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ARTICLE

Overview on the Microstructure and Mechanical Properties of Ultrafine-grained Al-Li Alloys Produced by Severe Plastic Deformation

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Abstract: This review reveals microstructure and mechanical properties of Al-Li alloys produced by SPD (severe plastic deformation) techniques. It focuses on the microstructure evolution during SPD, with the influence of internal and external factors. The strengthening mechanism of Al-Li alloy, mainly based on precipitation hardening, is presented. It is demonstrated that UFG (bulk ultrafine-grained) Al-Li may attain enhanced strength with relatively good ductility via grain refinement and multiple precipitates. Special attention is given to the superplasticity of UFG Al-Li alloys, especially to the high strain rate superplasticity (HSR SP). It suggests that UFG Al-Mg-Li alloy produced by SPD, particularly by equal-channel angular pressing (ECAP), is a promising candidate material for use in superplastic forming operations.

Key words: Al-Li alloy; severe plastic deformation (SPD); microstructure; mechanical properties; superplasticity

Aluminum-lithium alloys attract great interest in structural applications, especially in the aerospace construction, because of their lower density, higher strength, better stiffness than conventional aluminum aerospace alloys. Each weight percent of lithium lowers density by approximately 3% and increases modulus by 6% for aluminum-lithium alloys [1].

It is well considered that the development history of Al-Li alloys can be divided into 3 stages. Alcoa alloy 2020, the representative of first generation of Al-Li alloys, was used in the wings of the Navy's RA-5C Vigilante aircraft in 1958. The second generation of Al-Li alloys, developed in the 1970s (alloy 1420 in Russia) and the 1980s (alloys 2090, 2091 and 8090), contained Li concentrations above 2wt%. Although the density reduction (from 7 pct to 10 pct) and elasticity modulus increment (from 10 pct to 15 pct) were attractive, these products had a number of technical problems, which included high anisotropy of tensile properties, crack deviations, a low short-transverse fracture toughness and stress-corrosion threshold. These key negative performances were considered undesirable by airframe designers, which led to the development of 3rd-generation Al-Li alloys with reduced Li concentration (from 0.75 wt% to 1.8 wt%) since the late 1980 s. Alloys like 2195, 2196, 2198, 2199, 2297, 2397, 2050, AF/C489, were developed for space and aircraft applications[2-4].

However, despite of offering superior specific stiffness performance and low density compared to conventional aluminum alloys, Al-Li alloys are generally considered to have major disadvantages, such as the lack of significant ductility and poor toughness. Consequently, there is considerable interest in improving the strength-ductility combination of these alloys and much work has shown that with appropriate processing treatments, it is possible to obtain high strength with ductility, and even superplastic in several Al-Li alloys[5-9]. Since it is well known that grain size is one of the principal approaches for controlling mechanical properties of materials, severe plastic deformation (SPD)

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has been one of the most effective methods. It can provide high service properties and enhanced workability by refining microstructure greatly, which has at tracted much attention in the past several decades [10-12].

Since work first started in the SPD field, modern techniques such as equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulative roll-bonding (ARB) have been developed and successfully applied to obtain ultrafine-grained (UFG) microstructures in various materials, especially in aluminum alloys [13-15]. An attracting feature of these techniques is that they allow to produce fine-grain structures without changing the initial shape of billets during processing, and it is applicable to nearly all commercial alloys. Therefore, from a practical point of view, SPD of bulk billets appears to be one of the most promising processing methods of producing UFG Al alloys for various industrial applications[16, 17]. Such SPD techniques also have been applied to Al-Li alloys, e.g. Ref.[6-8, 18-21], to confirm the same principles of microstructure refinement. The objective of this paper is to review the advances in the area of the SPD processed Al-Li alloys. Emphasis will be laid on the evolution of microstructure and improvement of mechanical properties after SPD.

