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Research and Application of Advanced Superplasticity in Ultra-Fine Grained Aluminum Alloys and Composites

Final Report

by

R.Z. Valiev, R.K.Islamgaliev

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ABSTRACT

Ultrafine grained (UFG) Al 1420 alloy and Al-6061 metal matrix composite were processed by severe plastic deformation through severe torsion straining and equal channel angular pressing (ECAP). It is shown that the as-processed 1420 alloy exhibits enhanced superplasticity at relatively low temperatures and high strain rates and there is a significant increase of strength in the UFG Al-6061 metal matrix composite. Influence of severe plastic deformation on microstructure in these aluminum materials, features of their superplastic behavior and requirements to achieve enhanced superplasticity are discussed. Several articles of complex shape fabricated by high strain rate superplastic forming are demonstrated.

Keywords: *ultrafine grained materials, aluminum alloys, metal matrix composite, equal-channel angular pressing, severe torsion straining, high strain rate superplasticity.*

1. INTRODUCTION

In previous project (№ 68171-97-9006) we have shown that severe plastic deformation by equal-channel angular (ECA) pressing of commercial Al alloys leads to homogeneous UFG structure characterized by a mean grain size of about 1 μm and less, high angle grain boundaries and a fine dispersion of second phases. It was first demonstrated that high strain rate superplasticity (HSR SP) in UFG commercial Al alloys processed by ECA pressing could be achieved [1-3]. In the present project further experiments with aim to determine the precise requirements for achieving high strain rate superplasticity in cast aluminium alloys are performed. In addition, it is extended a range of materials under research including advanced Al composites, which through a smaller grain size can display enhanced strength and superplastic properties. The modernization a die and optimization a route for ECA pressing in order to fabricate samples with dimension of about 40 mm in diameter and 150 mm in length were conducted. These samples were used for demonstration a possible utilization of UFG Al alloys for production of light and high strengthened articles of a complex shape. The present Final Report describes the results of carrying out of the project «Research and application of advanced superplasticity in ultra-fine grained aluminum alloys and composites» ARO № 68171-98-M-5642, based on a mutual cooperation of teams of Prof. R.Z. Valiev (IPAM USATU, Ufa) and T. Langdon (USC, Los Angeles). The scientific team of Professor R.Z. Valiev has been responsible for processing, some structural characterization and investigations of mechanical properties of the processed Al-based alloys and composites. The Professor Langdon's team has been responsible for detailed investigations of mechanical behaviour of UFG alloys and also for some structural studies.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

The experiments were conducted using two different materials. First, the Russian alloy 1420 is a light-weight high strength material having a chemical composition of Al-5.5%Mg-2.2%Li-0.12%Zr. This alloy was fabricated by casting and contained a fine dispersion of δ'-Al_3Li and β'-Al_3Zr precipitates. The alloy was received in a non-superplastic condition after hot rolling with an initial grain size of 400μm. Second material is a metal matrix composite designated Al 6061-10vol%Al_2O_3(p) where p denotes particulates. This composite was fabricated by Duralcan USA (San Diego, California) using a proprietary casting technique in which an Al-6061 matrix alloy was reinforced with 10 volume % of irregularly shaped Al_2O_3 particulates. The nominal composition of the Al-6061 alloy is 1.0 wt% Mg, 0.6 %wt Si, 0.7 %wt Fe, 0.3 %wt Cu, 0.2 %wt Zn, 0.1 %wt Mn, 0.1 %wt Ti with the balance as Al. The composite was supplied in the form of a rod with a diameter of 19.1 mm. According to information provided by the manufacturer, the Al_2O_3 particulates were in the size range from 6 to 13 μm with an average size close to 10 μm. The as-received grain size was measured as 35 μm.

Severe plastic straining was introduced into the composite using both torsion straining and ECA pressing procedures. For torsion straining, small discs, having a diameter of 13 mm and a thickness of 0.3 mm, were strained in torsion at room temperature to a strain of ~7 under a pressure of 3.5 GPa: further details of the torsion straining procedure were given earlier [4, 5]. For ECA pressing, samples were cut with lengths of ~10 cm and these pieces were pressed through an ECA pressing die in which two channels, equal in cross-section, intersected at an angle of 90°. It can be shown that a single passage through the ECA pressing die corresponds to a strain of ~1 [6]. In the present investigation, samples of the Al 6061+10%Al_2O_3 composite were pressed for 8 passes at a temperature of 673 K plus an additional 2 passes at 473 K, thereby giving a total strain of ~10. All of the ECA pressing was conducted with rotation of the samples by 90° in the same direction between repetitive pressings.

The ECA pressing of the 1420 samples having a diameter of 20 mm was conducted in air using a special die. The samples were rotated by 90° in the same direction between each passage through the die. This procedure was selected because detailed experiments have shown that it leads most rapidly to a homogeneous microstructure of equiaxed grains separated by high angle boundaries[5, 7]. Samples were subjected to ECA pressing under three different conditions: (1) 4 passes at 673K to a strain of ~4, (2) 8 passes at 673K to a strain of ~8, (3) 8 passes at 673K and an additional 4 passes at 473K to a strain of ~12.

