higher than un-notch ones under T6 and T8, correspondingly. It was found that, the introduction of tri-axial stresses at the root of the notch, suppresses the plastic deformation of material and leads to yield strengthening. Similar behavior was also observed for UTS points under T6 and T8 conditions, which highlighted the role of precipitation characteristic on the resistance of plastic deformation based on types of heat treatments. One may claim that, the nature of precipitation such as the shape, size and distribution of these second phases was a function of heat treatment. The characteristics of precipitation alter the deformability of matrix, thus it is evident that the deformability of regions near the notch root modified based on the nature of second phases [16]. Therefore, it is expected that the amount of yield and UTS were greater in notch-T8 samples compared to T6 ones due to the discrepancy in the characteristics of precipitates in different heat treating conditions. Although the increment in the yield point is a prevalent phenomenon due to the multiple stresses in the vicinity of notch, this is not demonstrated notch-sensitivity. Indeed, the ratio of tensile strength of notched specimen to smooth ones is determined notch weakening or strengthening based on notch sensitivity [22]:

\[
NSR = \frac{S_{UTSN}}{S_{UTS}} \begin{cases} 
NSR > 1 & \text{Notch Strengthening} \\
NSR < 1 & \text{Notch Weakening}
\end{cases}
\]

Substituting the value of UTS in smooth and notch samples results in NSR values. It was observed that, the magnitude of NSR for T6 condition is about 0.98, which indicates notch weakening. This consequence is similar to Westerman et al [16] study, who worked on the tensile properties of notch samples of Al-6060 alloy under T8
In contrary to previous research [16], the value of NSR in this study for 2024-T8 condition is about 1.4, which is proved notch strengthening for Al2024 under T8 heat treatment or when it is subjected to cold-rolling before ageing during heat treatment sequences. Therefore, the phenomenon of notch sensitivity varies based on heat treatments and the chemical composition of material while the geometry of notch is even.

Although the value of yield point and maximum stress of specimens subjected to T8 heat treatment increase via introducing notch, the magnitude of toughness reduces tragically about 94%, which determines the role of ductility on toughness. In the other words, the existence of notch decreases the fracture strain severely, which diminish the energy absorption. The magnitude of this energy absorption reduction is greater for routine T6 heat treatment compared to T8 for about 28% at PA. In the other words, while the amount of ductility in T8 condition was lessen than T6 samples, the toughness enhancement governed by stress-bearing capacity that was higher in T8 condition.

Finally, considering figure 6, the FE and experiment results are totally converged which prove the failure prediction capability of FE model.

Microscopic examination

The fracture surface of central part of smooth samples under PA condition for both T6 and T8 treatments were shown in figure 7.

According to figure 7, three features of fracture were seen, i.e. micro-voids (denoted by blue arrow), cracked particles (denoted by yellow arrow) and matrix/particle deboning (denoted by red arrow). While the first feature specify the level of deformability, the second and third fracture micro-mechanisms are related to strengthening issue. In addition to fracture surfaces, the WDS images, which displayed the distribution of alloying elements were shown in figures 7(c) and (d).

Considering WDS maps, in addition to Al and Cu, which are the major elements of Al 2XXX alloy, other elements such as Mg, Mn, Si and Fe exist in the alloy that is used in this study. The distribution and spatial overlaps of elements indicated different components (precipitate/intermetallic) which were formed during heat treatments. It is well known that the nature of compounds, such as particles' size and distribution, particle/matrix bonding and their brittleness play an important role during deformation [36]. Considering this matter, the fracture surfaces of un-notched samples at PA condition under T6 and T8 treatments were shown in figure 8.
According to part a and b of figure 8, in both cases micro-voids, cracked particles and particles settled in the dimples (particle/matrix deboning) could be seen, however, the size and the depths of voids under T6 and T8 heat treatments are roughly differ from each other. The depths and width of dimples were shallower and smaller in PA-T6 samples compared to PA-T8 ones, these larger and deeper dimples in T8 samples, that specified more plastic energy absorption, results in toughness enhancement for approximately 20 percent compared with T6 treatment.

These dimples can be recognized significantly at higher magnification in part c and d of figure 8. The fracture surfaces of notched samples were displayed in figure 9 for both T6 and T8 treatments.

Particle cracking and deboning were major fracture features, which were clearly visible in all parts of figure 9. Indeed, stress concentration due to the presence of notch results in particle failure and an increment of dislocation density [16]. These two phenomena clearly decelerate void nucleation and coalescence, which lessen the ductility of the material. Moreover, the introduction of notch enhances the flow stress, which speeding up load transfer to the particles, so may results in early failure. The amount of ductility diminution depends on the stress concentration factors, such as shape, size and curvature radius of notch [25, 36]. In consequence, the effect of notch on deformability reduction was proved via comparing the elongation to failure of both smooth and notched samples (tables 3 and 4, respectively). Comparing the fracture surface of notched samples under T6 and T8, one may claim that the extension and depths of micro-voids were highlighted in T8 samples compared to T6 ones, which was displayed at higher magnification in figure 10 for PA condition.
Considering figure 10, in spite of dispersion of particle failure and consequently, severe decline of ductility and toughness in notched specimens compared to smooth ones, the existence of shallow voids under T6 treatment compared to T8 ones results in toughness reduction in the former treatment about 10 to 30 percent compared to the latter ones.