1 Microstructure of Al-Li Alloys by SPD Techniques

SPD techniques are characterized as a group of metal forming processes to obtain significant grain refinement, via introducing large plastic strains into bulk metallic materials. They usually require high strains (with true strain in excess of 6-8) at relatively low temperatures ($<0.4T_m$, where T_m is the material's melting temperature) [10].

1.1 Microstructure evolution of Al-Li alloys by SPD

Under the large strains during SPD process, homogeneous and equiaxed UFG microstructures with ultrafine grains (usually <1 μm) are achieved in bulk alloys such as aluminum [22,23], magnesium [24,25], iron [26], and some other alloys [27,28] . However, most of previous studies show that further refinement of the grain sizes of aluminum alloys produced by SPD is difficult, and few of SPD methods can achieve grain size below 0.3 μm. This is due to the dynamic recovery in aluminum alloys during deforming process[20,29]. An example is shown in Fig.1 using TEM with samples of 1420 Al[19]. It is clearly seen that ECAP processing at 350 ºC for 10 passes resulted in the formation of fine crystallites with an average size of about 1.6 μm.

Unlike Cu and Ti, Al and its alloys possess high stacking-fault energies, which promote dynamic recovery and recrystallization during SPD process. Plastic deformation is accommodated by dislocation slip and multiplication, while the refined grain/cell size is mainly determined by dislocation density. With the huge accumulative strain through SPD, relatively high density of dislocations are attained in Al. But for the effect of dynamic recovery, the generation and annihilation of dislocations could reach balance, limiting the increase in dislocation density and the further refinement of grains [30].

The grain refinement process is also associated with misorientation transformation. In the works on ECAP processed 1421 Al-Li alloys aiming at producing UFG microstructure[18], it was shown that the microstructural evolution during equal-channel angular extrusion occurs through continuous dynamic recrystallization, as illustrated in Fig.2. At the first several passes through the die, arrays of low-angle grain boundaries were dominant and the

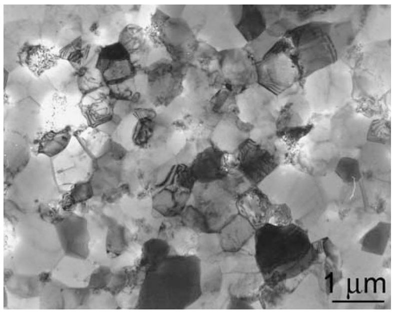

Fig.1 Typical ultrafine-grained structure in 1420 Al via ECAP at 350 ºC for 10 passes[19]

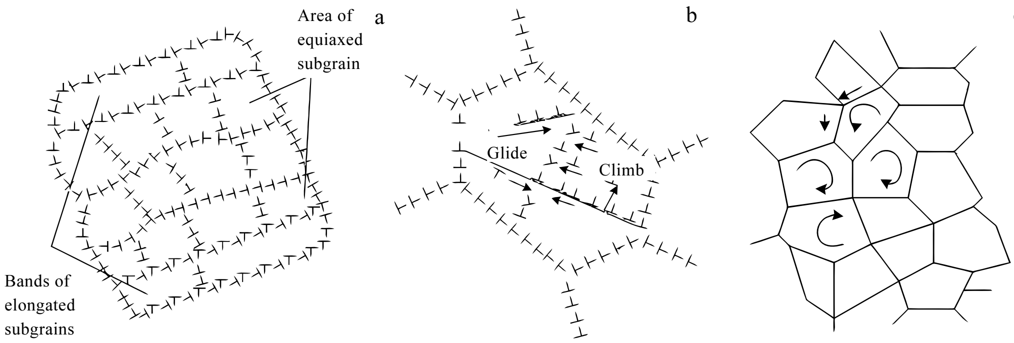

Fig.2 Schematic representation of microstructure evolution in the 1421 Al: (a) the formation of area of equiaxed subgrains alternating with bands of elongated subgrains; (b) interaction of low-angle boundaries with lattice dislocations resulting in progressive increase in their misorientation; (c) rotation of (sub) grains accelerates the increase in the misorientation of LABs

equiaxed subgrains formed alternating with area of elongated subgrains (Fig.2a). After that, mobile dislocations glided and climbed in the subgrains and were trapped by sub-boundaries, leading to an increase in their misorientation (Fig.2b). As a result, LABs eventually transformed into HABs at a high rate due to the transformation of the dislocation cell and sub-grain boundaries into HABs. In addition, the rotation of (sub) grains highly facilitated the transformation of LABs into HABs with increasing strain induced into the sample (Fig.2c). New grains evolved homogeneously both within interiors of initial grains and along old boundaries.