Two different dies were used to obtain UFG structure in 1420 alloy. Samples obtained through first one had diameter of 20 mm and length of 120 mm and were used to investigate of influence of ECA pressing regimes on superplastic behaviour. Massive samples with diameter of 40 mm and length of 200 mm of 1420 alloy were processed through the second die. For this a new ECA pressing set to fabricate these billets was manufactured. The given set is characterized by high wear resistance enables ECA pressing of billets at high temperatures up to 550°C. The set has allowed to product of massive UFG billets from Al alloys and composites necessary for fabrication of articles using an effect of high strain rate superplasticity.

The ECA pressed samples of 1420 alloy were prepared for examination by TEM by cutting small disks, grinding to a thickness of 150-180 μm and then thinning to perforation in a solution of 10%$HClO_4$, 20%$C_3H_8O_3$ and 70%C_3H_5OH at 278K. These samples were examined using an Hitachi H-8100 and JEM-100B electron microscope operating at 200kV and 100kV respectively. Selected area electron diffraction (SAED) patterns were obtained from selected regions of 2 μm^2.

Tensile samples were machined parallel to the longitudinal axes of the as-pressed cylinders with gauge length of 4 mm and gauge cross-sections of 3×2 mm^2. These samples were pulled to failure in air at selected elevated temperatures using an Instron testing machine operating at a constant strain rate of cross-head displacement at testing temperatures controlled within the range from 573 to 853 K. Since the ECA pressing of the Al 6061+10%Al_2O_3 composite introduced a strain of ~10, it is possible there may be some breaking of the $A1_2O_3$ particulates during pressing. This possibility was investigated by preparing polished sections of samples in both the unpressed and the ECA pressed condition and then examining these samples using a quantitative image analyzing facility attached to an optical microscope [8]. Linear traverses were made across both samples and the sizes recorded, measured parallel to the direction of the traverse, for >300 individual particulates.

3. RESULTS AND DISCUSSION

This section is divided into three parts. In first part influence of different regimes ECA pressing on microstructure and superplasticity behaviour of the ultrafine-grained 1420 alloy are considered. Mechanical properties and microstructure of the Al 6061-10%Al_2O_3 composite after torsion straining and ECA pressing are described in second part. In third part examples of superplastic forming of complex shape articles are demonstrated.

3.1. High strain rate superplasticity in the ultrafine grained Al-1420 alloy

3.1.1. Microstructures of Al-1420 alloy after ECA pressing

The microstructure of the Al 1420 alloy after pressing for 4 passes at a temperature of 673 K has been described in detail elsewhere [9]. Therefore, this report will concentrate exclusively on the microstructures within the samples subjected to the two ECA pressing procedures to higher total strains [10].

Figures 1 and 2 show microstructures at low and high magnifications for a sample ECA pressed for 8 passes at 673 K and Figs 3 and 4 show similar microstructures for a sample ECA pressed for 8 passes at 673 K and a further 4 passes at 473 K: the corresponding SAED patterns have aperture sizes of 12.3 μm at the low magnifications in Figs 1 and 3 and 1.25 μm at the high magnifications in Figs 2 and 4.

Inspection of Fig. 1 shows that the grains are reasonably uniform and equiaxed, there is a relatively low density of dislocations both within the grains and along the grain boundaries, and the average grain size is 1.3

μm. In Fig. 2, the same area is shown (a) with a bright field image and (b) with a (100) dark field image. It is apparent from Fig. 2(a) that there are small β'-Al_3Zr particles within the grains and in Fig. 2(b) there is evidence for a uniform distribution of very fine δ'-Al_3Li particles having a size of the order of 5 nm. These very small δ'-Al_3Li particles are probably precipitated during the air cooling following ECA pressing because it is anticipated that all of the 2.2% Li is dissolved in the Al matrix at the pressing temperature of 673 K [11].

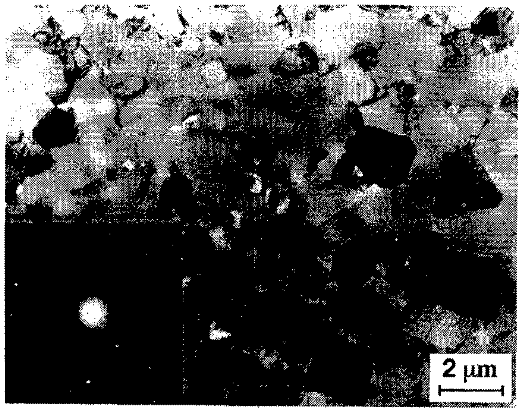


Fig.1. Microstructure and associated SAED pattern after pressing to a strain of ~8.