Therefore, it was obvious that, not only does applying T8 enhance the energy absorption of smooth samples, but also the amount of toughness increment is more major for notched geometry.

**Conclusion**

In this research the tensile and fracture behavior of Al2024 alloy was investigated for both smooth and notched samples under two T6 and T8 heat treatments. The main conclusions are as follows.

- In smooth samples, the amount of yield stress and UTS of T8 specimens were improved about 28% and 21% while the elongation at fracture and toughness were increased about 1.4% and 16%, respectively compare to T6 treatment.
- The ups and downs tensile behavior of Al2024 is not influenced by introducing notch on them. As it was shown the yield strength and UTS were increased by increasing time to the peak ageing condition, then they fall down again at OA. In contrary, the elongation at fracture reached the lowest value at PA condition and retrieve at OA time again.
- However, the value of NSR is less than unity for T6 heat treatment, which confirmed notch weakening, applying T8 heat treatment leads to notch strengthening with the value of 1.4 for NSR.
- Applying V-notches alter the contribution of three micro-mechanisms of fracture via intensifying the portion of cracked particle. Considering that, the heterogeneous distribution of fracture features results in toughness reduction severely in notched specimen compared to smooth ones.
- The strengthening mechanism in T8 treatment was approximately damped the destructive effects of notch and retrieve the amount of toughness in these samples compare to T6 ones. This issue was verified based on larger and deeper dimples in samples under T8 treatment, which demonstrated more energy absorption.

