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Original Research Article

Microstructure and mechanical properties of a thixoforged (semi solid state forged) Al–Cu–Mg alloy

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ABSTRACT

Al–4.4%Cu–1.4%Mg–0.7%Mn (AA 2024 grade) wrought alloys are forged in a semi solid state for 30% and 40% reductions at two increasing temperatures (525 °C and 535 °C). Additionally, the alloy is forged in the solid state at 450 °C for comparison purposes. The hardness and tensile properties of the forgings were evaluated and compared. The microstructure characterization, fracture morphology of the tensile failed samples of the forgings was performed with the aid of optical and scanning electron microscopes (SEM). The key findings of the present investigation are: (1) the microstructure of the thixoforged alloys shows a significant grain refinement with the grain size range of 3.5–8.7 μm through the recrystallization and partial remelting, thixotropic flow of liquid, grain boundary sliding, rotation and deformation, (2) the tensile strength, hardness and ductility properties of the thixoforged alloys are marginally higher than the solid state forged alloys, (3) the condition of 535 °C and 40% reduction is identified as the best thixoforging condition that gives the average grain size of 3.5 μm, and (4) the fractography of the thixoforged alloys shows spherical grain morphology failed by the ductile rupture mechanism and the fracture mode is intergranular with no evidences of solidification defects such as micro shrinkage pores and hot tearing.

1. Introduction

Thixoforging is an emerging energy efficient, semi solid metal forming process that has the potential to produce parts with superior mechanical properties and fine uniform microstructures [1,2]. This process has a high potential in automobile and aircraft applications such as brake cylinders, wheel, non-critical structural parts, fittings, fuel systems, electrical connectors, engine pistons and valve bodies [3]. Moschini [4] claims that semi solid processing technology saves 50% cost in manufacturing automobile fuel system components relative to the conventional manufacturing processes. Kenney et al. [5] showed the potential for greater production rate, weight saving and improved mechanical properties from thixoforging the A357 Al alloy over the conventional gravity die casting.

Thixoforging process is basically a combination of both casting and forging. The essential requirement for the thixoforging is that the alloy should have a definite solid + liquid region with a wide freezing range and a shallow liquid fraction–temperature curve slope, For instance: the hypo or hyper eutectic alloys are very well forged by this process [6]. In

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this process, a typical extruded bar alloy is heated to the temperature above the solidus line according to the phase diagram. The selection of temperature is dependent on the amount of solid or liquid fraction in the material. The solid fraction in the material for thixoforging is expected to typically lie between 60 and 95% [7]. The higher amount of solid fraction is usually preferred because it reduces the chance of volumetric defects, increases the stability of the material under its own weight, promotes the smooth laminar flow of liquid, and also improves the surface quality and the internal structure of the formed components.

At the forming temperature, the alloy recrystallizes and forms the solid globular grains surrounded by liquid films, called the semi solid or mushy state. In this state, the bonding between solid grains is weakened by the liquid and the flow stress of the material is lowered substantially. The mechanical restraints at the grain boundaries are relieved by the liquid. Due to this, the solid grains are allowed free rotation, displacement, relative sliding quite freely under deformation. Consequently, the material deforms smoothly like a lump of clay and forms easily under very low pressing force [8]. In addition, the solidification of liquid under pressure refines the microstructure. This kind of forming process is also known as recrystallization and partial remelting (RAP) process. This process has several advantages: (1) it eliminates the defects such as cold shut, gas porosity, shrinkage and any other volumetric defects carried forward to the forming stages, (2) it improves the mechanical properties by microstructure refinement, (3) it reduces the power consumption of the press by reducing the forming load requirement, (4) it provides cost and energy saving through higher production rate and longer tool life, and offers geometrical flexibility in the product design, and the possibility for automation, (5) it has the capability to form brittle and high melting point/reactive/strength alloys due to the reduced flow stress in the semi solid state, and (6) it has got the ability to produce near net complex shaped, thin sectioned, high integrity components with improved surface quality, yield and tight dimensional tolerances [1,3,5,9,10]. Some of the applications where this process has a promising future are: master brake cylinder, compressor housing, fuel rails, suspension parts, engine casing, brackets and mounts, steering knuckles, air intake casting, valve bodies, control arms, tie rods, compressor piston, mission and non-critical aircraft structural parts, electronic components such as notebook computer casing and mobile casing, and so on [2].

Studies on thixoforging of steels (100Cr6, C38 and X21OCrW12) showed the high potential of semi solid forging in improving the formability and mechanical properties of the products [11,12]. The advantages of high strength to weight ratio, high fuel efficiency, lower level of greenhouse gas and particulate emissions drive automotive industries to study the thixoforming characteristics of Al alloys. Recently, studies on thixoforming of Al alloys are also emerging for automotive applications [13]. For instance, Valer et al. [14] processed the Al–25%Si–5%Cu alloy through thixoforging and demonstrated that the thixoforged part has better fatigue resistance and fracture toughness than the extruded alloy. They attributed the better distribution of the primary Si particles developed by semi solid forming responsible for the properties improvement. Similar improvements are reported for thixoformed A356 alloy compared to sand/permanent mould/pressure die casting processes [1,15]. A review by Fan [2] compared the mechanical properties of A356, A357 grades Al–Si alloys processed by thixoforming, sand casting and permanent mould casting. He showed that thixoforming significantly improves the static and fatigue strength and ductility of the alloy by reducing or eliminating the volumetric defects such as porosity, hot tearing, shrinkage voids, segregation, and by microstructure refinement with enhanced chemical homogeneity. However, he also mentions that thixoforging processes have received limited attention so far. Further, most of the reports on thixoforging of Al alloys have been mostly based on the cast Al–Si alloys such as A356 and A357 grades [3,6,13,16]. The main disadvantages of cast alloys are inferior ductility, coarser grain structure and inferior strength especially fatigue strength. In contrast to the cast alloys, the wrought Al alloys such as AA 2014, AA 2024, AA 6061, AA 7075, AA 7050, AA 7085 grade alloys are promising in offering better strength and ductility properties with refined grain structure. Some thixoforging studies showing properties improvement are reported on the AA 7075 grade Al–Zn alloys and Al–Mg–Si alloys [17–20]. Particularly, Al–Cu based alloys such as AA 2014, AA 2024, AA 2219, AA 2124 grades are highly attractive and found in several aircraft applications such as heavy plates, extrusions, wheels, structural members and so on [21].