1.2 Affecting factors of microstructure in UFG Al-Li alloys

Both external (processing parameters, processing methods, etc) and internal factors (chemical component, original microstructure, etc) can affect the microstructure evolution process of Al-Li alloys fabricated by SPD.

On the one hand, the parameters and methods of processing technique definitely affect grain refinement of Al-Li alloys during SPD. For example, the processing temperature is a key factor affecting grain refinement process of Al-Li alloys. It was demonstrated on Al-Mg-Li and Al-Cu-Li alloys processed by ECAP in the temperature range from 340 to 410 ºC, and room temperature to 300 ºC, respectively[6,21,31]. With the increasing processing temperature, the average grain size increased, whereas the variation of dislocation density showed the opposite trend due to faster recovery. From the way to process SPD, the grain size of Al-Li alloys by HPT is generally smaller compared to other kinds of techniques. Investigation on microstructures of Al-Li 2198 alloy processed by HPT[32] showed that the grain size was significantly refined even up to nanometer scale. It is due to generally more intense and very high strains induced into the sample through HPT processing. Moreover, little frictional heat is produced during HPT resulted from the comparatively low processing temperature (normally room temperature) and rotational speed. As a consequence, the recrystallization and recovery are inhibited and the dislocation density dramatically increases, thus leading to higher dislocation densities, smaller grain sizes and a higher fraction of HABs [33].

On the other hand, microstructure refinement after SPD is influenced by chemistry of the alloys and presence of second phase precipitates or particles in the microstructure. For instance, in the case of alloys with higher lithium content, the SPD process resulted in fragmentation of the microstructure and, thus a smaller average grain size. It was reported that the average grain size of the Al-1.6Li aluminum alloy (0.4 μm) was much smaller than that observed in the Al-0.7Li alloy (0.6 μm) after the ECAE process[20]. This could be caused by the reduction in dynamic recovery with substitutional Li atoms. In addition, the precipitation or dissolution of second phase particles in the microstructure can also influence microstructure evolution by SPD. It was found that in the 2198-T8 alloy produced by HPT[30], the existing precipitates were broken up into small particles, thereby releasing large surface energy from those broken particles, which induced small particles to re-dissolve into the matrix and resulted in supersaturated solid solution. Then, the Zener pining effect on grain coarsening from particles was marginal, thus a much finer grain size.

2 Mechanical Properties of Ultrafine Grained Al-Li Alloys by SPD

2.1 Strengthening mechanisms of Al-Li alloys

Aluminum of high purity in the annealing condition has very low strength, nearly 10 MPa [10]. Generally, the strength of alloys is increased by obstacles that restrict dislocation motion within it. The commonly employed obstacles are other dislocations, internal boundaries (such as grains, subgrains, or cell boundaries), solute atoms and second-phase particles. In an Al-Li alloy, the effect of Li additions on the mechanical properties of aluminum alloys will depend on the lithium being in solution or existing as a second phase.

