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Microstructure and property of a functionally graded aluminum silicon alloy fabricated by semi-solid backward extrusion process

Kai Zhang [a], Hao Yu [a,*], Jun-you Liu [a], Yan-xia Li [b], Jian Liu [a], Jia-liang Zhang [a]

[a] School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Department of Materials, North China Institute of Aerospace Engineering, Langfang 065000, China

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ABSTRACT

In this paper, the microstructure and mechanical property of a graded aluminum silicon alloy were investigated and a new preparation method for the graded material was proposed. The cup-shaped sample was fabricated by the backward extrusion process during the semi-solid state of A390 cast alloy. Characteristics and distribution of the primary particles were assessed by the optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive spectrum (EDS) and image analyzer software. The results showed that the content of primary Si gradually decreased from the bottom region to the upper region. The hardness and wear rate of the samples were measured to evaluate the variation in the mechanical properties corresponding to the variation in microstructure. The hardness values and wear resistance along the axis of the cup-shaped sample gradually increased from the upper region to the bottom region and from the inner region to the outer layer, respectively. The maximum average hardness value is 138.7 HB. The observations of fracture surface were analyzed by scanning electron microscopy to understand the fracture mechanism. The results also indicated that the ultimate tensile strength (UTS) of the graded material after T6 treatment are 275 MPa, increases 32.3% compared to the original backward extrusion alloy. Optical microscopy and electron probe micro-analyzer were used to study the distribution of elements and the microstructure of different intermetallic phases formed. Electron microprobe analysis (EMPA) results showed that the content of the prominent elements (Cu, Fe, Mg) in the upper region was higher than for the bottom part of the cup-shaped specimens.

1. Introduction

Hyper-eutectic Al–Si alloys have the potential for excellent castability, low coefficient of thermal expansion, good thermal conductivity, high strength at high temperatures and wear resistance. Therefore, they are well suited to the automobile industry, aerospace and military applications, etc. [1,2]. Among the various classes of aluminum silicon alloys, the A390 alloy as an important hyper-eutectic aluminum–silicon alloy is used to fabricate automotive industry parts such as cylinder block or pistons. Their good mechanical properties and high wear resistance are essentially attributed to the presence of hard primary silicon particles distributed in the matrix [3–5].

Functionally gradient materials (FGMs) are materials with a gradual transition in composition and microstructure along the parts. FGMs filled the gap in the materials science where the parts require different properties in different positions and the optimal property is not achieved in the homogeneous cross-section materials [6,7]. For example, sometimes it is required that the bottom regions has the special properties such as good hardness and wear resistance or both of the upper region and bottom region have special properties for the piston parts [8,9]. FGMs can meet the requirement for various mechanical performances at specific locations in a component. This feature cannot be achieved in homogeneous materials. Therefore, there is a significant meaning to manufacture the gradient material to achieve the specific performance requirements of the parts. Despite these benefits, there are not many methods reported in fabricating gradient materials. The common methods used are centrifugal casting [9], melt infiltration [10], power ultrasonic casting [11], and electromagnetic separation method [12]. Centrifugal casting is one of the most effective methods for the processing of FGMs; because, the centrifugal forces cause heavier or lighter particles in the liquid metal to be displaced towards the outer and inner surface of the casting, respectively. This fabrication method utilizes the different densities of different particles acquired functionally gradient materials. However, since the density of primary Si is similar to the Al base, the distribution of primary Si in the A390 ring is not noticeable [6,9]. Furthermore, the other methods have the

* Correspondence to: Postal address: School of Materials Science and Engineering, University of Science and Technology Beijing, No. 30 Xueyuan Road, Haidian District, Beijing 100083, China. Tel./fax: +86 10 62326588.
E-mail address: yhzhmr@126.com (H. Yu).

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limitations of complex processes or the high cost of manufacturing, which no doubt decreases the advantages of those methods in the competitive market. As reported in some literatures, the microstructure of the backward extruded parts is inhomogeneous [13–18]. And some other studies have shown that when Al-25% alloy is heated to semi-solid temperature, separating flowing occurs between the liquid and primary Si under pressure, the fraction of primary Si increases in remaining alloy system with the liquid discharged-out [19]. Therefore, a functionally graded material can be acquired by backward extrusion process in the semi-solid state. Eventually, it can be deduced that the most important advantages of the new method were the lower process force for producing a particular part in comparison with the conventional method, and consequently reduced machining and material cost. It also changes the overall mechanical and physical properties as a result of the variation in the morphology and the Si-fraction, and if the graded materials with an excellent combination of high strength and wear resistance, it will be widely applied in the automotive industry. Nevertheless, the novel method fabricate the graded hyper-eutectic aluminum silicon alloy materials are scarcely reported.