To the best of my knowledge, the thixoforging of wrought Al alloys, particularly Al–Cu alloys such as AA 2014, AA 2024, AA 2219, AA 2124 grades, are not attempted seriously so far because of the difficulty in thixoforming due to the narrow freezing range and higher sensitivity of the liquid fraction with the temperature [7,22]. In light of these facts, the present study investigates the possibility of thixoforging the AA 2024 (Al–4.4%Cu–1.4%Mg–0.7%Mn–0.5%Fe) alloy. The mechanical properties of the semi solid state forged alloy were measured and compared with the conventional solid state forging.

2. Experimental procedures

In this study, the AA 2024 alloy was selected for thixoforging. The exact composition of the extruded bar alloy was Al–4.4% Cu–1.4%Mg–0.7%Mn–0.5%Fe alloy according to the atomic emission spectroscopy (SPECTROVAC). The alloy was forged in the solid + liquid (S + L) region in the phase diagram to simulate the thixoforging conditions. Two temperatures (525 °C and 535 °C) were selected in the S + L region in an Al–Cu–Mg–Mn phase diagram to conduct the thixoforging operations. The solidus and liquidus temperature of AA 2024 alloy are 515.8 °C and 640.6 °C, and the slope of the solid fraction versus temperature up to the solid fraction of 60% is 0.014 according to Table 1 given in Fan [2] and the report by Liu and Fan [23]. From these data, the calculated amount of solid fraction in the AA2024 alloy for 525 °C and 535 °C is approximately 12.8% and 26.8% respectively. The reason for the selection of high solid fraction in the present study is that (1) it enhances the kinetics of spheroidisation by reducing the shape factor according to the morphological evolution equation given by Blais et al. [24] that helps in grain refinement during semi solid forging, (2) it is less sensitive to temperature

Table 1 – Designation and properties of solid state and thixoforged AA 2024 Al alloys.

Designation	Mean grain size (μm)	Average hardness (BHN)	Yield strength (MPa)	Ultimate tensile strength (MPa)	% ductility
450A	41 ± 15	123.1	365	416	4.11
450B	33 ± 14	128.7	360	428	4.65
525A	8.7 ± 5	134.2	340	435	5.84
525B	6.4 ± 3	133.6	326	439	5.88
535A	7.6 ± 3	137.8	336	448	7.74
535B	3.5 ± 2	138.3	337	447	8.12

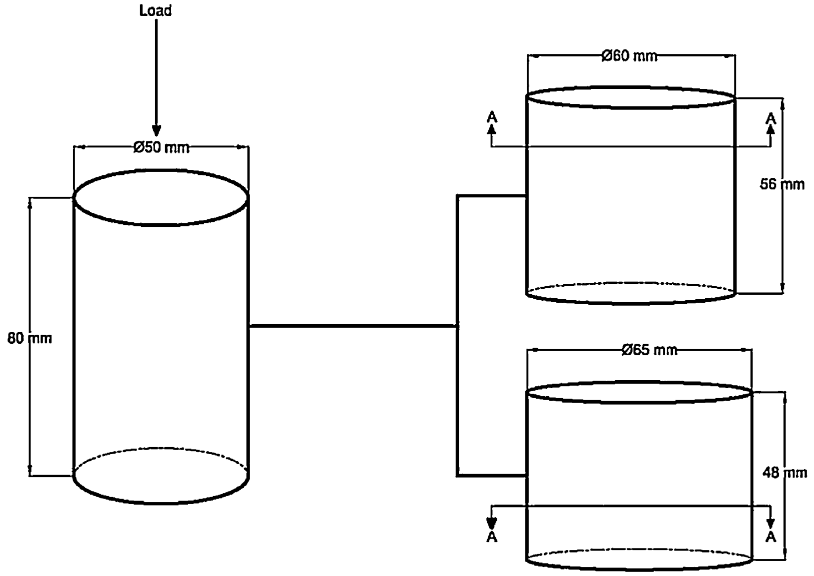

Fig. 1 – Schematic of the forging design.

and allows smooth laminar flow of liquid during the deformation [9], and (3) the stability of the material under its own weight increases under the condition of loading and free state. The isothermal holding time for the alloy in the semi solid state before forging was 30 min. The isothermal holding time is essential to obtain a globular grain structure because the mere heating to the semi solid temperature does not produce the microstructure (recrystallized equiaxial grains surrounded by liquid) required for thixoforming as reported by Birol [17]. Selected time was based on the study by Dong et al. [19]. In their study on thixoforging of the AA 7075 Al alloys at 580 °C, it was found that 30 min was sufficient to spheriodize the grains without the dendritic or rosette morphology beyond that the grains begin to grow abnormally. Additionally, the alloy was forged in a single phase (α) region at 450 °C for the properties comparison. The designation of the alloys forged at different temperatures and % reductions is given in Table 1. The forming tools were coated with the graphite lubricants before the forging. They were internally heated to 250 °C to avoid thermal losses during the forging. The forging operations were conducted in a 10,000 kN hydraulic press at a die speed of 33.3 mm/s. Alloys were subjected to 30% and 40% reduction at each forging temperature. After the forging, the alloy was immediately quenched in hot water bath maintained at 40–70 °C to avoid microstructure coarsening due to the longer solidification time. The forging method sketch was illustrated in Fig. 1.

