Original Article

Impact of solid-solution treatment on microstructural characteristics and formability of rotary-swaged 2024 alloy tubes

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ABSTRACT

Rotary swaging is a process usually applied to reduce the entire or local diameter and size of rods and tubes. In this study, the effects of the rotary swaging process and subsequent softening heat treatments, namely full annealing and solid-solution treatment, are investigated. The results show that rotary swaging refines grain size, decreases the eutectic phase fraction, enhances mechanical strength, and decreases mechanical elongation. Solid-solution treatment enhances work hardening ability and improves uniform elongation, and is thus more suitable for enhancing the formability of rotary-swaged alloys. The factors that affect microstructural characteristics and mechanical properties are discussed.

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1. Introduction

Extruded 2024 aluminum tubes are often applied in the aircraft industry due to their high strength-to-weight ratio and good fatigue resistance. Rotary swaging, a process that utilizes short strokes at high frequency and small deformation, is usually used to reduce the entire or local diameter of tubes and rods. This process improves surface quality, reduces material use, and shortens feeding time [1–3]. It can be used at high temperature or room temperature and is often applied to low-ductility materials such as high-strength steel and superalloys. Fig. 1(a) shows an illustration of the reduction of tube diameter via rotary swaging [2], where A is a supporting ring, B is a pressure roller, C is a thrust piece, D is a swaging die, E is a high-hardness mandrel, and F is a tube (workpiece in this study). As-fabricated tubes are plunged into the center of the rotary swaging machine with a mandrel of suitable diameter. As the swaging machine works, the swaging dies (D) and thrust pieces (C) rotate around the swaging axle at high frequency. When pressure rollers (B) push the thrust pieces (C), the swaging dies (D) hit and deform the tube (F). The rotation continues at high rate, resulting in a large number of small deformations on the tube with each short stroke. The rotation rate, which also represents the swaging rate, can reach about 6000 rpm. Fig. 1(b) shows the front view and side view of rotary swaging process [4] and Fig. 1(c) shows a photograph of rotary swaging machine (customized HA40-10VUE, Felss, Königsbach-Stein, Germany) applied in the present research.

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In practical applications, rotary-swaged alloys are often subjected to further forming processes such as bending, forging to a specific shape, or twisting. However, rotary swaging is a superplastic deformation process [5,6], which introduces a large number of dislocations and strains into materials, leading to a large drop in mechanical ductility and formability. Therefore, softening heat treatments are necessary for rotary-swaged alloys before further forming processes. The softening heat treatments considered in the present study are full annealing and solid-solution treatment. Full annealing, which can relieve almost all internal stress (by decreasing the density of dislocations introduced by cold working), is the most commonly used heat treatment for softening cold-worked aluminum alloys [1,7]. The general procedures are: (1) heating aluminum alloys to 415–440 °C, which is above the recrystallization temperature, and holding for 2–3 h, (2) cooling at a slow rate of below 28 °C/h to 230–260 °C, and (3) cooling to room temperature in an air furnace. In general, elongation and formability can be enhanced via static recovery in full annealing. According to previous studies [1,7], full annealing allows 1050 aluminum alloys to be softened rapidly and greatly improves the elongation of 6061 aluminum tubes for the hydroforming process. However, the total duration of full annealing is about one day, which is too long for industrial applications. Therefore, solid-solution treatment is applied in the present study for enhancing formability [8,9]. The solid-solution treatment process consists of two steps: solution heat treatment and water quenching. In the solutionizing step,
the alloy should be heated to a temperature just below the incipient melting point for an adequate duration to allow all the eutectic phases and precipitated phases to dissolve to form a single-phase solid solution. Subsequently, quenching in water at an adequate cooling rate is used to inhibit the formation of precipitates, resulting in a supersaturated solid solution. Solid-solution treatment can affectively soften aluminum alloys but the forming process needs to be carried out immediately after solid-solution treatment to avoid natural aging (i.e., the spontaneous aging of a supersaturated solid solution at room temperature that increases hardness and strength). According to a previous study [8], the softening degree of solid-solution treated alloys is higher than that of fully annealed alloys under a slow tensile strain rate for 6082 aluminum alloys. In this research, the softening effect of solid-solution treatment on 2024 aluminum tubes is compared with that obtained using full annealing. Solid-solution treatment is shown here to improve the formability of 2024 tubes, especially rotary-swaged 2024 tubes. Moreover, this study shows that solid-solution treatment is more suitable than full annealing for enhancing the formability of rotary-swaged 2024 tubes.