It is widely accepted that the general strengthening mechanism in the Al-Li alloys is precipitation hardening, while the soluted lithium only produces a small degree of solid solution strengthening. Precipitation hardening is originated from shearing and by-passing of particles by dislocations. If the precipitates are small, dislocations are prone to cut through the particles. While precipitates are hard and large, the dislocations bypass the particles and thereby form some dislocation loops. This precipitation hardening in a binary Al-Li alloy is mainly derived from the presence of a large volume fraction of the metastable, coherent and ordered precipitates (δ'-Al_3Li phase) with a LI2(Cu_3Au) type superlattice structure [34]. The δ'-Al_3Li phase has been observed in Al-Li, A1-Mg-Li [35,36], and Al-Cu-Li alloys [37]. It contributes to the high values of elastic modulus observed in these alloys, due to the high intrinsic modulus itself. Generally, δ'-$A1_3Li$ precipitate has a spherical shape, possessing a cube-cube orientation and a crystallographic structure similar to that of the aluminum matrix with a small lattice misfit, reported to vary from 0.025 to 0.33% depending on stoichiometry and temperature [1,38] .

However, due to the challenge of strengthening aluminum-lithium alloys with coherent lithium-rich phases δ'-Al_3Li, Cu and Mg are generally added to the Al-Li alloys to promote precipitation of T_1 (Al_2CuLi –hexagonal structure), θ' (Al_2Cu –cubic structure), and S′ (Al_2CuMg -cubic structure) phases [4,39]. The presence of these precipitates is beneficial to strength of Al-Li-*X* alloys, primarily because they act as strong obstacles, which are more resistant to shear by dislocation during deformation. The association of

Cu and Li favours formation of the T_1 phase, and precipitates of the Al-Cu sequence (GP zones, θ'' and θ', usually) as well. In such Al-Cu-Li alloys, T_1 phase is usually the most common second phase, with θ' phase appearing for higher Cu/Li contents, and δ' phase existing only at relatively low temperatures[21,37,40-42]. While Mg addition to Al-Li alloys would result in more significant weight savings and also an increased strength because of the low density and high solubility of magnesium, respectively. In addition, Mg lowers the solubilities of Li and other alloying elements in Al matrix, thereby enhancing the precipitations of some fine δ' phases [35,43,44]. For instance, experiments conducted by J. M. Kim et al. [45] illustrated that the microhardness and tensile strength were significantly higher in the high Mg (2.5wt%) Al-Li alloys, compared to low Mg (1wt%) alloy, because of the increased solid solution strengthening by Mg, reduced grain size, and enhanced precipitation of fine phases such as Al_3Li, Al_3Zr and $Al_6Cu(Li, Mg)_3$. In the presence of both Mg and Cu, one can also find precipitates of the Al-Cu-Mg sequence (GPB zones, S′/S).

Usually, it is considered that the best mechanical properties in these alloys are found when a majority of fine T_1 phase is formed. In early studies, T_1 precipitates were described as strong un-shearable particles similarly to the θ' phase. However, researchers recently found a transition in precipitate-dislocation interaction mechanism from shearing to by-passing when T_1 precipitates coarsen[46,47]. Even so, the strengthening capacity of T_1 phase is much higher than that of the S phase and δ' precipitates. It is confirmed by A. Deschamps et al [48]. They compared the yield strength of three kinds of alloys, in which Li, Mg and Cu content were varied, thus possessing different phases. Moreover, the introduction of a prior plastic deformation before aging has been examined to help promote the precipitation of finer particles of T_1 phases relative to the δ' precipitation [49]. So the kinetics of hardening is accelerated and the harmful effect of grain boundary precipitation and PFZ is limited, which are highly beneficial to the strength and fracture toughness of Al-Li products.

2.2 Improvement of strength in UFG Al-Li alloys

From the Hall-Petch equation (Eq. 1) [50], the prediction that the yield strength of a polycrystal increases linearly with $d^{-1/2}$ has been substantiated in a number of materials.

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \tag{1}$$

As a result, refining grain structures through severe plastic deformation is a promising way to increase the ultimate and yield stresses of materials. In the last few decades, some work has been carried out on the severely deformed Al-Li alloys to study the mechanical properties and strengthening mechanisms.