The forged alloys were subjected to the following heat treatment cycle:

Solutionizing at 493 ± 5 °C for 1 h followed by water quenching to room temperature, and subsequently aged at 191 ± 5 °C for 12.5 h followed by normal air cooling.

After the heat treatment, samples were extracted for tensile, microstructure and hardness testing. The sample extraction plan in the forged alloy is illustrated in Fig. 2.

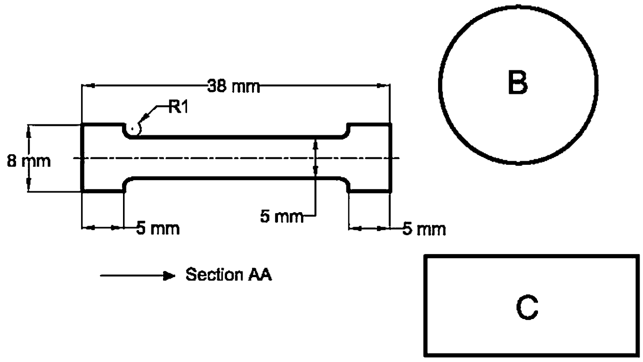

Fig. 2 – Sample extraction plan in the forging.

Tensile tests were conducted at a cross head speed of 1 mm/min in a 25 kN Instron universal testing machine. The hardness of the alloy was measured using the Brinell scale (WOLPERT hardness tester). The indenter type, size, and the indentation load were steel and 1 mm, and 100 N respectively. ASTM E8/E8M and ASTM E10 standards were followed for tensile and hardness testing respectively. All the tests were conducted at 50% humidity and 23 °C temperature conditions. The samples for microstructure characterization were prepared by standard metallographic techniques and etched with Keller's solution (1 ml HF + 1.5 ml HCl + 2.5 ml HNO_3 + 95 ml H_2O). The microstructure of the samples was analyzed in the optical (Nikon Epiphot) and scanning electron microscopes equipped with an energy dispersive X ray spectrometer (SEM/EDS) (Hitachi TM-3000, Japan). All the tests were conducted at room temperature of 28 °C. The fracture surface of the tensile failed samples was analyzed in the SEM to identify the failure modes of the thixoforged alloy.

3. Results and discussion

3.1. *Microstructure*

The microstructure of the semi solid and solid state forged alloys is presented in Fig. 3. The solid state forged alloy shows a typical elongated α-Al grain morphology structure with small dispersed particles in the direction perpendicular to the forging load application with relatively higher variation in grain size, as seen in Fig. 3(a)–(b). Further, elongated grain structures increase with an increase in the amount of deformation, as seen in Fig. 3(b). In contrast, it is noted that the microstructure of semi solid processed alloys shows globular (equiaxed) shape α-Al grains without any appreciably elongated morphology or dendritic solidified structures. These grains are surrounded by a solidified liquid phase in the thixoforged alloys as seen in Fig. 3(c)–(f). The absence of interconnected grains confirms that the shear force from the thixoforging process fragments the elongated grains. Comparing the average grain size between the solid and thixoforged alloys, thixoforged alloys show a significant grain refinement over the solid state forged alloy, as seen from SEM images in Fig. 4. Particularly, the alloy forged for 40% reduction at 535 °C shows a very fine grain structure with the mean grain size of 3.5 μm. Further, it is noted that the forming defects such as hot cracks, oxide inclusions and residual porosity are not observed in the thixoforged alloys.

A nearly spherical grain structure in the thixoforged alloys indicates that the heating to a semi solid state ensures the transformation of globular solid grains morphology before the forging operation. The reduction of interfacial energy between the solid and liquid phases provides a driving force for the globular structure formation [2]. The defects such as vacancies and dislocations, in other words the strain energy stored in the material, are expected to be very high in the starting bar material due to the heavy deformation from the extrusion process. With an increase of forging temperature, the motion of dislocations by climb and cross slip mechanisms is activated. This process reduces the free energy of the system by initiating a gradual recovery and recrystallization process. The recrystallization creates fine, strain free-equiaxed grains in the material below the solidus temperature. Subsequent partial melting in the isothermal holding stage above the solidus temperature assists in fragmentation of ripening grains. In addition to the above, the AA 2024 alloy inherently has a non-faceted interface that assists in globularization by the minimum mechanism of the interfacial energy [25,26]. The fragmented grains evolve as a globular morphology by eliminating the areas of high curvature by atomic diffusion of solutes from the liquid [1]. This process is usually referred to as recrystallization and partial remelting process (RAP) [27]. It is noted that the holding time selected in the present study is sufficient to transform the globular morphology structure in the alloy and is not exceeded to cause any grain growth. Also, it provides adequate time for the liquid to form and spread evenly along the grain boundaries. This liquid forms the intergranular channels and separates the grains. During the press forging, the spherical grains surrounded by a liquid film are subjected to the forging pressure. Initially, solid grains establish contact by squeezing out the surrounding eutectic liquid film. The liquid thixotropically flows under the shear force and forms the liquid path between the solid skeleton structures. The solid grains slide past each other and deform under pressure. They also rotate to accommodate strain during deformation. After a sufficient deformation, they undergo continuous dynamic recrystallization that helps to refine grains. The flowing liquid also assists in continuous deformation of solid grains and reduces the press force significantly by its thixotropic properties. In short, the mechanisms responsible for the deformation during the thixoforging are: (1) the thixotropic flow of liquid films around the grain boundaries, (2) solid grains rotation and sliding, and (3) the plastic deformation of grains and subsequent dynamic recrystallization.