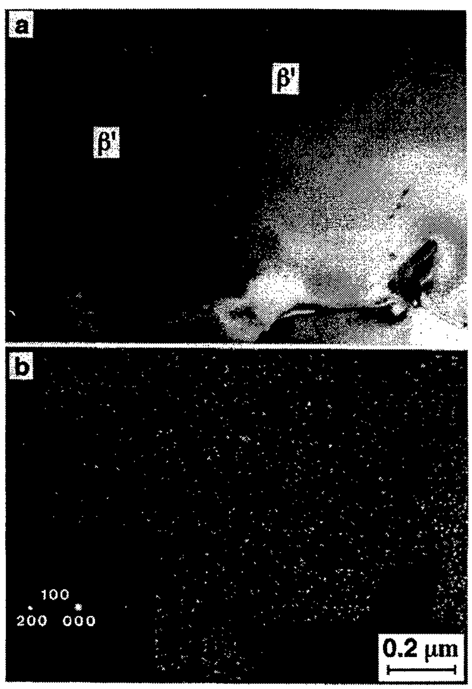


Fig.2. Appearance of the microstructure at a high magnification for the sample in Fig.3: (a) bright field image showing the presence of β'-Al_3Zr particles and (b) (100) dark field image showing a distribution of very fine δ'-Al_3Li particles.

The microstructure after ECA pressing to a strain of ~ 12 was again equiaxed, as shown in Fig. 3, but in this condition there was a higher density of dislocations both within the grains and along the grain boundaries and, in addition, the measured grain size was reduced to ~0.8 μm. The higher dislocation density in this material is consistent with the larger strain introduced by the ECA pressing but the smaller grain size is not consistent with the earlier observations, also for the Al 1420 alloy, where the grain size appeared to remain constant at ~1.2

μm after ECA pressing under these conditions [12, 13].

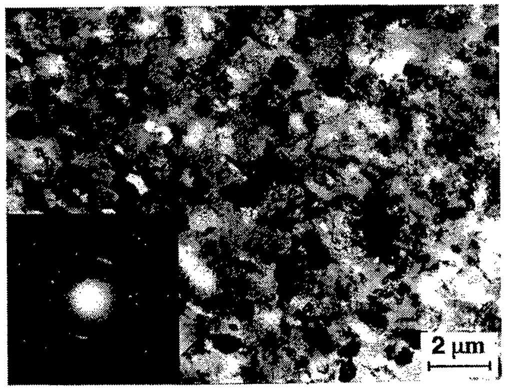


Fig. 3. Microstructure and associated SAED pattern after pressing to a strain of ~12.

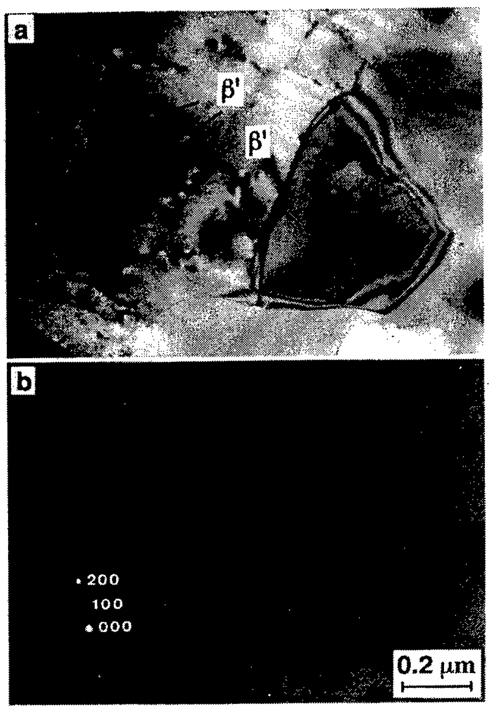


Fig. 4. Appearance of the microstructure at a high magnification for the sample in Fig. 5: (a) bright field image showing the presence of β'-Al_3Zr particles and (b) (100) dark field image showing a distribution of extremely fine δ'-Al_3Li particles.

More work is needed to determine the reason for this apparent discrepancy although it should be noted that the ECA pressing in the present experiments was conducted using route B_c whereas the earlier ECA pressing was conducted without any rotation of the samples using processing route A [14]. Figure 4 again shows (a) a bright field image and (b) a (100) dark field image, with small β'-Al_3Zr particles visible in Fig. 4(a) and evidence for a uniform distribution of very fine δ'-Al_3Li particles in Fig. 4(b) with a measured average size of ~3 nm. The smaller size of the δ'-Al_3Li particles in this sample by comparison with Fig. 2(b) is probably a consequence of the lower pressing temperature of 473 K which was used for the final 4 passes in this material, since this lower temperature permits a reprecipitation of some of the dissolved Li atoms.

3.1.2. Characteristics of tensile testing

Several samples were subjected to ECA pressing using the three different procedures described above and they were then pulled to failure at testing temperatures from 573 to 723 K [10]. The results from these tests are documented in Fig. 5 after ECA pressing (a) for 4 passes at 673 K, (b) for 8 passes at 673 K and (c) for 8 passes at 673 K and 4 additional passes at 473 K: in addition, each plot includes three datum points obtained at 603 K using the unpressed alloy with a grain size of ~400 μm [13]. Although there is some limited scatter in the various plots shown in Fig. 5, several general conclusions may be reached.