The work hardening behavior of metallic materials can be used to judge formability. The work hardening effect is characterized by the work hardening rate, work hardening exponent \((n)\), and work hardening capacity \([10–15]\). The work hardening rate and work hardening exponent \((n)\) are used in this study to investigate the work hardening behaviors. High value of work hardening rate and work hardening exponent generally implies high ductility, toughness and formability, especially uniform elongation at room temperature \([11,12,15]\). Therefore, ductility and formability can be effectively enhanced by improving the work hardening ability. A metallic material with a high work hardening rate and a high work hardening exponent will have a more uniform elongation because its necking degree is low \([10,11,14,15]\). This study shows that the solid-solution treatment enhances the work hardening ability of 2024 tubes. Solid-solution treated materials possess high work hardening rates and work hardening exponents. Notably, the work hardening ability of solid-solution treated rotary-swaged 2024 tubes is the highest in this study. The results demonstrate that the formability of 2024 tubes subjected rotary swaging process can be effectively improved using solid-solution treatment.

2. Materials and experimental methods

Extruded 2024 aluminum tubes subjected to stress relief annealing (Hwan-Chee Metal Corporation, Tainan, Taiwan) were used as the initial material. Stress relief annealing is used to decrease the strength of workpieces to prolong the life of swaging machines. The as-extruded 2024 aluminum tubes were heated in an air furnace at a holding temperature of 430 °C for 2 h and then cooled in the air furnace at a slow cooling rate to room temperature. These initial tubes are hereafter designated as F for representing the as-fabricated 2024 tubes from cooperative supplier. The code “F” is always used to represent the as-fabricated materials in industrial applications. Their composition, determined using a glow discharge spectrometer, is shown in Table 1. The major alloying elements are Cu (4.2%), Mg (1.5%), Mn (0.6%), Si (0.1%), and Fe (0.1%). The rotary-swaged tubes made using as-fabricated tubes are hereafter denoted as RS. The dimensions of the as-fabricated and rotary-swaged tubes are shown in Fig. 2(a). The thickness, outer diameter, and inside diameter of as-fabricated tubes (F) are 5, 35, and 30 mm, respectively; those of rotary-swaged tubes (RS) are 2.7, 29.7, and 27 mm, respectively. The area shrinkage ratio for the rotary swaging process is about 60%. More than 10 as-fabricated tubes and rotary-swaged tubes, respectively, were used to confirm the repeatability of microstructural evolution and mechanical properties results. The microstructural characteristics and mechanical properties of samples of each kind were found to be steady. Three directions, namely extrusion direction (ED), normal direction (ND), and transverse direction (TD), shown in Fig. 2(b), are defined to indicate along which plane or direction observations were conducted for convenience of analysis and presenting the data.

In this study, the rotation rate of the rotary swaging machine was 2500 rpm. The workpieces were also rotated and plunged at a stable feeding speed in the rotary swaging process for enhancing the uniformity of deformation. The rotation rate of the tube was 100 rpm and the feed speed was set to 50 mm/min.

In order to investigate the influences of softening heat treatments on the 2024 aluminum alloys, the microstructural characteristics and mechanical properties of solid-solution treated 2024 aluminum tubes and those of fully annealed 2024 aluminum tubes were measured and compared.

The conditions for full annealing were decided based on the results of a previous study [16]. Full annealing consists of three steps: (1) the specimens are annealed at 430 °C for 2 h, (2) the temperature is lowered to 230 °C with a slow rate of 25 °C/h, and (3) finally cooled to room temperature in an air furnace. The total duration of full annealing is quite long (about 20 h), making the method inefficient. Fully annealed swaged tubes are designated as RSO. Solid-solution treatment was conducted at 510 °C for 2 h based on the results of a preliminary study [17]. After the solute atoms had dissolved to form a single-phase solid solution, specimens were quenched in water to inhibit the formation of precipitates.