With an increase of the semi solid forging temperature, the liquid fraction in the alloy increases which in turn increases the thickness of the liquid film surrounding the solid grains. Hence, the distance between the solid grains increases that makes difficult the grain coalescence by grain boundary migration. Further, the spheroidisation process of the grains is also accelerated by the faster removal of high curvature through enhanced diffusion facilitated by the liquid [28]. This helps to form a nearly ideal spherical shape grain. More amount of liquid in the alloy makes the alloy deform easily under the relatively low press force. In this condition, the solid grains easily rotate, accommodate larger strains. The grains elongate with the increasing strain. Increasing dislocation density and the movement of dislocations by slip form the dislocation pile-up. Further these dislocations rearrange to form the high angle boundaries through dynamic recovery and eventually break and refine by continuous dynamic recrystallization. Hence, the grain refinement occurs in the alloy through dynamic recovery and recrystallization mechanisms. The presence of liquid film around the solid grains prevents the grain coalescence and avoids grain coarsening. This effect is increased with the increase of the semi solid forming temperature and the amount of deformation. Table 1 shows clearly that an increase of the forming temperature and/or the amount of deformation marginally reduce the grain size in the thixoforging conditions. The % reduction effect on the grain

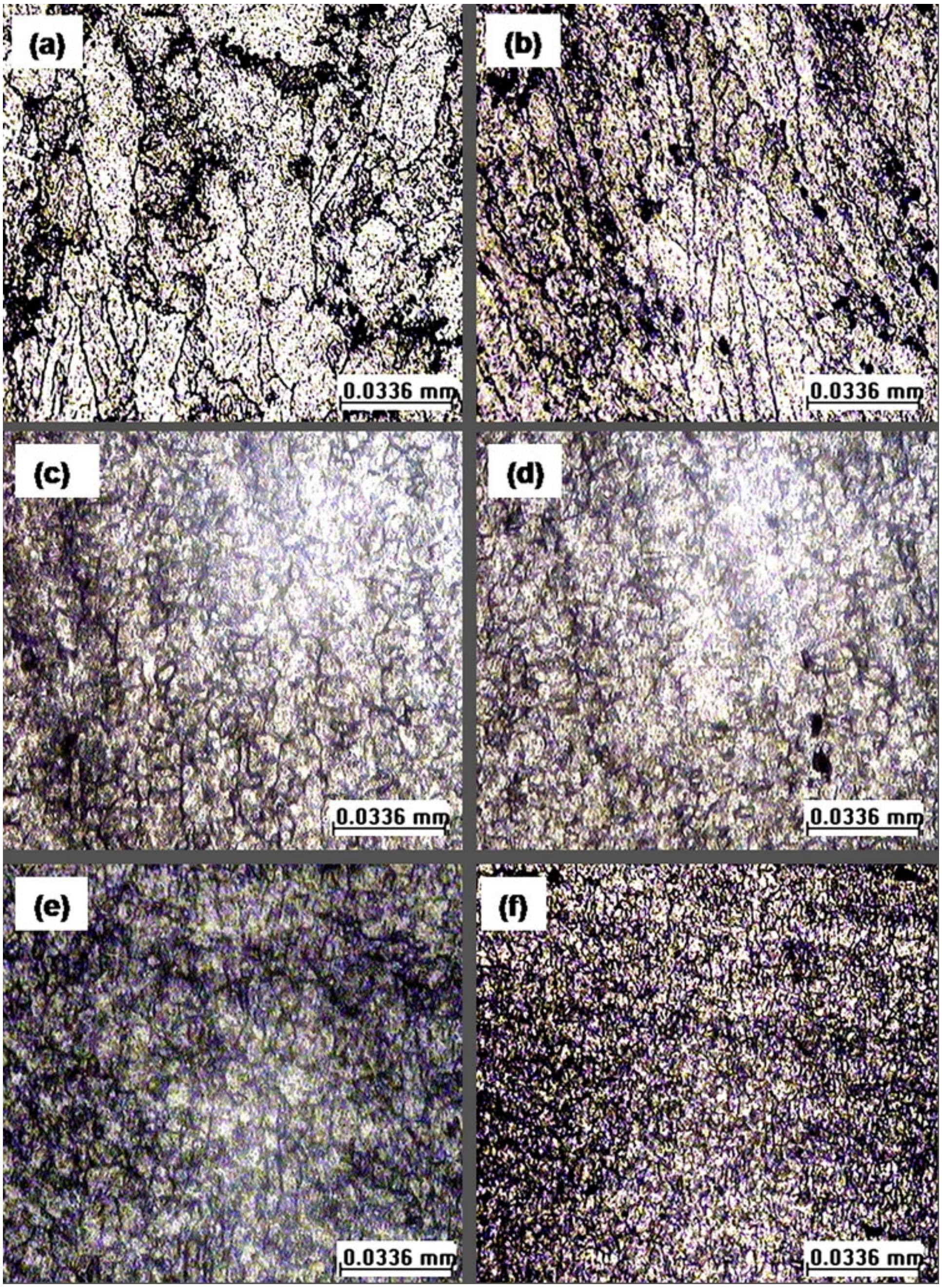

Fig. 3 – Microstructure of the solid state forged alloy at 450 °C, (a) 30%, (b) 40%, the thixoforged alloy at 525 °C, (c) 30%, (d) 40%, at 535 °C, (e) 30% and (f) 40%.

refinement is slightly better than the forming temperature effect, as seen in Table 1. It is because increasing amount of deformation enhances strain energy stored in the material and accelerates the dynamic recrystallization of solid grains and consequent grain refinement. However, the grain refinement does not alone improve the properties of Al alloys. Other factors such as grain boundary defects, precipitate distribution also affect the properties of the alloy. The above facts may be clear while comparing the strength properties of 525B and 535A thixoforged alloys. Despite of relatively fine grain size, the 525B condition gives less tensile strength than the 535A condition, as given in Table 1.