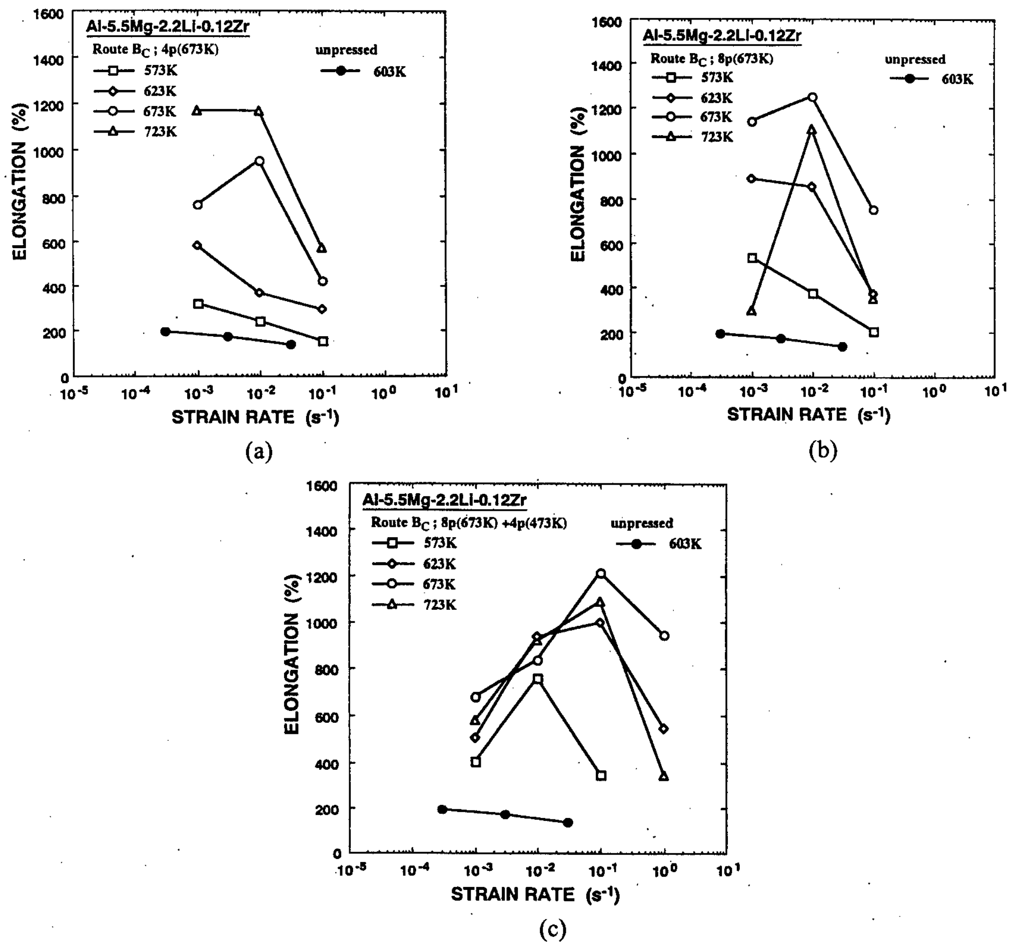


Fig. 5. Elongation to failure versus strain rate for samples prepared by ECA pressing (a) through 4 passes at 673K, (b) through 8 passes at 673K and (c) through 8 passes at 673K and 4 passes at 473K.

First, HSR SP is generally defined as the occurrence of superplastic ductility at strain rates at and above 10^{-2} s^{-1} [15] and it is apparent therefore that HSR SP was achieved in the present samples under all three ECA pressing conditions. The results in Fig. 5(a) after ECA pressing for 4 passes at 673 K are consistent with the relatively low ductilities reported earlier for this pressing condition when it is noted that the earlier tensile tests were restricted to a temperature of 603 K [9, 13] and it is now evident that higher temperatures are needed to achieve elongations to failure up to and above 1000%. Second, Figs 5 (b) and (c) both reveal HSR SP but the results are more favorable in Fig. 5(c) with the high ductility displaced to faster strain rates when the ECA pressing is continued to the higher strain of ~12. The improvement in HSR SP in Fig. 5(c), as evident especially by the elongations to failure recorded at a strain rate of 10^{-1} s^{-1}, is consistent with the smaller grain size attained after the ECA pressing of this material as documented in Fig. 3. It is apparent also that ECA pressing to the higher strain of ~12 leads to very high elongations at the very fast strain rate of 1 s^{-1}: for example, an elongation to failure of 950% was recorded in this material at a strain rate of 1 s^{-1} when testing at 673 K.

The evidence from Figs 5(b) and (c) suggests that a temperature of 673 K is probably the optimum for HSR SP in this alloy. Therefore, Fig. 6 shows the appearance of the specimens pressed to a strain of ~12 and then tested to failure at 673 K. It is apparent that all of these samples exhibit the two fundamental characteristics of superplastic flow [16]: uniform deformation within the gauge length and an absence of any localized necking so that failure occurs ultimately by pulling down to a point.