The total duration of solid-solution treatment was only 2 h, much shorter than that of full annealing. The measurement of tensile mechanical properties was carried out immediately after water quenching to avoid precipitation hardening and natural aging. Natural aging behavior was also evaluated using Rockwell hardness (HR) to discuss the hardening degree because that aging might still occur. The solid-solutionized as-fabricated specimens and solid-solutionized rotary-swaged specimens are designated as FW and RSW, respectively. The code “W” is used to represent the specimens carried out solid-solution to the practical industrial applications. It is due to the specimens are carried out “water quenching” to form a

<p>| Table 1 – Chemical composition of 2024 aluminum tubes. |</p>
<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt.%</td>
<td>4.18</td>
<td>1.52</td>
<td>0.63</td>
<td>0.14</td>
<td>0.15</td>
<td>0.01</td>
<td>0.07</td>
<td>0.02</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
supersaturated alloy after solid-solution treatments at a high temperature.

In order to investigate effects of rotary swaging and two softening heat treatments on the microstructural evolution of 2024 aluminum alloys, the specimens were polished using SiC papers from 80# to 5000# (the number before # means how many hard particles in per square inch), Al₂O₃ aqueous suspension (particle size: 1.0 and 0.3 μm), and SiO₂ polishing suspension. After polishing, specimens were etched using Keller’s reagent and optical microscopy (OM) (BX41M-LED, Olympus, Tokyo, Japan) was used to observe the morphology of the samples. ImageJ software (National Institutes of Health, New York, NY, USA) was used to calculate and quantify the area fraction of eutectic phases to estimate the solid solution degree. The contrast and brightness of metallographic images was adjusted to identify the phases of interest. Two-dimensional (2D) X-ray diffraction (XRD) (SMART APEX II, Bruker, USA) was used to qualitatively analyze the phases and energy-dispersive X-ray spectrometry (EDS) of scanning electron microscopy (SEM) (JSM-7000 & JSM 7001, JEOL, Peabody, MA, USA) was used to observe the morphology of phases and analyze the compositions of various phases.

A universal material tester (HT-2402, Hung Ta Instrument Corporation, Taichung, Taiwan) was used for the tensile test to determine the effects of rotary swaging and softening heat treatments on the mechanical properties of 2024 aluminum tubes. The mechanical properties of F, RS, RSO, FW, and RSW were measured at room temperature with the initial strain rate set at 1.67 × 10⁻³ s⁻¹ for evaluating formability. The specimens were cut from the circular tube walls by wire electrical discharge machining along the axial direction as presented in Fig. 3(a). The dimensions of the tensile specimens are shown in Fig. 3(b). The gauge length is 20 mm and the gauge width is 5 mm. The thicknesses of the specimens before and after rotary swaging are 5 and 2.7 mm, respectively. The tensile direction is parallel to the ED direction. Each datum is the average value for three samples. After the tensile test, the mechanism of tensile fracture was analyzed. The analysis included two parts: (i) the fracture surface of fracture specimens was observed using SEM and EDS; (ii) the subsurface morphologies of fracture specimens were observed using OM after mounting, polishing, and etching. In addition to the mechanical properties and tensile fracture mechanism, the work hardening behavior of various specimens was determined and compared. The engineering tensile curves with stress and strain were estimated from tensile test results. Four engineering mechanical properties, namely yield stress (YS), ultimate tensile stress (UTS), uniform elongation (UE), and total elongation (TE), are calculated from the tensile curves. YS is defined as the stress at which a material begins to deform plastically and the yield point is the point where nonlinear deformation begins. The plastic strain offset was set at 0.002. UTS is the maximum engineering stress in a tensile test; it indicates the end of uniform elongation, and the start of localized necking. UE is the plastic deformation degree at the maximum loading and represents the plastic elongation before necking. TE, also known as elongation at break, is the elongation of the original gauge length of a tensile specimen at fracture, including both uniform elongation and post-uniform elongations.