Another important observation is the uniform size and shape of grains in the thixoforged products. This helps to eliminate the anisotropy properties caused by the elongated grains in the conventional solid state forging products. Hence, the thixoforging is useful to solve the problem of properties variations with respect to the grain orientation.

3.2. *Tensile properties and hardness*

The mechanical properties of the solid state and semi solid state forged alloy are given in Table 1. The tensile stress-versus-strain curve for the alloys is presented in Fig. 5. The

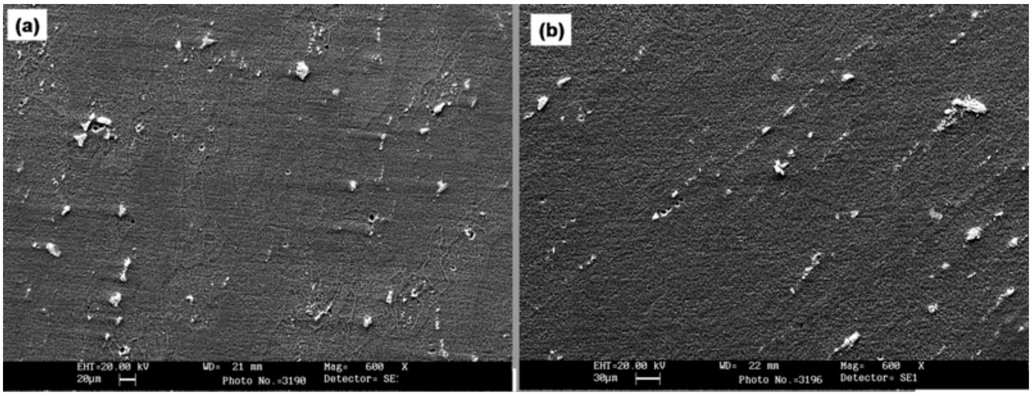

Fig. 4 – SEM microstructure images of (a) solid state forging (450 °C and 40%) and (b) thixoforging (535 °C and 40%).

tensile strength, hardness and % elongation of the thixoforged alloys are relatively better than the solid state forged alloy especially at higher forging temperature (535 °C). Between the thixoforged alloys, the tensile strength, hardness and % elongation increase with an increase of thixoforging temperature. Similar results are obtained for the thixoforged Al–3.8%Si alloys with increasing forging temperature [13]. The alloy forged at 535 °C shows the highest tensile strength and ductility. This result indicates that the amount of liquid fraction in the semi solid state has a role in influencing the mechanical properties. The results demonstrate that the increased liquid fraction is beneficial in improving the tensile properties. The increased effects of grain refinement with increasing temperature help in improving the strength and ductility properties. In contrast, the yield strength of the solid state forged alloy (450A and 450B) is slightly higher than the thixoforged alloy despite of possessing the relatively coarser grain structure. It is important to note that the tensile samples are extracted from the longitudinal (main working) direction. It is usual that the properties especially yield strength are maximal in the longitudinal direction because of the preferred orientation of the grains and strain hardened grain structures. Because of the longitudinal orientation of the sample, the yield strength of the solid state alloy is slightly higher. Also, in the semi solid state, the liquid usually forms at the grain boundaries due to their high energy. Upon quenching from the thixoforging condition, the solute segregation at the grain boundaries is probable to occur due to insufficient time for diffusion. The ensuing heat treatment process develops a relatively non-uniform precipitate structure in the thixoforged alloys due to the high solute concentration at the grain boundary. As the yield strength of the alloy is decided by both the grain size and the precipitate distribution. The relatively better distribution of the precipitates inside the grains in the solid state forged alloys has probably compensated the negative effects of coarse grain structures. The better precipitate distribution has greater effects on improving the yield strength by blocking dislocations through Orowan strengthening (dislocation cutting or overlooping the particles), dislocation strengthening through the formation of geometrically necessary dislocations and effective load sharing. Therefore, the improved precipitate distribution makes the yield strength of the solid state forged alloy (450A and 450B) marginally better. With an increase of the thixoforging temperature, the yield strength decreases and the tensile strength increases for the thixoforged alloys. Similar trends of decreasing yield strength and increasing tensile strength with the increasing thixoforging temperature are observed for the AA 7075 alloy by Bolouri and Kang [29]. They suggested that the increased thickness of the solidified liquid and the reduced fraction of primary α Al grains with the increasing the temperature deleteriously influence the yield strength properties. Also, the improved shrinkage pore-free solidified liquid structure with the increasing thixoforging temperature helps to improve the tensile properties by the adequate liquid feeding to compensate for solidification shrinkages. The ductility of the thixoforged alloys is better than that of the solid state forged alloys. This indicates that the uniform precipitate structure can only improve the strength through minimizing interparticle spacing and not the ductility in the

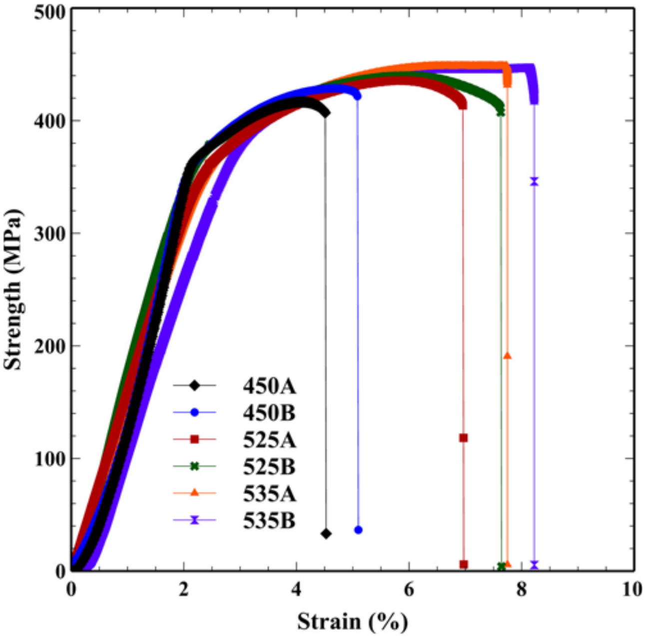

Fig. 5 – Tensile test graphs for the solid state (450 °C) and thixoforged (525 °C and 535 °C) alloys. In caption, A stands for 30%, B stands for 40%.