For the SPD-processed Al-Li alloys, the strength can be improved via grain refinement based on the Hall-Petch theory (Eq.1), and dislocation accumulation based on work hardening. As we mentioned, relatively high density of dislocations and ultrafine-grained microstructure may rise from the huge accumulative strain through SPD. A dislocation when reaches a boundary cannot slip further, but pile up near these boundaries. Likewise, the movement of a dislocation can be hindered by the presence of other dislocations. Consequently, as the total grain boundary area and dislocation density increase after SPD process, the resistance to dislocation motion becomes much more pronounced. Thus, a large number of grain boundaries and high dislocation density contribute to the high strength after SPD processing at low temperatures, and these will be the major strengthening contributions before precipitation occurs[51,52]. For instance, J. Han[53] and Z. X. Zhu [32] found that HPT processing significantly increased the mechanical properties (both hardness and strength) of 2198Al-Li alloy mainly due to greatly refined grain size and dislocation strengthening. Since there were no precipitates visible within the microstructure, however, high-density dislocations were introduced into the grains by HPT at ambient temperature.

It is seen from Minoru Furukawa's study[5] that Vickers microhardness shows a linear relationship with $d^{-1/2}$ in the Al-Mg-Li alloy for specimens annealed at temperatures above 700 K, but at lower annealing temperatures the Hall-Petch relationship breaks down because of the presence of other strengthening mechanisms. That is varying size and volume fraction of δ'-Al_3Li precipitates in each specimen. Precipitation hardening response of UFG Al-Li alloys is different compared to that of coarse-grained ones. They have an acceleration of the secondary phase hardening based on those precipitates discussed above. For one thing, UFG microstructure fabricated by SPD processing is characterized by a high density of grain boundaries and crystallographic defects like vacancies and dislocations, resulting in increased effective diffusion paths. This is able to induce accelerated precipitation kinetic since it is controlled by diffusion of solute atoms. Thereafter, it appeared that SPD processing may result in faster precipitation strengthening by the mutual and combined effect of newly introduced dislocations and formation of the hardening nanometer particles as the latter can strongly pin dislocations. For instance, M. Cabibbo[54] reported that the age-hardening response of AA2091 (Al-Li-Cu-Mg) was dominated by the T_1 (Al_2CuLi) and the S' (Al_2CuMg) precipitation, and the time-to-peak of the hardness curve was considerably shortened after ECAP at 210 ºC. For another, the large volume of grain boundaries and lattice defects formed during SPD consequently providing more nucleation sites for precipitation. Coupled with the breakage effect by heavy deformation, large numbers of fine precipitates can be introduced by SPD process and combined thermal treatment, thus leading to accelerated precipitation hardening. According to M.

Furukawa et al.[7], it was found that the microhardness peak was attained more rapidly in the aging curve for the ECAP processed Al-Mg-Li alloy, because of more nucleation sites for δ-AlLi and T-Al_2MgLi phases. Another example was the research on the ultrafine-grained structure in AA2091 (Al-Li-Cu-Mg) alloy conducted by S.W. Lee et al.[55]. It was concluded that a further increase in microhardness appeared by aging the HPT processed alloy at specified temperature, due to the formation of a fine dense dispersion of δ'-Al_3Li precipitates within the small grains and no significant grain coarsening occurred.

In conclusion, enhanced strength and accelerated hardening could be achieved in Al-Li alloys by SPD process to generate ultrafine grains, with high density of dislocations and fine precipitates.

2.3 Plastic deformation and ductility of ultrafine grained Al-Li alloys

Generally, A1-Li alloys exhibit low ductility and poor fracture toughness, which greatly restrict its applications. The adverse properties primarily stem from shear localization during plastic deformation. In particular, the ordered δ' phase is well known to result in planar slip, due to its ordered, shearable nature, and therefore its presence is considered to be at least partially responsible for the poor ductility and susceptibility to intergranular fracture of Al-Li alloys[48, 56]. Various modifications in alloy chemistry and fabrication techniques have been used in an attempt to improve the ductility while maintaining a high strength. One approach aims at overcoming the problems caused by strain localization is refinement of the grain size[8,14,15]. It is worth noting that SPD processed Al-Li alloys can exhibit enhanced strength and relatively good ductility in some papers. For example, M. Furukawa et al. [7] demonstrated that ECAP-processed Al-Mg-Li alloys with the very fine grain size exhibit high strength and good ductility at room temperature as compared to conventional Al-based alloys containing Li. This result is provoking that it offers greater opportunities for improved structural performance of Al-Li alloys for next generation aerospace applications.