The work hardening rate and work hardening exponent (n) were obtained from true stress–strain curves, which is calculated from the engineering stress–strain curve [10,11] using σ_T = ln(1+ε) and ε_T = σ(1+ε), where σ_T is the true stress, ε_T is the

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**Fig. 2** – (a) Dimensions of as-fabricated and as-swaged 2024 tubes and (b) definitions of directions.

**Fig. 3** – (a) Illustration of sampling position and (b) dimensions of tensile specimens.
true strain, $\sigma$ is the engineering stress, and $\varepsilon$ is the engineering strain. The work hardening rate is the slope (which varies with true strain) of the true stress–strain curve. The work hardening exponent is obtained from the Hollomon relationship $[10-13]$: 
$$\sigma_T = K\varepsilon^n$$
where $\sigma_T$ is the true stress, $\varepsilon_T$ is the true strain, $K$ is the strength coefficient, and $n$ is the work hardening exponent. This relationship is commonly used to characterize the plastic deformation behavior of metallic material. Usually, a high $n$ value indicates a stronger work hardening effect. Typical $n$ values for metals with excellent formabilities at room temperature, such as rolled Mg–3Gd–1Zn ($n = 0.29$) [18], AM30 ($n = 0.17$) [19], several aluminum alloy sheets ($n < 0.36$) [20] and pure coarse-grained Cu ($n = 0.35$) [21] are about 0.2–0.5 [18–21].

### 3. Results and discussion

#### 3.1. Natural aging behavior of 2024 aluminum extruded tubes

Since formability is the focus of this research, how to enhance tensile elongation, and thus formability and deformation capacity, was the aim in the experiments. Precipitations that form during natural aging should be avoided as much as possible because they decrease tensile elongation. The tensile test was thus carried out immediately after solid-solution treatment to avoid natural aging, which generates precipitations and decreases the elongation and formability at room temperature. Nevertheless, since natural aging is spontaneous at room temperature and may have occurred, natural aging behavior was investigated in this study. In practical applications, solid-solution treatment should be carried out just before the further manufacturing process for best formability. The natural aging curves of solid-solution treated as-fabricated specimens (FW) and rotary-swaged specimens (RSW) are performed. Both curves show the hardness increasing with increasing natural aging time. The peak aging durations of FW and RSW are almost identical (about 12 h). The hardness of FW is slightly higher than that of RSW at any given natural aging time. The peak aging hardness values of FW and RSW are about 100 and 97 HRF, respectively. The results indicate that the hardness of these two specimens did not significantly increase in the first hour of natural aging. The tensile properties measured in the first hour are thus useful for evaluating formability. The reason for the hardness of FW being higher than that of RSW is determined using microstructural observation in the next section.

#### 3.2. Microstructural characteristics and phase analysis

Etched metallographic images taken along the ED direction of the five specimens (F, RS, RSO, FW, and RSW) are shown in Fig. 4. Both coarse and fine grains exist in the as-fabricated 2024 alloys (F), as shown in Fig. 4(a), but only fine grains with high uniformity exist in rotary-swaged 2024 alloys (RS), as shown in Fig. 4(b). For the as-fabricated 2024 tubes, the average grain size of fine grains is about 8 $\mu$m and that of coarse grains is about 28 $\mu$m. The average grain size of fine grains in rotary-swaged 2024 tubes is about only 4–5 $\mu$m. These results indicate that the rotary swaging process can uniformly refine all alloy grains, likely via dynamic recrystallization. The non-uniform grain distribution in F is due to grain coalescence. When the crystal orientations of neighboring grains are similar, the grains will easily merge, forming coarse grains.