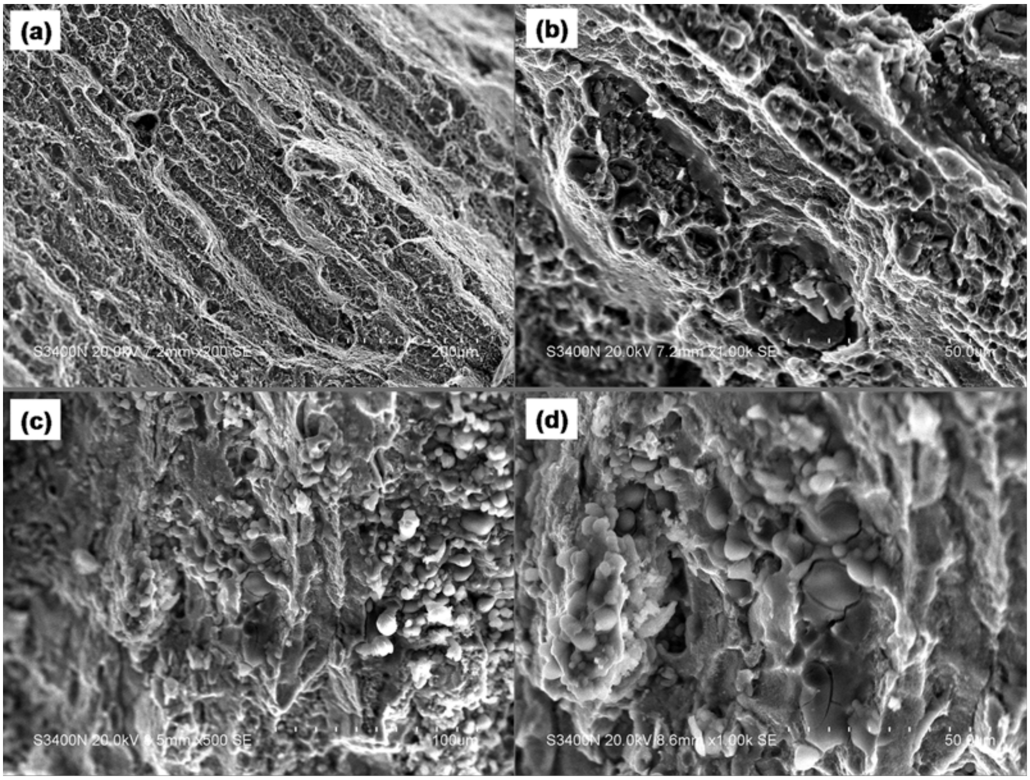

Fig. 6 – Fractographs of the alloy (a) and (b) solid state (450 °C, 40% reduction condition) forging and (c) and (d) thixoforging (535 °C and 40% reduction condition).

solid state forged alloys. The ductility increases with an increase of thixoforging temperature. This result is attributed to the better defect free structure of the solidified liquid, enhanced plastic deformation of the globular α-Al grains and much finer grain structures. Similar higher elongation was reported for the thixoformed AA 7075 alloy [19].

The effect of % reduction (strain imparted to the forging) on the tensile properties of the solid state and thixoforged alloys is not important, as seen from Table 1. Also, there is no appreciable change in the microstructure between the alloys thixoforged with increased % reduction. This hints that the grain refinement is not significant with the increase of the strain in the semi solid forging beyond the strain of 0.3 under the selected experimental conditions. The chance of liquid segregation defects increases with the increasing of forging load that offsets the improvement of properties by more straining [29].

3.3. *Fractography*

Fractographs of solid state (450 °C and 40% reduction) and thixoforged (535 °C and 40% reduction) alloys are shown in Fig. 6. The fracture surface of the solid state forged alloy has a mixture of cleavage facets with the river pattern, tears ridges and non-uniformly distributed dimples, as seen in Fig. 6(a). In addition, several particle removed sites are clearly seen in high magnification image (Fig. 6(b)). The particle removed sites are an indication of interface failure. These features also suggest that the strengthening of the matrix is caused by the dislocation bowing around the particles by Orowan mechanism rather than shearing the particles during deformation. The micro cracks nucleate at these interface void sites and propagate by joining together during the deformation. This process leads to the certain degree of ductile fracture by ductile rupture and micro void coalescence mechanisms. Further, the observation of river patterns indicates that cracks propagate through parallel planes before fracture. In short, the quasi cleavage fracture with severe particle interface decohesion failure is predominately observed in the solid state forged alloy. The fracture appears transgranular in nature. In contrast, the fracture surface of the thixoforged alloy shows the structure of spherical morphology with cracks running along the periphery of the grains. This indicates that the fracture is intergranular. The grain boundary liquid is rich with the solutes due to their low melting point which, upon solidification, segregates around the grain boundaries. The solute rich grain boundaries are easier path for crack propagation due to their brittle nature. Hence, the material fails by an intergranular manner. Similar type of fracture is reported for the thixoforged AA 7075 alloy [18]. Bolouri and Kang [30] explained that the fracture of the thixoforged alloy occurs by rupturing of solidified grain boundary liquid phases and/or by the separation of between the spherical grains and the solidified liquid phase. In the present study, the fracture surface of the thixoforged alloy shows the rupturing of grain boundary phases. This fracture mode supports the observation of high elongation values in the thixoforged conditions. Further,