To optimize ductility-strength combination in SPD processed Al-Li alloys, it is clearly important to suitably combine the two processing parameters: deformation temperature and subsequent aging treatments.

The correct processing temperature controls dislocation density and precipitate size. A study by M. A. Munoz-Morris [6] examined the role of ECAP straining at various temperatures to obtain balanced strength with ductility. It is demonstrated that higher temperature (150~200 ºC) processing is always accompanied by improved elongation to failure while maintaining strength. That is because although dislocation density is reduced somewhat after high-temperature processing, most importantly, precipitates appear, which is responsible for delaying strain localization and fracture. As a result, homogeneously distributed fine precipitates appear to improve elongation, both to ultimate tensile strength and to failure in most cases. For instance, S. M. Liu et al. [57] concluded that fine and homogeneous S' precipitates made deformation homogeneous and would increase the ductility of ECAP-processed 8090 Al-Li alloy. ECAP produced a lot of dislocations, on which S' precipitates exhibited a tendency to nucleate. S' phase has an open-packed structure, and there are no densely packed potential slip planes lying parallel to matrix slip planes. Then dislocations are not likely to penetrate the laths of S' phases, but bow around it, therefore, preventing the development of bands of coplanar slip.

However, too fine precipitates will shear during mechanical testing, thus inducing strain localization and more rapid failure. From the experiments performed by M. A. Munoz-Morris[21], it may be deduced that a balance of moderately high dislocation density, and relatively fine T_1 particles slightly coarser than a dangerous 1.0~1.5 nm range, which was strengthened without being very easily sheared, seemed the best way to achieve high strength with good ductility in the Al-Cu-Li alloy. While the best way to achieve this purpose was to carry out ECAP at room temperature, or at 150~200 ºC, with possible subsequent annealing at 150~200 ºC for further precipitation, with the precise selection depending on the balance of better strength or better ductility that was desired. So aging treatment is another way to optimize ductility-strength combination in SPD processed Al-Li alloys. Z. C. Wang et al.[8] reported that the 5091 Al-Mg-Li alloy, severely deformed to a strain of 10 using ECAP, had substantially improved elongation with no corresponding loss of tensile strength after annealing treatment. It was believed to be due to the natural aging taking place after quenching from annealing temperatures, when Li and Mg was taken into solution. It compensated for the reduction in yield stress after annealing treatment. S. W. Lee et al. [55] also illustrated that HPT-processed 2091 alloy achieved a further increased stress without a loss of ductility after aging under peak conditions of 150 ºC for 56 h.

The results illustrate that the ductility of Al-Li alloys can be improved by SPD, but depends strongly on the processing technique, internal structure and annealing state. There are still very limited researches on improving the strength-ductility combination and on its mechanisms of Al-Li alloys by SPD techniques, thus further investigations are eagerly needed in this respect.

