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Microstructures and mechanical properties of spray deposited 2195 Al-Cu-Li alloy through thermo-mechanical processing

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ABSTRACT

A large-scale billet of 2195 Al-Cu-Li alloy was prepared by spray deposition technology. The hot extrusion, solution treatment, pre-stretching, and aging treatment were performed on the deposited billet. It was found that the yield strength, ultimate tensile strength and elongation of the T83-treated alloy reach 600 MPa, 632 MPa and 10%, respectively. The microstructures of the deposited alloy in the thermo-mechanical processing were studied by optical microscopy, scanning electron microscopy and transmission electron microscopy. The mechanical properties were examined by tensile test. It was found that the spray deposited alloy presents a microstructure with fine equiaxed grains and low segregation degree. After hot extrusion, a typical fibrous structure with incomplete recrystallization is formed. After solution and aging treatments, lots of T_1 and δ′ phases precipitate in the matrix, leading to significant increase of the tensile strength. Pre-stretch prior to aging treatment produces a fine homogeneous distribution of the T_1 plates throughout the matrix, which lead to an excellent tensile performance. The ductility of aged alloys is affected by the microstructure of grain boundary. Narrow precipitate free zone and dispersed grain boundary precipitates with small size are beneficial to improvement of alloy's ductility.

1. Introduction

Al-Cu-Li alloys are of great interest to the aerospace industry in view of their low density, high strength, excellent corrosion resistance and weldability. In particular, their high specific strength and stiffness can bring significant weight savings, which have played key role in many advanced aerospace applications such as NASA space shuttle, Air bus 380 and Falcon-9 [1–5].

Strength and ductility are two of the most important mechanical properties for aerospace structural materials. Large ductility as well as high strength allows the materials to have superior damage tolerance and high durability in service [6]. Therefore, the method to simultaneously enhance strength and ductility of the materials, especially for Al-Cu-Li alloys widely used in aerospace industry, has drawn most attention for many years. The general approach for strengthening and toughening of Al-Cu-Li alloys is a series of thermo-mechanical treatments which typically include hot deformation processing for as-cast billet and following solid solution and aging treatments for the deformed alloy [7–14]. By the previous efforts, the mechanical property of 2195 alloy has been improved significantly. However, the peak strength of the alloy is mostly still 550-590 MPa, and the breaking elongation is often below 9% [7–13]. In a newest study [14], the UTS strength has been increased up to 634 MPa by adding 0.25 wt% Sc into the 2195 alloy, but the yield strength (YS) of the alloy was only about 534 MPa, and corresponding elongation was about 9.2%. Therefore, simultaneously endowing the 2195 Al-Cu-Li alloy with a high tensile strength and good ductility is still a challenge.

At present, mechanical properties of polycrystalline materials including Al-Cu-Li alloys can be effectively enhanced by grain structure control method such as severe plastic deformation (SPD) [15,16] and bimodal microstructure design [17,18]. However, the above methods are confronted with poor process stability in operations, and not suitable to produce large bulk material required for commercial applications [19,20]. Based on the rapid solidification technology, spray deposition can produce the large-scale billets with fine and homogeneous microstructure, and avoid common problems associated with casting process such as dendritic segregation and coarse microstructure [21]. Such a good microstructure tends to decrease the holding time during homogenization treatment and lead to excellent mechanical properties [21,22]. In recent years, it has found that the spray deposited Al-Zn-Mg-Cu alloys processed by appropriate thermo-mechanical treatments exhibited unparalleled combinations of strength and ductility [22–24]. So, the application of spray deposition in preparing 2195 alloy may be a promising way to improve the mechanical properties of the alloy.

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In spray deposited alloys, micro-pores within matrix and small degree of segregation are the inevitable defects. Therefore, a series of thermo-mechanical processes, including homogenization, hot deformation, solid solution and aging treatment, are required to eliminate the defects and obtain high quality alloy products. In the processes, the microstructures of alloy are changed, and the final properties of alloy are consequently influenced. So, it is necessary to study the microstructures and mechanical properties in the thermo-mechanical processes for improving processing technique and to optimize the properties of alloy.

In this work, a large-scale billet of 2195 alloy was firstly prepared by the spray deposition technology. Then, the spray deposited alloy was subjected to a series of thermo-mechanical processing including homogenization, hot extrusion, solid solution and aging treatments. The changes of microstructures and properties in the thermo-mechanical processes were investigated. The effect of different aging treatment on microstructures was studied in detail by transmission electron microscope (TEM). The influence of microstructures on mechanical properties was analyzed. Finally the fracture morphologies were observed, and fracture mechanism was analyzed. The results in this study can provide key information for further study on hot forming and heat treatments of the spray deposited 2195 alloy.

2. Material and experimental details

The large-scale spray deposited billet of 2195 alloy with size of about Ø520 × 1100 mm (roughly 590 kg) was prepared in Haoran Co., Ltd., Jiangsu, P.R. China. The chemical compositions of the spray deposited 2195 alloy were obtained by using inductively couple plasma atomic emission spectroscopy (ICP-AES), as shown in Table 1.