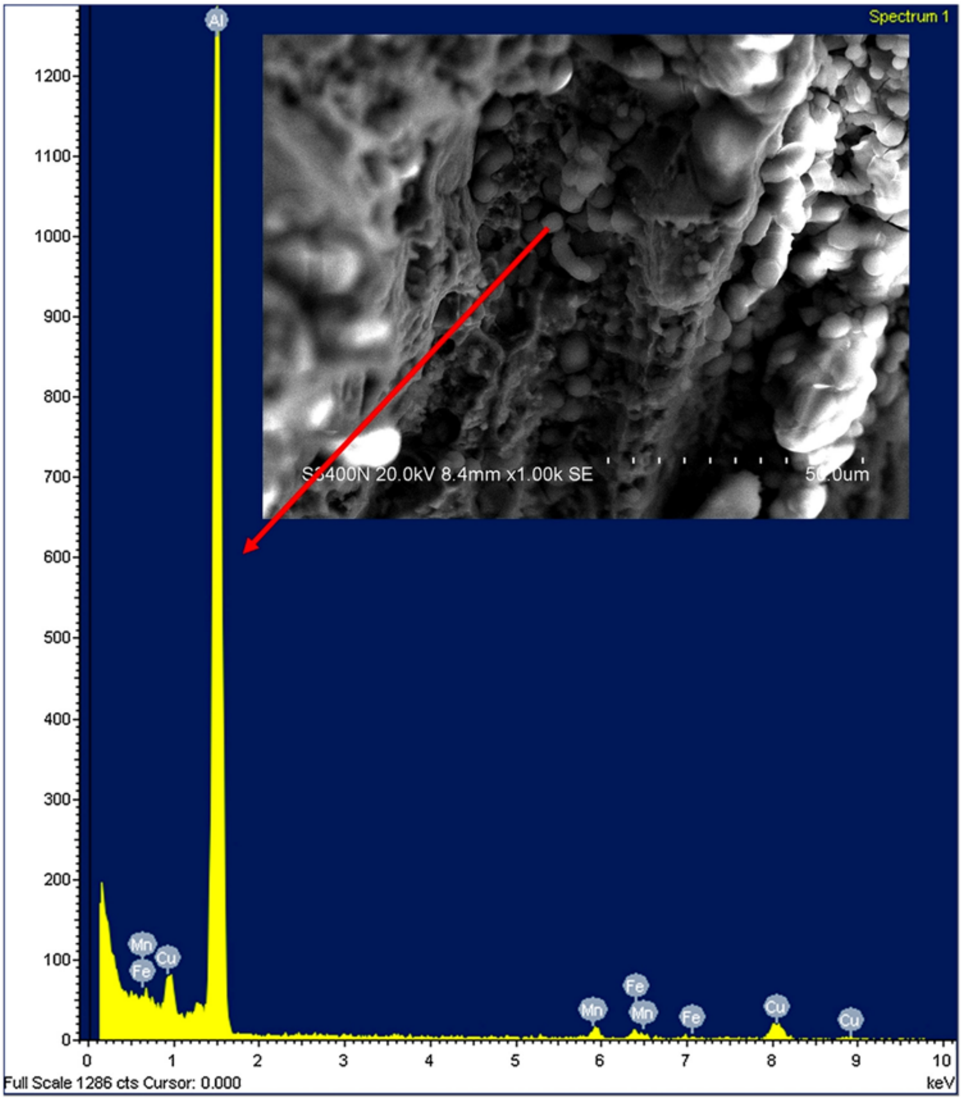

Fig. 7 – Composition analysis on the globular grains by EDAX for the alloy thixoforged for 40% reduction at 535 °C.

there is no feature of fracture of individual equiaxed grains. The absence of micro shrinkage pores defects around the grains for the 535B alloy indicates that there is a sufficient liquid feeding among the equiaxed grains to compensate for microshrinkage during solidification of the liquid. The EDX analysis of the spherical region, as shown in Fig. 7, shows that these regions constitute Al, solutes (Cu, Mn) and impurities (Fe).

4. Conclusions

The Al–4.4%Cu–1.4%Mg–0.7%Mn–0.5%Fe (AA 2024) wrought alloy is formed using thixoforging process under the high solid fraction conditions (12.8% and 26.8%). The microstructure, mechanical properties and fracture mechanisms were studied for the thixoforged alloys. The results are compared with the alloy forged in the solid state. The main conclusions of the present investigation are:

1. Significant grain refinement is possible by forging the alloy in the thixoforged conditions through the successive processes of recrystallization, partial remelting, thixotropic flow of liquid, grain boundary sliding, grain rotation, grain deformation, and dynamic recrystallization.
2. The tensile strength, hardness and ductility properties of the thixoforged alloys are marginally higher than the solid state forged alloys.
3. The process condition of 535 °C and 40% reduction is identified as the best thixoforging condition that gives a maximum grain refinement (average grain size of 3.5 μm).
4. The effects of % reduction and temperature are marginal in improving the grain refinement, tensile, hardness properties for the selected thixoforging conditions.
5. The fractography of the thixoforged alloys shows clearly spherical grain morphology failed by ductile rupture process during tensile testing and the fracture mode is completely intergranular with no evidences of solidification defects such as micro shrinkage pores and hot tearing.

REFERENCES

[1] D.H. Dirkwood, Semisolid metal processing, International Materials Reviews 39 (1994) 173–189.