2.4 Superplastic behavior of ultrafine grained Al-Li alloys

Superplastic deformation can be used in high-temperature forming of complex shapes for which forging operations, with their higher strain rates, are not suitable. Thus, superplasticity is widely researched in the aluminum-lithium alloys, particularly for aerospace applications [58-61]. Since it is possible to attain a very fine grain size by introducing an intense plastic strain through SPD processing, earlier researches on the superplasticity of UFG Al-Li alloys demonstrated that SPD is a suitable way to make the Al-Li alloy a candidate material for superplastic forming operations. For example, the ECAP-processed 1420 material had the maximum elongation of 550 pct at a strain rate of 3.3×10^{-3} s^{-1} and a testing temperature of 603 K[7]. Compared to thermomechanical processing which is often used to attain superplastic Al-Li alloys, SPD has two distinct advantages. First, the grain sizes are substantially smaller after SPD than that of alloys achieved by thermomechanical treatments. Since the strain rate in superplasticity varies inversely with the grain size rised to a power of two, a reduction in grain size to the submicrometer level leads to the occurrence of superplastic flow in the region of high strain rate superplasticity at strain rates $>10^{-2}$ s^{-1} [62]. Second, SPD processing is a relatively simple technique which can be applied to many different materials without any significant changes [63]. Therefore, superplastic behavior of ultrafine grained Al-Li alloy processed by SPD, especially Al-Mg-Li alloys, has been studied in recent decades.

Microstructure plays an important role in superplastic deformation. A fine-grained equiaxed microstructure is required for superplastic behavior, and the structure must be resistant to grain growth at the temperatures and time duration of superplastic deformation [50]. UFG metals, in general, are characterized by high internal stresses, dislocation density and nonequilibrium structure induced by SPD, which makes them usually sensitive to thermal treatment[64-66]. As a result, the presence of precipitates that can effectively pin the deformation induced boundaries of ultrafine grains at elevated temperatures is important for superior superplastic properties. Early works conducted by M. Furukawa et al.[5] had found that the grain size of the ECAP-processed 1420(Al-Mg-Li-Zr) alloy was reasonably stable up to temperatures as high as 700 K, equivalent to 0.75 T_m. It was attributed to the presence of a fine dispersion of metastable β'-Al_3Zr precipitates. Afterwards, it was found that the addition of Sc was likely to be more effective than Zr in inhibiting grain growth at elevated temperatures by the study of F. Musin et al.[29]. The grain size of 1421 Al after static annealing was smaller than that in the 1420 Al, and the ultrafine grain structure in the 1421 Al exhibited increased stability under superplastic deformation, which could be due to the presence of coherent Al_3(Sc,Zr) dispersoids.

In superplastic forming (SPF) industry, high strain rate superplasticity (HSR SP) is particularly attractive. Because it effectively reduces the long forming time resulted from the relatively low forming speeds (typically up to 10^{-3} s^{-1}), thereby expanding the utility of SPF technology for a much wider range of applications. There is experimental evidence from superplastic alloys that a decrease in grain size will lead both to an increase in the superplastic capability of the material and to the occurrence of optimum superplasticity at faster strain rates. As early as 1998, the occurrence of high strain rate superplasticity in an ultrafine-grained material were reported for an Al-5.5% Mg-2.2% Li-0.12% Zr alloy, which exhibited a maximum elongation of 1180 pct without failure at a temperature of 623 K using a strain rate of 10^{-2} s^{-1} [67]. And the results demonstrate that it is necessary to press to a sufficiently high strain by ECAP in order to develop a homogeneous microstructure. Sungwon Lee et al.[63] also found that the Al-5.5%Mg-2.2% Li-0.12%Zr alloy, which was pressed by ECAP to a strain of ~12, obtained elongations to failure of 1210% and 950% at strain rates of 10^{-1} and 1 s^{-1} at a temperature of 673 K, respectively. Later on, 1421 alloy with addition of Sc had been found a better performance in the HSR SP, attributed to the pinning effect of Al_3(Sc,Zr) dispersoids. Fanil Musin et al. [29] reported that ECAP-processed 1421 Al exhibited the highest elongation of 1850% without failure appeared at a temperature of 400 ºC and initial strain rate of 1.4×10^{-2} s^{-1} as illustrated in Fig.3, while R. K. Islamgaliev et al. [31] presented that an ECAP processed 1421 alloy had a superplastic elongation of ~1500% at 400 ºC using an initial strain rate of $10^{-1}s^{-1}$.