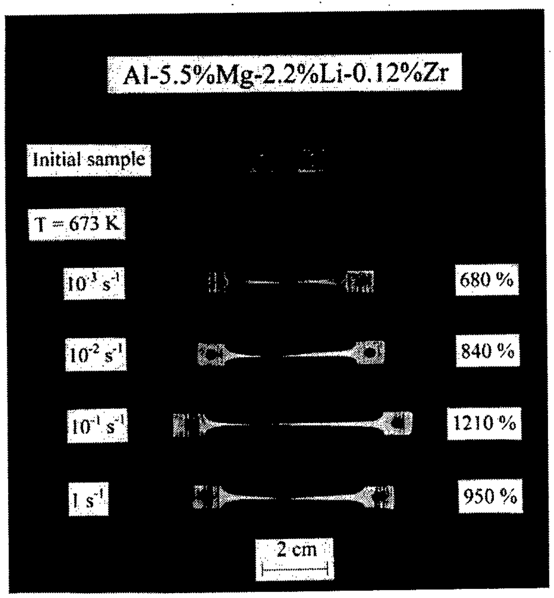


Fig.6. Appearance of specimens prepared by ECA pressing to a strain of ~12 and pulled to failure at high strain rates at 673K.

3.1.3. Microstructures of Al-1420 alloy after tensile testing

Fig. 7 illustrate the microstructure of sample ECA pressed to a strain of ~12 after tensile testing [17]. Inspections of Fig. 7 shows a two-phase structure containing coagulated particles of the second- phase, 0.1-0.2 μm in size. Using EDS analysis it was shown that these particles are T-Al_2LiMg-phase which can be formed in Al-Li-Mg alloys at temperatures above 200°C. This alloy is reasonably stable up to high temperature of 400°C since grain size during deformation remains less than 1 μm, though some relaxation of the structure occurs, attributed to some decrease in a level of internal stresses, as shown in Fig. 7.

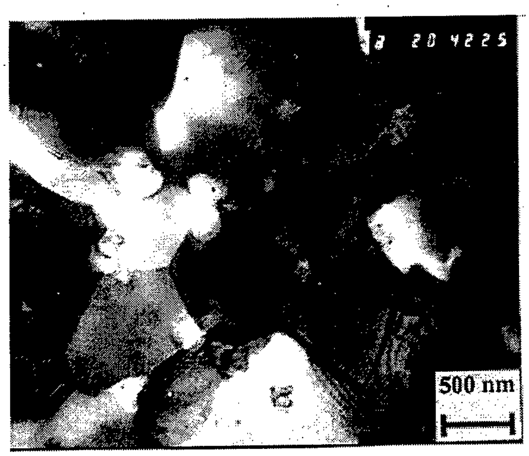


Fig. 7. Microstructure of the Al 1420 alloy after tensile testing at 673K with a strain rate of 10^{-1} s^{-1}.

3.1.4. Discussion

The superplastic forming industry uses forming rates for sheet metals which are typically in the range of 10^{-3} to 10^{-2} s^{-1} and utilizing strains which are equivalent to tensile strains of the order of 300-400% [18, 19]. The present project demonstrates the feasibility of achieving these and higher strains at very rapid strain rates in a commercial cast aluminum alloy by subjecting the material to intense plastic straining through the process of equal-channel angular pressing. For example, an elongation of 950% was recorded in this study for a sample tested at 673 K with a strain rate of 1 s^{-1} after ECA pressing to a strain of ~12 (Fig. 6): for this strain rate, this elongation appears to exceed any reported elongation for the standard metal matrix composites and powder metallurgy aluminum-based alloys which are generally associated with HSR SP [15].

This work establishes ECA pressing as a viable processing tool for achieving the ultrafine-grained microstructure which is an important prerequisite in order to attain HSR SP. Nevertheless, the introduction of an extremely fine grain size through ECA pressing is not a sufficient criterion to achieve HSR SP because it is necessary also that the grains remain reasonably stable at the high temperatures required for diffusion-controlled superplastic flow.

Earlier results demonstrated the potential for achieving a very fine grain size in an Al-Mg solid solution alloy but this alloy was not capable of exhibiting HSR SP because the grains grew rapidly at temperatures above ~ 450 K and this is equivalent to the relatively low homologous temperature of 0.48 T_m where T_m is the absolute melting temperature of the material [13]. This difficulty was avoided in the present investigation because grain growth is restricted in the commercial Al 1420 alloy through the presence of a fine dispersion β'-Al_3Zr particles which remain stable at the high temperatures required for superplastic flow.