In order to obtain the functionally graded materials in this work, the cup-shaped samples were fabricated by using backward extrusion process during the semi-solid state of A390 aluminum silicon alloy. The microstructure at different parts of the cup-shaped samples was observed, and the hardness and wear resistance at different locations of the cup-shaped sample were tested. Furthermore, the main elements (Cu, Mg, Fe) and intermediate phase distribution of the cup-shaped specimen were investigated by EMPA, and the mechanical properties, particularly the tensile properties of the initial alloys and the cup-shaped samples after T6 treatment were compared.

2. Experimental and backward extrusion process

The composition of A390 aluminum silicon cast alloy investigated in this study is listed in Table 1. The density of the alloy was 2.73 kg/m^3. The solidus and liquidus temperatures of this alloy were obtained as 558 °C and 664 °C by using differential thermal analysis (DTA).

Table 1
The composition of A390 aluminum alloy (wt%).

Si	Cu	Fe	Mg	Mn	Ni	Ti	Al
16.6	4.52	0.82	0.43	<0.01	<0.02	<0.10	Bal.

2.1. Semi-solid billet preparation

The A390 aluminum silicon casting alloys were reheated to a temperature between solidus and liquidus in order to obtain fine and globular microstructure which is required for the semisolid extrusion forming. Therefore, the heated temperature window was chosen equal to 580–590 °C, in order to get a not too high solid fraction but also a not too low solid fraction in the subsequent backward extrusion process, namely to avoid big changes of solid fraction due to variation in temperature.

2.2. The backward extrusion process

Fig. 1(a) shows the geometric model in this backward extruded process, and a half is adopted for its symmetrical character, and the diameter of cup shell is 45 mm.

Fig. 1(b) shows a schematic of the die of backward extrusion. The main parts of the die setup including matrix, sleeve, punch, guide shafts and the holder plate of guide shafts. The extrusion process was performed under a hydraulic press of 20 kN. The preheating temperature of the die was 200 – 300 °C and coated with paints in the mold. The unprocessed initial billets of A390 aluminum silicon alloy were machined to cylindrical specimens with a diameter of 44 mm and 44 mm in height. The ductile iron mould and the billets placed into the die at the same time were

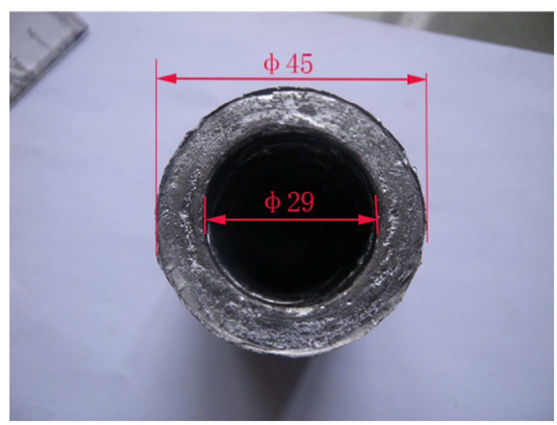

Fig. 2. Typical cup-shaped samples made by backward extrusion.

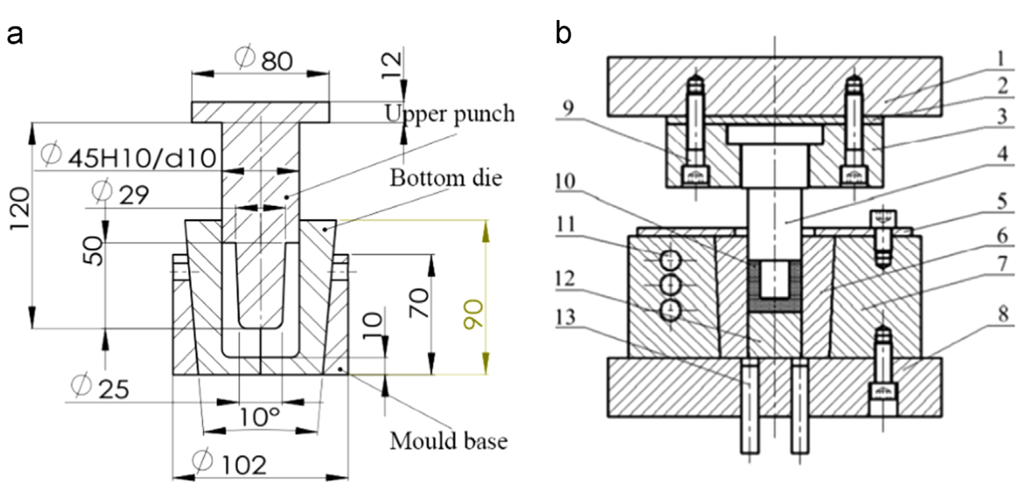

Fig. 1. (a) Geometric model of the die; (b) Schematic diagram of die backward extrusion[17]: 1—Upper pattern plate; 2—Backing plate; 3—Mounting plate;4—Upper punch; 5—Pressure back; 6—bottom die; 7—Die sleeve; 8—Down pattern plate; 9—Screw bolt; 10—Workpiece;11—Resistance wire; 12—Mould core; 13—Ejector pin.