[2] Z. Fan, Semisolid metal processing, International Materials Reviews 47 (2002) 49–85.

[3] J. Choi, J.H. Park, J.H. Kim, S.K. Kim, Y.H. Kim, J.H. Lee, A study on manufacturing of aluminium automotive piston by thixoforging, International Journal of Advanced Manufacturing Technology 32 (2007) 280–287.

[4] R. Moschini, Production of automotive components by pressure die-casting in the semi-liquid state, in: Proceedings on International Conference on Aluminium Alloys: New Process Technologies, 1993.

[5] M.P. Kenney, J.A. Courtois, R.D. Evans, G.M. Farrior, C.P. Kyonka, A.A. Koch, K.P. Young, Semisolid Metal Casting and Forging, 9th ed., ASM International, Metals Park, OH, 1988.

[6] S.A. Sajjadi, H.R. Mezatpour, M.T. Parizi, Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al_2O_3 composites fabricated by stir and compo-casting processes, Materials & Design 34 (2011) 106–111.

[7] H. Atkinson, Current status of semi-solid processing of metallic materials, Advances in Material Forming 352 (2007) 81–98.

[8] M. Kiuchi, R. Kopp, Mushy/semi-solid metal forming technology – present and future, CIRP Annals – Manufacturing Technology 51 (2002) 653–670.

[9] G. Vaneetveld, A. Rassili, J.C. Pierret, J. Lecomte-Beckers, Improvement in thixoforging of 7075 aluminium alloys at high solid fraction, Solid State Phenomena 141 (2008) 707–712.

[10] M.C. Flemings, Behavior of metal alloys in the semisolid state, Metallurgical Transactions A 22 (1991) 957–981.

[11] G. Hirt, H. Shimahara, I. Seidl, F. Kuthe, D. Abel, A. Schonbohm, Semi-solid forging of 100Cr6 and X210CrW12 steel, CIRP Annals – Manufacturing Technology 54 (2005) 257–260.

[12] E. Becker, R. Bigot, L. Langlois, V. Favier, J.C. Pierret, P. Cezard, Metallurgical and mechanical analysis from thixoforging steel shape, International Journal of Material Forming 1 (2008) 977–980.

[13] A.A. Reis, J.R. Oliveira, R.M. Oliveira, E.A. Vieira, Thixoforging of Al–3.8%Si alloy recycled from aluminum cans, Materials Science and Engineering: A 66 (2013) 461–465.

[14] J.V. Goni, J.M. Rodriguezibabe, J.J. Urcola, Strength and toughness of semi-solid processed hypereutectic Al/Si alloys, Scripta Materialia 34 (1995) 483–489.

[15] J.P. Gabathuler, H.J. Huber, J. Erling, Aluminium alloys: new process technologies, Metallurgia Italiana 69 (1993) 169–180.

[16] S.G. Shabestari, E. Parshizfard, Effect of semi-solid forming on the microstructure and mechanical properties of the iron containing Al–Si alloys, Journal of Alloys and Compounds 509 (2011) 7973–7978.

[17] Y. Birol, Potential of cast EN AW7075 billet as thixoforging feedstock, Materials Science and Technology 28 (2012) 553–559.

[18] S. Chayong, H.V. Atkinson, P. Kapranos, Thixoforming 7075 aluminium alloys, Materials Science and Engineering: A 390 (2005) 3–12.

[19] J. Dong, J.Z. Cui, Q.C. Le, G.M. Lu, Liquidus semi-continuous casting reheating and thixoforming of a wrought aluminum alloy 7075, Materials Science and Engineering: A 345 (2003) 234–242.

[20] W. Eidhed, C. Limmaneevichitr, H. Tezuka, T. Sato, The development of new Al–Mg–Si alloys for thixoforming, Materials Science Forum 519 (2006) 377–382.

[21] Alumatter, 2010 http://aluminium.matter.org.uk/aluselect/01 applications.

[22] D. Liu, H.V. Atkinson, P. Kapranos, W. Jirattiticharoean, H. Jones, Microstructural evolution and tensile mechanical properties of thixoformed high performance aluminium alloys, Materials Science and Engineering: A 361 (2003) 213–224.

[23] Y.Q. Liu, Z. Fan, Critical Assessment of Thermal Properties of Al Alloys – Internal Report, Brunel University, Uxbridge, UK, 2001.

[24] S. Blais, W. Loue, C. Pluchon, Structure control by electromagnetic stirring and reheating at semi-solid state, in: Proceedings of the 4th International Conference on the Semi-Solid Processing of Alloys and Composites, 1996.

[25] W. Kurz, D.J. Fisher, Fundamentals of Solidification, vol. 28, Trans. Tech. Publications, 1984, pp. 34–43.

[26] H.K. Jung, C.G. Kang, Reheating process of cast and wrought aluminium alloys for thixoforging and their globularization mechanism, Journal of Materials Processing Technology 104 (2000) 244–253.

[27] M.Z. Omar, H.V. Atkinson, E.J. Palmiere, A.A. Howe, P. Kapranos, Microstructural development of a high performance HP9/4/30 steel during partial remelting, Steel Research International 75 (2004) 552–560.

[28] K.N. Campo, C.T.W. Proni, E.J. Zoqui, Influence of the processing route on the microstructure of aluminum alloy A356 for thixoforming, Materials Characterization 85 (2013) 26–37.

[29] A. Bolouri, C. Kang, Thixoforging of wrought aluminum thin plates with microchannels, Metallurgical and Materials Transactions A 45 (2014) 609–735.

[30] A. Bolouri, C. Kang, Correlation between solid fraction and tensile properties of semisolid RAP processed aluminum alloys, Journal of Alloys and Compounds 516 (2012) 192–200.