Superplasticity has often been attained in commercial alloys by developing an appropriate thermomechanical treatment, typically combining elements of solution treating, ageing and rolling, which lead ultimately to recrystallization and a grain size sufficiently small that tensile testing gives high elongations to failure. However, it should be noted that thermomechanical processing has two distinct disadvantages by comparison with the utilization of an ECA pressing procedure. First, the recrystallized grain sizes are generally substantially larger after thermomechanical treatments by comparison with the ultrafine grain sizes which are achieved in ECA pressing and this means that the superplastic range of strain rates will tend to be lower than those required for HSR SP in thermomechanically processed materials. Second, the development of an appropriate thermomechanical treatment for any selected alloy is time consuming since it depends critically upon the precise composition and the nature of the microstructure in the unprocessed material. By contrast, ECA pressing is a relatively simple technique which can be applied to many different materials without any significant changes, thereby negating the need to conduct a series of detailed experiments in order to optimize the various procedures which make up thermomechanical processing.

Thus, ultrafine grained structure in the 1420 alloy can be processed by ECA pressing and a significant grain size refinement results in enhanced superplastic properties. At the same time, deformation behaviour of UFG 1420 alloy essentially depends on regimes ECA pressing which determine volume fraction, sizes and distribution of precipitates of excesses phases.

3.2. Influence of severe plastic straining on microstructure and mechanical properties in metal matrix composite Al 6061-10vol%Al_2O_3.

3.2.1. Experimental results and discussion

Figures 8 and 9 show typical microstructures in the samples subjected to torsion straining and ECA pressing, respectively, together with the appropriate SAED patterns [8]. Inspection shows that substantial grain refinement has been achieved using both processing procedures and the mean grain sizes were estimated as ~0.2 μm after torsion straining and ~0.6 μm after ECA pressing. It is apparent from the SAED pattern in the sample subjected to torsion straining that the microstructure consists of an array of many very small grains having an essentially random distribution of orientations. It is also apparent from Fig. 8 that the grain boundaries are not well defined but rather they are poorly delineated and generally irregularly shaped or curved. Furthermore, the contrast within the grains is non-uniform and indicative of a highly strained structure. Similar observations were reported earlier for an Al-Mg solid solution alloy subjected to torsion straining and it was shown, using high-resolution electron microscopy, that there were regions adjacent to the grain boundaries containing significant lattice distortions [20]. Observations of this type demonstrate that the grain boundaries introduced by intense plastic straining are in a high-energy non-equilibrium configuration. The grain boundaries and grain interiors appear similar after ECA pressing, as shown in Fig. 9, and again the structure consists of an array of very small grains with poorly defined boundaries and many extrinsic dislocations contained within the grains.

Fig. 8. Microstructure and SAED pattern after torsion straining.

Fig. 9. Microstructure and SAED pattern after ECA pressing.

The Vickers microhardness was measured before and after intense plastic straining and as a function of annealing temperature up to 500°C. The results are shown in Fig. 10, where the measured microhardness in the as-received condition is ~650 MPa and this value is increased to ~1600 MPa and ~1200 MPa after torsion straining and ECA pressing, respectively. Thus, intense plastic straining increases the strength of the composite by factors of ~2 or close to ~3, with the higher strength attained by torsion straining because of the smaller grain size in this material. It is apparent from Fig. 10 that the microhardness decreases at elevated temperatures in the sample subjected to torsion straining whereas it increases initially to a maximum value of ~1400 MPa after annealing for 1 hour at 100°C in the sample subjected to ECA pressing. A similar initial increase in the microhardness with low temperature annealing has been reported also in other materials [21, 22] and this trend is generally interpreted in terms of a rearrangement of the non-equilibrium grain boundaries into a more equilibrated structure. At temperatures above ~100°C, there is a similar decrease in the microhardness with increasing annealing temperature for both the torsion strained and the ECA pressed samples. This decrease is due to the occurrence of grain growth at these elevated-temperatures: for example, the grain size was measured as ~2 μm in both the torsion strained and the ECA pressed samples after an anneal for 1 hour at 250°C.

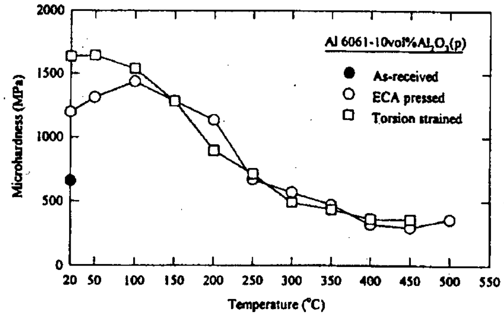
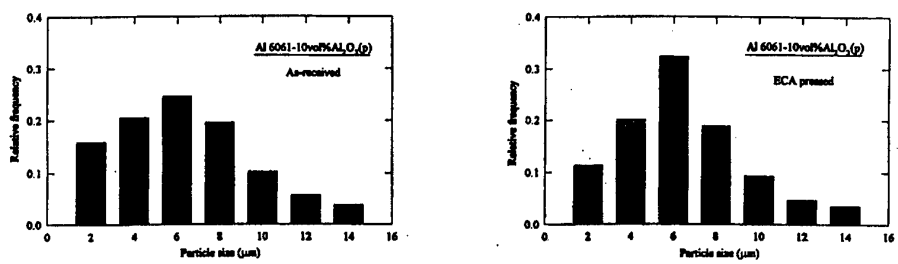


Fig. 10. Variation of microhardness with annealing temperature after torsion straining or ECA pressing.