Fig. 4(c) shows that the grain distribution of fully annealed rotary-swaged 2024 alloys (RSO) is uniform. The average grain size of RSO is about 13 $\mu$m, slightly larger than that of RS. This indicates that full annealing led to low-degree grain growth, mostly in the isothermal step with a temperature
of 430 °C (for 2 h), which is high enough for grain growth. This also indicates that the strain energy introduced by rotary swaging led to grain growth. Fig. 4(d and e) shows that solid-solution treatment led to obvious grain growth in as-fabricated specimens and rotary-swaged specimens. The grain sizes of solid-solution treated as-fabricated 2024 alloys (FW) and solid-solution treated rotary-swaged 2024 alloys (RSW) are much larger than those of F, RS, and RSO due to the high temperature of solid-solution treatment. Notably, the grain distribution of FW, in which both coarse and fine grains exist, is non-uniform but that of RSW, in which only fine grains exist, is uniform. In FW, the average grain size of fine grains is about 11 μm and that of coarse grains is about 74 μm. The average grain size in RSW is about 85 μm. The results demonstrate that rotary swaging makes the grain distribution uniform with or without heat treatment. The original grain distribution (i.e., before heat treatment) affected the grain distribution after heat treatment. The hardness of FW being higher than that of RSW can be explained by grain distribution. The existence of fine grains in FW resulted in high hardness.

OM metallographic images were taken along the ED direction without etching for the five specimens to calculate the area fraction of eutectic phases to understand the solid solution effects of rotary swaging and softening heat treatments on eutectic phases. Because precipitated phases are too small to observe in OM images, the fraction of eutectic phases was calculated and the degree of solid solution was quantified. A lower fraction of eutectic phases indicates a higher degree of solid solution. The OM images are shown in Fig. 5 and the eutectic phase fractions are quantified by ImageJ calculations as shown in Fig. 6. The fraction of eutectic phases greatly drops after solid-solution treatment. The eutectic phases dissolved during solid-solution treatment due to the high temperature. The eutectic phase fraction of RS (8.60%) is lower than that of F (10.90%), and that of RSW (1.20%) is lower than that of FW (1.62%), showing that the rotary swaging process increases the degree of solid solution. The rotary swaging process refines particle second phases, leading to higher amounts of solid solution. Full annealing also increases the degree of solid solution; the eutectic phase fraction of RSO (6.73%) is lower than that of RS (8.60%). Heat treatments and rotary swaging both enhance

Fig. 5 – Microstructure (along ED direction) before etching of (a) F, (b) RS, (c) RSO, (d) FW, and (e) RSW.

Fig. 6 – Second phase fraction for various specimens.
the degree of solid solution. The enhancement obtained with solid-solution treatment is higher than that obtained with full annealing due to the former’s high holding temperature.

XRD and EDS were used to analyze and identify the eutectic phases in the five kinds of specimen. Fig. 7 shows the XRD patterns of the specimens. The phases in all specimens identified using XRD are the same, including three eutectic phases: Al$_2$CuMg (S phase), Al$_2$Cu$_2$Fe (N phase), and Mg$_2$Si (β phase).

The semi-quantitative data on the surface of the alloy specimens using EDS are shown in Fig. 8. Based on the results from previous studies [22,23] and the present XRD results, all alloy specimens have the similar eutectic phases. The light gray irregular particles are Al$_2$CuMg (S phase, marked as “a”), the black particles are Mg$_2$Si (β phase, marked as “b”), and the light gray splinters are Al$_2$Cu$_2$Fe(Mn) (N phase, marked as “c”). Notably, the eutectic phase fraction of the solid-solution treated specimens (FW, RSW) decreased. This result indicates that the rotary swaging process makes the crystal phases in the Al matrix finer, and thus the eutectic phases are more easily dissolved into the Al matrix.