The spray deposited alloy was subjected to a series of thermo-mechanical processing including homogenization, hot extrusion, solid solution, and aging treatments. Fig. 1 shows the schematic diagram for the whole processes. Firstly, the deposited billet was machined into a round bar with the diameter of 480 mm. Then, homogenization treatment was performed at 470 °C for 8 h in an induction heating furnace to obtain the homogenous microstructure. The homogenized alloy was extruded to a round bar with the diameter of 160 mm on 80 MN extrusion press. The temperatures of container, extrusion die, and billet were set as 440 °C, 430 °C, and 470 °C, respectively, and the ram speed was set to be 1.8 mm/s. Subsequently, several samples were cut from the extruded bar, and solution treated at 490 °C/1 h and 520 °C/1 h, followed by water-quenching. Finally, the samples after solid solution were treated under different aging conditions to investigate the aging hardening behavior and the evolution of microstructures as well as tensile properties during the aging.

Fig. 2 shows the sampling positions and dimensions of the samples in this study. To minimize the influence of the initial microstructures on test results, all the samples were cut from the same radius of the extruded bar, as shown in Fig. 2(a). The dimensions of the hardness test sample are shown in Fig. 2(b). The dimensions of the tensile specimen were determined according to ASTM E8-M-04 standard, as shown in Fig. 2(c). The hardness test samples were subjected to different aging time treatments in the temperature range 150–190 °C, and the soaking time from 0 up to 72 h. Hardness values were measured with a HV-1000 micro-hardness tester. In order to study the tensile property of the alloy under different aging treatments, ambient uniaxial tensile test was carried out on a MTS electrical testing machine. Test parameters were also defined according to ASTM: E8-M-04 standard; the tensile speed was set as 1.5 mm/min, and the strain was monitored by a 25 mm clip gauge extensometer.

Table 1
Measured compositions (wt%) of the spray deposited 2195 alloy.

Elements	Cu	Li	Mg	Ag	Zr	Mn	Si	Fe	Al
wt%	3.72	1.06	0.44	0.31	0.12	0.23	0.09	0.13	Bal.

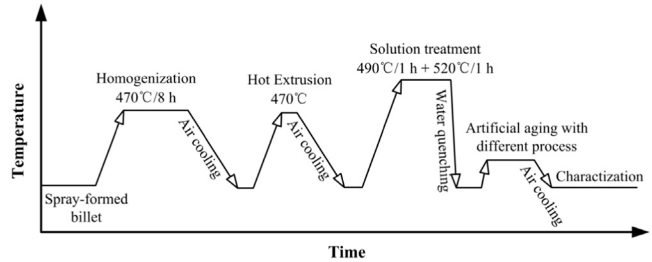

Fig. 1. Schematic diagram for the thermo-mechanical processes of spray deposited 2195 alloy.

The optical microscope (OM), scanning electron microscopy (SEM) and TEM were used to study the changes of microstructure in the thermo-mechanical processes, and the fracture morphologies of tensile specimens were observed by SEM. For optical microscopy observation, the samples were mechanically ground with SiC papers up to 1200 grits and finally polished into mirror with 2.5 μm and 1.5 μm diamond polishing agent on the grinding machine. And then chemical etching in the solution of 0.2 ml HF, 18 ml HCl, 7 ml HNO_3 and 42 ml H_2O was conducted to perform OM analyses. But the samples used for energy dispersive spectroscopy (EDS) analysis should not be etched for a relatively accurate result of chemical composition. Thin foils for TEM observations were firstly prepared by mechanical grinding to a thickness of 50 μm, then electrochemical polishing at −30 °C with a double jet electrochemical machine operated at 14 V. The electrolyte consists of 30% nitric acid and 70% methanol. The TEM images were acquired on a JEM-2100 microscope, operated at 200 kV.

3. Results and discussion

3.1. Microstructures of spray-deposited and extruded alloys

Fig. 3 shows SEM micrographs of the spray deposited alloy. Fig. 3(a) reveals the typical equiaxed grains with size of 50–80 μm, which distinguishes from the dendrite structure of conventional as-cast aluminum alloy [12,13]. This microstructure with the fine equiaxed grain is attributed to the advantages of spray deposition technology including rapid solidification and high spray speed. Most of the atomized droplets have already solidified before depositing on the collector due to the high cooling rate. The strong shock of atomized droplets resulted from high spray speed can break the previously deposited grains, which equivalently increases the number of external nucleus, thus leading to grains refinement. From Fig. 3(a) and (b), it can be found that a few small pores with size of 1–5 μm appear on the triangular grain boundary, which weakens the mechanical property and decreases the densification degree of the deposited alloy. The density of the spray deposited alloy is 2.6421 g/cm^3 measured by Archimedes method, while the extruded alloy exhibits the density of 2.6941 g/cm^3. If supposing that the extruded alloy is completely densified, the densification degree of the spray deposited alloy is 98.07%.

From Fig. 3(a) and (b), it can also be found that the non-equilibrium phase distributes on the grain boundaries as chain-like shape. This phase is formed in the process of solidification due to the segregation of alloy elements. Analysis by Image Pro Plus software indicates that a value around 2.5% in area for the non-equilibrium phases is a low value when compared with conventional as-cast aluminum alloy which can reach a value of 7–8% [13,25,26]. And the EDS result reveals that Al, Cu, and Fe elements exist in the non-equilibrium phase. In high magnification SEM micrograph, as shown in Fig. 3(b), the needle-like phase and granular phase can be found inside grains. These phases exhibit large size, especially for the needle-like phase, the size in its length is more than 10 μm. Fig. 3(c) shows microstructure of the homogenized