Detailed measurements indicated there was little or no breaking of the Al_2O_3 particulates after ECA pressing to a strain of ~10, and the average particulate sizes were measured as 7.5 ± 3.1 and 7.5 ± 3.3 μm in the as-received and in the ECA pressed condition, respectively. In addition, the distributions of particle sizes were similar in these two conditions, as indicated in Figs. 11(a) and (b) where the particulate sizes are plotted in increments of 2 μm. Although the present experiments using ECA pressing reveal no breaking of the particulates, it is interesting to note that some limited particulate cracking has been reported in the Al 6061-10vol%Al_20_3(p) composite after extruding up to an extrusion ratio of 256 [23]. In the present investigation, the ECA pressing was conducted up to an equivalent extrusion ratio of $>2\times10^{-4}$ but the measurements reveal an absence of any significant particulate cracking. This apparent dichotomy may arise for two reasons. First, it is possible that the potential for cracking was reduced in the present investigation because of the relatively high temperatures employed for the ECA pressing. Second, it is important to note that the ECA pressing procedure necessitates no reduction in the sample cross-section because of the absence of any confining aperture and this suggests that the mechanics of extrusion and ECA pressing are different.



(a) (b)

Fig.11. Particulate size distributions (a) before and (b) after ECA pressing.

Tensile testing of several samples in the ECA pressed condition failed to reveal any evidence for very high superplastic ductilities. The maximum elongations to failure were recorded in this investigation at the highest testing temperature of 853 K where the values were ~150%, ~100% and ~90% for the three testing strain rates of 1×10^{-3}, 1×10^{-2} and 1×10^{-1} s^{-1}, respectively. The failure to attain high strain rate superplasticity in this material after ECA pressing may be associated with the presence of the relatively large Al_2O_3 particulates within the matrix which would probably tend to inhibit the occurrence of easy grain boundary sliding or, as reported elsewhere for a cast aluminum alloy [12], it may be associated with the need to optimize the ECA pressing conditions in order to attain a more equilibrated and thermostable microstructure. It is worth noting in this respect that the paniculate sizes recorded in Fig. 11 are substantially larger than the sizes recorded in aluminum-based metal matrix composites exhibiting high strain rate superplasticity where the average particle sizes are often < 1 μm [24].

Thus, severe plastic deformation can be succesfully used for formation of UFG structure not only in casting alloys but also in metal matrix composites. It enables to start the investigations of deformation behaviour of these advanced materials.

3.3. Examples of superplastic forming of complex shape articles.

Superplastic forming (SPF) is a well-established technology making use of the high or superplastic ductilities which may be achieved in some sheet metals in order to fabricate compex parts [25, 26]. In practise, the use of this technology in industrial applications is currently limited because of the relatively low strain rates associated with the optimum superplastic properties and the consequent long times required to form a component using SPF. For example, at strain rates of $\sim 10^{-3}$-10^{-2} s^{-1}, the production forming times are typically ~20-30 minutes for each part. These long times necessarily restrict the SPF technology to high-value components and limited production runs in industries such as aerospace and constructions.

In principle at least, the industrial application of SPF could be significantly enhanced if the optimum superplastic properties were attained at higher strain rates: for example, if forming was conducted in the strain rate range of $\sim 10^{-1}$-1 s^{-1}, the forming times would be effectively reduced to a few seconds for each component. From this viewpoint high strain rate superplasticity observed in UFG Al alloys is very attractive for SPF of complex shape articles. This part illustrates practical examples of some products fabricated from the UFG Al-1420 alloy in IPAM USATU. In Fig. 12 it is shown view of the article of "Piston" type having a complex shape fabricated from the UFG Al 1420 alloy by SPF at the condition of HSR SP.

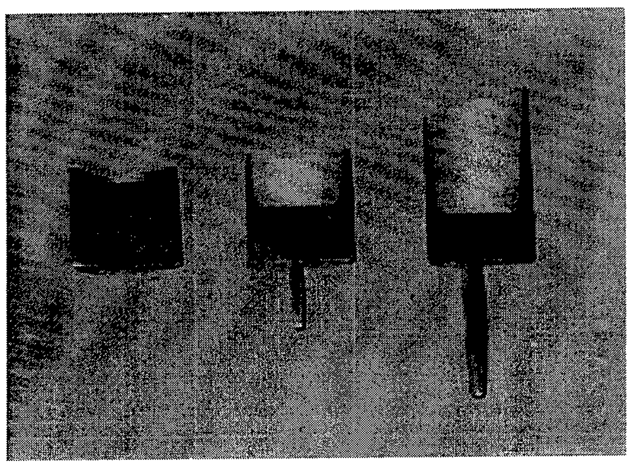


Fig. 12. View of the article of "Piston" type fabricated from the Al 1420 alloy by
(a) forming of coarse-grained alloy at T=20°C, (b) forming of coarse-grained alloy at T=350°C,
(c) forming of UFG alloy using an effect of HSR SP at T=350°C and $\varepsilon=3\times10^{-1}$ s^{-1}.