3.3. Tensile mechanical properties and formability

Fig. 9 shows the stress–strain curve of all tensile tested specimens. It can be found that the tensile curves of the heat treated materials (FW, RSW) are above the F and RS materials, indicating that the solid-solution treatment promoted the material strength. Note that the jagged curve occurred in the stress–strain curves due to a dynamic strain aging (DSA), which help to improve the work hardening rate of materials. The rotary swaging process improves tensile strength, but decreases tensile ductility (Fig. 10). This result attributed to the rotary swaging process introducing a large number of dislocations in material [24,25]. The tensile strength (tensile elongation) of the RSO specimen is lower (higher) than that of the RS one. The density of dislocations introduced by the rotary swaging decreases after full annealing, leading to an increase of tensile elongation and a decrease of tensile strength [1,7]. TheYS of RSW specimen is lower than that of RS one, and the elongation of RSW specimen is much higher than that of RS one, indicating that the solid-solution treatment also softens RS specimen. Yield strength is often measured for evaluating a resistance to deformation. Lower yield strength means lower resistance to deformation. Notably, the UE and TE values of RSW specimen are higher than those of RSO one. This indicates that the elongation improvement obtained by solid-solution treatment is much higher than that obtained by full annealing, especially in terms of uniform elongation. High uniform elongation is a principal factor that determines a formability of material because non-uniform deformation might induce weak spots in the material, which may initiate cracks. Uniform elongation is an important factor in many manufacturing processes, such as hydroforming, forging, and bending. Moreover, the TE value of the RSW specimen is higher than that of the RSO one. The tensile strength of the RSW specimen is higher than that of the RSO one, indicating that the operating load range of the RSO specimen is narrower. The higher loading request of the RSW specimen can be overcome by advanced equipment. The RSW specimen has better formability than the RSO specimen, indicating that the solid-solution treatment is more advantageous than the full annealing to improve the formability of the rotary swaging material.

Fig. 11 shows the tensile fracture characteristics of the five specimens. For the RS specimen, the fracture surface is flatter than that of the other specimens. Some cleavages, a tensile brittle fracture characteristic, appear on the fracture surface. The features of the fracture surface result from brittle fracture. A lot of dimple fractures appear on the F, FW, RSO, and RSW specimens. Microrivots coalescence and ductile fracture caused these dimple fractures. Large dimples initiate at eutectic particles and small dimples initiate at precipitated phases. The particles in the large dimples are Al$_2$CuMg and Al$_2$Cu$_2$Fe(Mn), as determined using EDS. Compared with the solid-solution treated rotary-swaged specimens (FW and RSW), the RSO specimen has more amount of large dimple fractures, which attributed to the RSO specimen has higher eutectic phase fraction (Fig. 6). That may be the reason why the elongation of the RSO specimen is lower than that of the FW and RSW specimens.

The fractures subsurface of the five specimens are shown in Fig. 12. Eutectic phase particles broken by tensile stress appear at the breaking surface and subsurface. This attributed to the cracks initiated at eutectic phase particles and interconnected, which eventually leads to fracture. The eutectic phase fraction of the RSO specimen is much higher than that of the FW and RSW specimens. It is a factor in the elongation of the RSO specimen being lower than that of the RSW and FW specimens. The natural aging and dynamic precipitation occurred in the FW and RSW matrix, causing a high yield strength and ultimate tensile strength [26].

3.4. Mechanisms affecting mechanical properties

Fig. 13 shows the work hardening rate of all alloy specimens. The discussion of the work hardening behavior of the RS specimen is excluded due to the elongation of the RS specimen is very low. The work hardening rates of the FW and
Fig. 8 – SEM–EDS semi-quantitative elemental analysis of (a) F, (b) RS, (c) RSO, (d) FW, and (e) RSW specimens surface.

RSW specimens are much higher than those of the F and RSO at all true strains, indicating that solid-solution treatment improves work hardening ability. Notably, the RSW and RSO specimens have higher work hardening exponents (n) value, indicating that rotary swaging will increase the n value. According to a previous study [27], a low work hardening exponent or rate resulted in rapid instability, with the tensile flow stress reaching a maximum followed by a localization of deformation necking. Materials with high n value have high ductility and formability. These results demonstrate that the
combination of rotary swaging and solid-solution treatment affectively improves formability, which retard the occurrence of necking and enhance uniform elongation. The n value of RSW is higher than 0.3, it is reasonable to anticipate that it has excellent plastic deformation ability at room temperature based on the previous researches [18–21].

