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Original Research Article

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

T.R. Prabhu*

CEMILAC, Defence R&D Organization, Bangalore 560037, India

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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

* Tel.: +91 953 553 1407; fax: +91 80 2523 6516.
E-mail address: ramprabhu.t@gmail.com

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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