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Effect of compound loading on microstructures and mechanical properties of 7075 aluminum alloy after severe thixoformation

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ABSTRACT

Solid–liquid segregation often occurred during thixoforming of wrought aluminum alloys, which can result in uneven structures and mechanical properties. In this work, a novel compound loading method was introduced in thixoforming 7075 aluminum alloys. The results show that the solid–liquid segregation can be alleviated evidently by compound loading, and the microstructures of periphery area were improved significantly. As the secondary loading displacement increased from 0 mm to 5 mm, the ultimate tensile strength (UTS) of the periphery area increased little (~510 MPa), and the yield strength (YS) even decreased slightly from 486 MPa to 470 MPa. However, the elongation to fracture of the periphery area increased from 1.94% to 4.3% with increment of 122%. On the contrary, the compound loading has limited effect on the tensile mechanical properties of the center area. The tensile fracture surfaces exhibited typical brittle rupture in the periphery area, while the fracture surfaces of the center were dominated by a large number of dimples and tear ridges showing typical ductile fracture features. Compound loading is an effective method to homogenize the microstructures and mechanical properties of thixoformed wrought aluminum alloys.

1. Introduction

Semi-solid processing (SSP) is a powerful technology for forming alloys to near net shaped products with high mechanical properties comparable to forging parts (Atkinson, 2005). Much work has been done on preparation of semi-solid slurries and exploitation of processing methods since SSP was proposed by Flemings and co-workers at MIT in the early 1970s (Flemings, 1991). Thixoforming is a semi-solid processing route which involves reheating suitable material into the semi-solid state and then forming it to near net shaped components (Birol, 2008). The ideal semi-solid alloy consists of solid spheroids surrounded by liquid matrix, so it will be thixotropic, i.e., it flows when sheared but if allowed to stand it thickens again. Commercial thixoforming is generally based on casting alloys such as A356 (Menargues et al., 2015) and A357 (Haghdadi et al., 2013) which provide good fluidity to fill dies owing to a relatively high volume of Al–Si eutectic (Hassas-Irani et al., 2013). However, the industrial application of thixoforming on wrought aluminum alloys were limited, because most of them have small processing window (the temperature range corresponding to suitable liquid fraction of 0.4–0.6) and relatively lower fluidity in the semi-solid state (Atkinson et al., 2008). Besides, the fluidity of liquid and solid is quite different, so segregation between liquid and solid phases often occurred during semi-solid processing, especially for severe thixoformation of wrought aluminum alloys. It should be noted that solid-liquid segregation only exists in the semi-solid state, and the segregation can result in uneven structures at room temperature (e.g., solid solution and eutectic mixture). With a large degree of probability, the amount of eutectic will be similar to the quantity of the liquid phase.

7xxx series are the strongest wrought aluminum alloys, and are widely used for aerospace application. It will be of great significance to thixoform 7xxx series aluminum alloys into near net shape, because these alloys are usually machined from wrought state with much wastage.

In recent years, increasing attention has been given to thixoforming of wrought aluminum alloys. Some work has been done on solid–liquid segregation and the resulting uneven microstructures and mechanical properties. Liu et al. (2003) studied the microstructural evolution and tensile mechanical properties of thixoformed high performance aluminum alloys, including 2000, 6000 and 7000 series and high-strength casting alloy 201. The results showed that

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Table 1
Composition of aluminum alloy used in this study (wt.%).

Zn	Mg	Cu	Cr	Mn	Fe	Si	Al
5.84	2.17	1.41	0.20	0.22	0.26	0.21	Balance

all alloys could fill the ceramic/graphite die successfully. The tensile properties of thixoformed 201 alloy are much higher than those of the permanent mold casting. The mechanical properties of thixoformed wrought aluminum alloys are quite close to the wrought target. Rogal et al. (2013) studied the thixoformability of 7075 aluminum alloy with Sc and Zr additions. They found the microstructure of the thixoformed part consisted of globular grains surrounded by precipitates of secondary phase, and the average tensile strength was 495 MPa after post-forming heat treatment. Cho and Kang (2000) studied the effect of processing parameters such as pressure, die temperature and speed on the microstructures and mechanical properties of thixoformed aluminum alloys. They found the ultimate strength, yield strength and elongation were increased with increasing applied pressure. However, remarkable segregation between solid and liquid phased still occurred, which resulted in decrease of hardness from the center to the periphery. Kang et al. (2006) have paid much effort to study the solid–liquid segregation behavior during thixoforming of aluminum alloys. They found increasing the punch speed and optimizing the gate shape would be useful for alleviate the segregation degree during thixoforming (Kang and Seo, 2003). Previous work has shown that the mechanical condition during thixoforming has large effect on the microstructures and mechanical properties of the thixoformed components, and it is essential to make the semi-solid slugs in three-dimensional compression stress state during thixoforming (Chen et al., 2012).