The fluctuations in the stress–strain curve of FW and RSW reveal that the DSA behavior occurred in these two alloy specimens in the tensile test (Fig. 9). The DSA results from the dynamic interaction between mobile dislocations and diffusing solutes, which is related to the concentration of solid solution [28–31]. The DSA is also a possible factor in the enhancement of work hardening rate [32,33]. DSA contributes to the stabilization of stacking faults and favors dislocation

![Graph showing stress-strain curves](image)

**Fig. 9** – The stress–strain curves of F, FW, RS, RSO, and RSW specimens.

![Comparison of strength and elongation](image)

**Fig. 10** – Tensile mechanical properties of F, RS, RSO, FW, and RSW specimens: (a) strength and (b) elongation.

![Micrographs of tensile fracture surfaces](image)

**Fig. 11** – Tensile fracture surfaces of (a) F, (b) RS, (c) RSO, (d) FW, and (e) RSW specimens.
planar slip, promoting the multiplication of dislocations [33]. In addition, the stress–strain curves of the RSO and F specimens also possess a slightly fluctuation. The possible reason is that large numbers of eutectic particle phases also restricted the slipping of dislocations, but dislocations also can get rid of them, resulting in a fluctuating stress–strain curve. There should be almost no solutes in the RSO and F in theory because the RSO specimen has fully annealed, and the F specimen has annealed and fully natural aged (the F specimen has been placed at room temperature for a long time).

The mechanism of softening heat treatment effects is as follows: (1) the precipitated phases formed in nature aging at room temperature and dynamic precipitates generated in the tensile test enhance the tensile strength of
solid-solution treated materials [26]. The slipping of dislocations is restricted by the precipitated phases, resulting in an increase of tensile strength. (2) The work hardening effect, characterized by the work hardening rate and the work hardening exponent, can be enhanced by solid-solution treatment, resulting in high uniform elongation and formability. (3) DSA occurs in solid-solution treated specimens under tensile stress. DSA enhances the work hardening effect because dynamic precipitates exist in supersaturated solid-solution specimens [26]. Dynamic precipitation is a probable reason for the enhancement of the work hardening ability. (4) The stress relief degree obtained with full annealing (RSO) is higher than that obtained with stress relief annealing (F), and thus the strength of RSO is lower than that of F.

The mechanism of rotary swaging effects is as follows: (1) rotary swaging decreases the eutectic phase fraction, decreasing the probability of stress concentration at eutectic phases. It affects the mechanical properties. (2) Rotary swaging increases work hardening ability. A material with a high work hardening effect generally has high uniform elongation and high formability. (3) Rotary swaging refines the eutectic phases and enhances the solid solutionization degree. It increases the degree of precipitation, resulting in high strength and a high work hardening effect. (4) The dislocations introduced by rotary swaging cannot be totally removed [11]. The remaining dislocations become nucleation sites for precipitating phases. This may enhance strength and the work hardening effect.

The combination of solid-solution treatment and rotary swaging absolutely enhances ductility and formability because they enhance the work hardening effect. Solid-solution treatment is more suitable than full annealing for enhancing the formability of rotary-swaged material. Compared to full annealing, solid-solution treatment enhances formability and shortens total fabrication duration. The only drawback is that the materials must be processed immediately after solid-solution treatments to avoid nature aging.

4. Conclusion

(1) Rotary swaging refines grain size, makes the distribution of grains uniform, and decreases the eutectic phase fraction. However, all specimens had identical eutectic phases, namely Al_{3}CuMg (S phase), Al_{3}Cu_{2}Fe (N phase), and Mg_{3}Si (β phase). Besides, rotary swaging increases tensile strength, especially yield stress, but greatly decreases tensile elongation.

(2) Solid-solution treatment leads to grain growth, greatly increases the solid solution degree, and improves tensile elongation more than does full annealing. The solid-solutionized rotary-swaged specimens had higher tensile elongation than that of solid-solutionized as-fabricated specimens, proving that rotary swaging enhances elongation, especially uniform elongation.

(3) The rotary swaging process and solid-solution treatment improve the work hardening ability, which is characterized by the work hardening rate and the work hardening exponent. Formability and elongation increase with increasing work hardening ability.

(4) Rotary-swaged alloys can be subjected further forming process after suitable softening treatment such as solid-solution treatment, which is better than full annealing treatment. Solutionized rotary-swaged alloys had the highest formability; they had the highest uniform elongation and highest work hardening effect. The total fabrication duration for solid-solution treated specimens was shorter than that for those subjected to full annealing.

Conflicts of interest

The authors declare no conflicts of interest.

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