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**References**

[1] Snopinski P, Tanski T, Matus K and Rusz S 2019 Microstructure, grain refinement and hardness of Al–3%Mg aluminum alloy processed by ECAP with helical die Archives of Civil and Mechanical Engineering 19 287–96
[2] Xu C, Zheng R, Hanada S, Xiao W and Ma C 2018 Effect of hot extrusion and subsequent T6 treatment on the microstructure evolution and tensile properties of an Al–6Si–2Cu–0.5Mg alloy Materials Science & Engineering A 710 102–10
[3] Liu Y, Jiang D, Li B, Yang W and Hu J 2014 Effect of cooling aging on microstructure and mechanical properties of an Al–Zn–Mg–Cu alloy Mater. Des. 57 79–86
[4] Moya C K S, Weisss M, Xia J, Shao G, Ringer S P and Ranzia G 2012 Influence of heat treatment on the microstructure, texture and formability of 2024 aluminium alloy Materials Science and Engineering A 552 48–60
[5] Yang R, Liu Z, Ying P, Li J, Lin L and Zeng S 2016 Multistage–aging process effect on formation of GP zones and mechanical properties in Al–Zn–Mg–Cu alloy Trans. Nonferrous Met. Soc. China 26 1183–90
[6] Starke E A and Staley JT 1996 Application of modern aluminum alloys to aircraft Prog. Aerosp. Sci. 32 131–72
[7] Wang S C, Staring M J and Gao N 2006 Structural changes on aging Al-Cu-Mg alloys Scripta Materialia 54 287–91
[8] Ringer S P, Hono K, Polmear I J and Sakurai T 1996 Nucleation of precipitates in aged Al-Cu-Mg (Ag) alloys with high Cu:Mg ratios Acta Material. 44 1483–98
[9] Ringer S P, Caraher S K and Polmear I J 1998 Response to comments on cluster hardening in an aged Al-Cu-Mg alloy Scr. Mater. 39 1559–67
[10] Ringer S P, Marceau R K W, Sha G, Ferragut R and Dupasquier A 2010 Solute clustering in Al-Cu-Mg alloys during the early stages of elevated temperature ageing Acta Mater. 58 4923–39
[11] Alexopoulos N D, Velonaki Z, Stergiou C I and Kourkoulis S K 2017 Effect of ageing on precipitation kinetics, tensile and work hardening behavior of Al-Cu-Mg (2024) alloy Materials Science & Engineering A 700 457–67
[12] Li H, Xu W, Wang Z, Fang B, Song R and Zheng Z 2016 Effects of re-ageing treatment on microstructure and tensile properties of solution treated and cold-rolled Al-Cu-Mg alloys Materials Science & Engineering A 650 254–63
[13] Mirzaei M, Roshan M R and Jahromi S A J 2015 Microstructure and mechanical properties relation in cold rolled Al 2024 alloy determined by x-ray line profile analysis Materials Science & Engineering A 620 44–9
[14] Huang Y, Chen Z G and Zheng Z Q 2011 A conventional thermo-mechanical process of Al-Cu-Mg alloy for increasing ductility while maintaining high strength Scr. Mater. 64 382–5
[15] Zhao Y, Yang Z Q, Zhang Z, Su G Y S and Ma X L 2013 Double-peak age strengthening of cold-worked 2024 aluminium alloy Acta Mater. 61 1624–38
[16] Westermann I, Pedersen K O, Børvik T and Hopperstad O S 2016 Work-hardening and ductility of artificially aged AA6060 aluminium alloy Mech. Mater. 97 100–17
[17] Torabi A R 2017 Tensile failure in blunt V-notched ductile members: a new formulation of the equivalent material concept Eng. Fract. Mech. 184 1–13
[18] Derpenski J and Seweryn A 2016 Ductile fracture of EN–AW 2024 aluminium alloy specimens with notches under biaxial loading, Part 1 - experimental research Mech. Mater. 97 100–17
[19] Paneda E M, Busto S D and Betegon C 2017 Non-local plasticity effects on notch fracture mechanics Theor. Appl. Fract. Mech. 92 276–87
[20] Nath S, Das K and Dath U K 2006 Effect of microstructure and notches on the fracture toughness of medium carbon steel Naval Architecture and Marine Engineering 3 15–22
[21] Majzoobi G H, Kashfi M, Bonora N, Iannitti G, Ruggiero A and Khadem M 2018 Damage characterization of aluminum 2024 thin sheet for different stress tri-axialities Archives of Civil and Mechanical Engineering 18 702–12
[22] Agogino A M 1978 Notch effects, stress state and ductility J. Eng. Mater. Technol. 100 348–55
[23] Cao R, Wen J X, Liu H J and Chen J H 2018 Notch sensitivity and failure behavior of TiAl and K418 alloys J. Mater. Eng. Perform. 27 3374–85
[24] Sai P and Sandstrom R 2016 Slow strain rate tensile tests on notched specimens of copper Materials Science & Engineering A 663 108–15
[25] Murata M, Yoshiida Y and Nishiwaki T 2018 Stress correction method for low stress identification by tensile test using notched round bar Journal of Materials Processing Tech. 251 65–72
[26] Prudhomme M, Billy F, Alexis J, Benuit G, Harom F, Lariat P, Ogden G, Blanc C and Henaff G 2018 Effect of actual and accelerated ageing on microstructure evolution and mechanical properties of a 2024-T351 aluminium alloy Int. J. Fatigue 100 60–71
[27] Baso Y and Trettler R 2004 Ductile crack formation on notched Al2024-T351 bars under compression–tension loading Materials Science and Engineering A 384 385–94
[28] Zhuana X, Ma Y and Zhao Z 2019 Fracture prediction under non proportional loadings by considering combined hardening and fatigue–rule-based damage accumulation Int. J. Mech. Sci. 150 51–65
[29] Zhou J, Liu J, Xu S, Huang S, Meng X, Sheng J, Zhang H, Sun Y and Feng A 2018 Improvement in fatigue properties of 2024-T351 aluminum alloy subjected to cryogenic treatment and laser peening Surface & Coatings Technology 345 31–9
[30] Yuan S P, Wang R H, Liu G, Li R, Park J M, Sun J and Chen K H 2010 Effects of precipitate morphology on the notch sensitivity of ductile fracture in heat-treatable aluminum alloys Materials Science and Engineering A 527 7369–81
[31] Lagoda T, Bilous P and Blacha L 2017 Investigation on the effect of geometric and structural notch on the fatigue notch factor in steel welded joints Int. J. Fatigue 108 224–31
[32] Reis D A P, Couto A A, Dominguex N I, Hirschmann A C O, Zepka S and Neto C M 2012 Effect of artificial ageing on the mechanical properties of an aerospace aluminium alloy 2024 Defect and Diffusion Forum 326–328 193–8
[33] Shahsavari A, Karimzadeh F, Rezaei A and Heydari H 2015 Significant increase in tensile strength and hardness in 2024 aluminum alloy by cryogenic rolling Procedia Materials Science 11 84–8
[34] Zhong H, Rometsch P A, Zhu Q, Cao L and Estrin Y 2017 Effect of pre-ageing on dynamic strain ageing in Al-Mg–Si alloys Materials Science & Engineering A 687 323–31
[35] Zheng R, Sun Y, Ameyama K and Ma C 2014 Optimizing the strength and ductility of spark plasma sintered Al 2024 alloy by conventional thermo-mechanical treatment Materials Science & Engineering A 590 147–52
[36] Torabi A R, Berto F and Razavi S M J 2018 Ductile fracture prediction of thin notched aluminum plates subjected to combined tension-shear loading Theor. Appl. Fract. Mech. 97 280