Forming of coarse-grained alloy at T=20°C (Fig. 12(a)) was stopped at initial stage because load equal 29kg/mm^2 was not sufficient to fill in die shape at thin ribs of rigidity having thickness about of 0.5 mm at edges. Further load increasing could be lead to failure of die.

Forming of coarse-grained sample at T=350°C (Fig. 12(b)) was not total, because load equal 29kg/mm^2 was not sufficiently again and ribs of rigidity was formed only in half of length. At the same time significant decrease of load took place during forming of third sample at $\varepsilon=10^{-1}$ s^{-1} corresponding HSR SP regime. Total and lengthened ribs of rigidity with thickness of 0.5 mm at edges and total length of 27 mm was formed.

In Fig.13 it is shown article of "Piston" type fabricated from the UFG Al 1420 alloy by SPF at the conditions of HSR SP with following mechanical processing. This material is supposed to be used in small overall internal combustion engines.

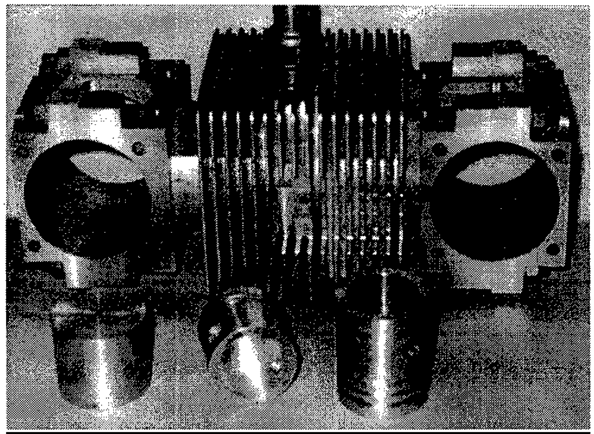


Fig. 13. View of the article of "Piston" type fabricated from the UFG Al 1420 alloy which is supposed to be used in small overall internal combustion engines (it is shown on the figure behind the piston).

The UFG Al-1420 alloy enables to fabricate complex shape article at temperature of 350°C, which significant lower temperature of isothermal forming at 450°C. The decrease of the SPF temperature provides following advantages:
- productivity rise by decrease heating time of sample and die
- expenditure of energy decrease because of straining at lower temperatures;
- possibility of application for die manufacture more cheaper steels.
- possibility of application more ecological (smoke free) technological lubrications during forming.

CONCLUSIONS

1. Three different ECA pressing procedures were investigated. The results show that each of these procedures gives samples which are capable of exhibiting high strain rate superplasticity. Optimum results were obtained using a material which was ECA pressed to a strain of 12. In these samples, tensile testing at a temperature of 673 K gave elongations to failure of 1210% and 950% at strain rates of 10^{-1} and 1 s^{-1}, respectively.
2. Significant grain refinement, down to the submicrometer level, was achieved in an Al-6061 metal matrix composite reinforced with 10 vol% Al_2O_3 particulates using both the torsion straining and ECA pressing procedures. The strength of the composite, as estimated from microhardness data, was increased by almost a factor of ~2 by ECA pressing and close to a factor of ~3 by torsion straining.
3. After ECA pressing to a strain of ~10, quantitative metallography revealed no evidence for any breaking of the Al_2O_3 particulates.
4. Ultrafine grained A1 1420 alloy allows to fabricate complex shape articles by high strain rate superplastic forming at temperature of 350°C and strain rate of 3×10^{-1} s^{-1}.
5. The following publications were fulfilled and prepared in the frames of this project:
   - R. Z. Valiev, R. K. Islamgaliev, N. F. Kuzmina, Y. Li and T. G. Langdon, Scripta Mater., V.40, 177 (1999).
   - S. Lee, P. B. Berbon, M. Furukawa, Z. Horita, M. Nemoto, N. K. Tsenev, R. Z. Valiev and T. G. Langdon, Mater. Sci. Eng. A (1999) in press.
   - R. Z. Valiev and R. K. Islamgaliev, Mat. Sci. Forum, V. 304-306, 39 (1999).
   - R. K. Islamgaliev, N. K. Tsenev, A. M. Shammazov, N. F. Yunusova, M. M. Bickbulatov, Abstracts of the Int. Conf. on Investigation and Application of Severe Plastic Deformation, August, Moscow, 1999, p. 98.
   - R. Z. Valiev, Nanostructured Materials from Severe Plastic Deformation, Proceedings of the IV Int. Conf. on Nanostructured Materials, Stockholm, June, 1998, in press.
   - R. Z. Valiev, R. K. Islamgaliev, Fiz. Metall. Metalloved., 85, 3, 161 (1998).

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