Although much work has been done on thixotropic behavior and segregation phenomenon during thixoforming of aluminum alloys, there are few reports about optimizing the mechanical conditions and in turn improving the uniformity of microstructures and mechanical properties. In this work, a novel compound loading method was proposed and applied in thixoforming wrought aluminum alloys. The aim is making the semi-solid slug in three-dimensional compression stress state by applying compound loading in severe thixoformation. The effect of compound loading on microstructures and mechanical properties of 7075 alloy after severe thixoformation was studied.

2. Experimental procedure

2.1. Thixoforming process

Commercial extruded 7075 aluminum alloy rods of 80 mm diameter in T6 condition were used as the starting materials. The composition of the starting material is given in Table 1.

According to recrystallization and partial melting (RAP) route (Kirkwood et al., 1992), which describes the process that recrystallization occurs during reheating and as liquid forms it penetrates the recrystallized boundaries to form spheroids, the extruded rods which have undergone plastic working are potential to be thixoformed directly after semi-solid remelting.

Before thixoforming, slugs with 80 mm in diameter and 50 mm in height were cut from the as-received rods, and then remelted into the semi-solid state and thixoformed into a flange-shaped die. In this work, multistep reheating regime was adopted in RAP route that the 7075 alloy was firstly reheated to a hyperthermal temperature 650 °C for 10 min, and then isothermally held at 620 °C for 10 min. The liquid fraction of 7075 alloy is about 40% at 620 °C, and the details of multistep reheating regime were described in the previous work Chen et al. (2013).

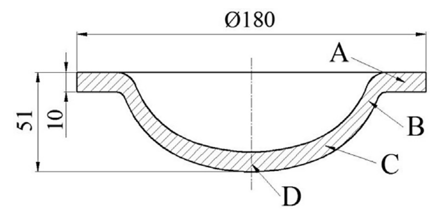

Fig. 1. Schematic diagram of thixoformed part (mm) with marked place of structural analysis.

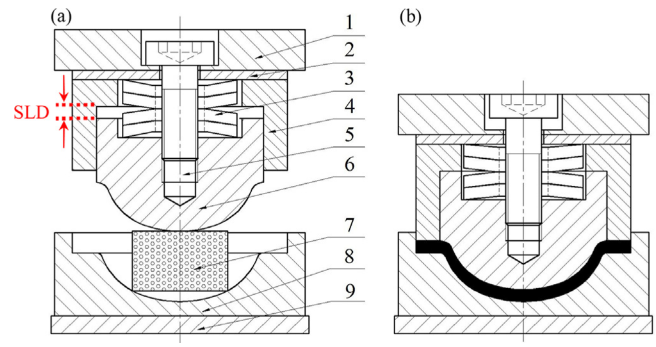

Fig. 2. Schematic diagram of thixoforming dies: before thixoforming (a) and after thixoforming (b) 1-Upper pattern plate, 2-Backing plate, 3-Disk spring, 4-External punch, 5-Stay bolt, 6-Internal punch, 7-Semi-solid slug, 8-Cavity die, 9-Lower pattern plate.

Fig. 1 shows the schematic diagram of thixoformed part. The thixoformation is very severe that the height of semi-solid slug is reduced from 50 mm to 10 mm while the diameter increased from 80 mm to 180 mm.

1-Upper pattern plate, 2-Backing plate, 3-Disk spring, 4-External punch, 5-Stay bolt, 6-Internal punch, 7-Semi-solid slug, 8-Cavity die, 9-Lower pattern plate.

Fig. 2 shows the schematic diagram of thixoforming dies fitted with compound loading system. As depicted in Fig. 2(a), the compound loading device consists of an external punch, an internal punch and a series of disk springs. Before thixoforming, the disk springs could be pre-tightened by the stay bolt. The internal punch was adjusted to depart from the external punch for a distance, which is defined as the secondary loading displacement (SLD), as indicated in Fig. 2(a). During thixoforming, the semi-solid slug was firstly thixoformed by the internal punch under the elastic force of disk springs (first loading). As the thixoforming continuing, the disk springs were compressed gradually so as to force the semi-solid slug to fill the dies. When the internal punch contacted with the external one, the two punches continued moving downward to apply all pressure of the hydraulic press on the semi-solid slug (second loading). If the secondary loading displacement was adjusted to 0 mm before thixoforming, this method could be regarded as direct loading.

Thixoforming was carried out on a vertically hydraulic press, which could provide the maximum load of 2000 kN and loading velocity of 100 mm/s. The slugs were remelted in electric resistance furnaces via multistep reheating regime and thixoformed into a flange-shaped die. A hole with a diameter of 2 mm and a depth of 10 mm was drilled into the center of the top of each slug, and the temperature of slug was monitored by a K-type thermocouple embedded in the hole. After the required temperature was reached, the thermocouple was rapidly removed from the slug, and the slug was put into the dies (previously heated to 400 °C)