It is reasonable to conclude that SPD, especially ECAP, is a viable processing tool for achieving the ultrafine-grained microstructure of Al-Li alloys and is potential for attaining high strain rate superplasticity. However, most of the literatures on the superplasticity of the UFG Al-Li alloy sheets mainly concentrated on the development of the methods for the material with fine equiaxed grains and the optimization of superplastic condition. The superplastic mechanism of SPD processed Al-Li alloy with ultrafine-grain microstructure is still needed to be further investigated.

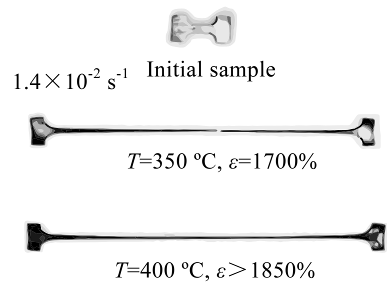

Fig.3 Examples of high superplastic elongation in 1421Al after ECAP processing at 350 and 400 ºC, 1.4×10^{-2} s^{-1} [29]

3 Innovative Potential and Prospects of the UFG Al-Li Alloys

UFG Al-Li alloys, in combination with advanced design concepts, reduced density, increased strength with ductility and great potential in HSR SP, offer opportunities for improved structural performance in various engineering sectors such as aerospace, constructions, automotive, defence, electronics. However, improvements in specific strength are not the only indicator of improved performance for aerospace materials; durability (e.g., corrosion and fatigue resistance) and damage tolerance (e.g., residual strength and fatigue crack growth) are also needed to be considered further. Few studies have been conducted on the latter properties of UFG Al-Li alloys.

On the other hand, a typical small size of SPD processed samples and their very high cost are the main obstacles for a wide commercialization of the UFG Al-Li alloys. Development of the continuous SPD processes as well as processes for fabrication of larger shape parts with UFG microstructure, not only for Al-Li alloys but also for all the engineering materials, need to be studied immediately.

4 Summary

In recent years, Al-Li alloys are of great interest in structural applications, because of their lower density, higher strength and better stiffness. But the lack of significant ductility and poor toughness severely limit its application. Severe plastic deformation (SPD) is demonstrated to be a promising way to achieve microstructure refinement and enhance properties, offering UFG Al-Li alloy great opportunities for next generation aerospace applications.

The present overview shows that microstructure refinement and enhanced overall properties is achieved in UFG Al-Li alloys. A variation of external (e.g. processing parameters, processing methods) and internal factors (e.g. Chemical component, original microstructure) is demonstrated to affect the microstructure evolution process during SPD. The strengthening mechanisms in the ultrafine-grained Al-Li has been present from aspects of grain refinement, dislocation accumulation and precipitation hardening. An improved ductility in UFG Al-Li alloys has also been developed though a few topics particularly, synergy of strength-ductility combination mechanisms. Moreover, the high strain rate superplasticity of UFG Al-Li alloy is particularly attractive, leading to its prospects in modern commercialization. It is worthy to focus current research activities on mechanisms and multifunctional properties (ductility, corrosion, fatigue resistance, etc) of the UFG Al-Li alloys due to wide gaps in fundamental understanding of microstructural effects on those properties since they might play an important role in further commercialization. Development of the continuous SPD processes as well as fabrication of larger shape parts with UFG microstructure can be marked as another important trend in modern research on the UFG Al-Li alloys.

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大塑性变形制备超细晶铝锂合金的组织及力学性能研究进展

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摘　要：综述了大塑性变形工艺制备超细晶铝锂合金的显微组织及其力学性能，分析了大塑性变形过程中铝锂合金的组织演变及其影响因素。铝锂合金的强化机制主要是基于析出强化，结合大塑性变形得到的超细晶粒组织可以显著提高强度和塑性，并得到优异的超塑性。表明大塑性变形加工铝锂合金，尤其是等通道挤压制备的超细晶铝镁锂合金在超塑性工业具有广阔的发展前景。

关键词：铝锂合金；大塑性变形（SPD）；显微组织；力学性能；超塑性

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