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Production of high strength Al-Zn-Mg-Cu alloys by spray forming process①

WEI Qiang(韦 强), XIONG Bai-qing(熊柏青), ZHANG Yong-an(张永安), ZHU Bao-hong(朱宝宏), SHI Li-Kai(石力开)
(General Research Institute for Nonferrous Metals, Beijing 100088, P. R. China)

[Abstract] High strength Al-Zn-Mg-Cu alloys were produced by spray forming process, and compacted by hot extrusion. The results show that the as-deposited billets have fine-grained microstructure and low porosity. After heat treatment, mechanical properties increase greatly: tensile strength up to 754 MPa, yield strength up to 722 MPa, fracture elongation up to 8%, and elastic modulus up to 72 GPa, respectively.

[Key words] spray forming; Al-Zn alloy; hot extrusion; mechanical properties
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1 INTRODUCTION

Al-Zn (7××× series) alloys have been widely used because of high strength, corrosion-resistance and other good properties[1,2]. But a practical content limit of 7% Zn (alloys 7075, 7175 and 7475 etc) is imposed for conventional cast materials because of solute macro-segregation and coarse-grained microstructure[3]. Previous attempts to produce high solute 7××× series alloys by using the PM technology were not successful, since great high increase in strength was always linked to unacceptable low ductility levels[4~6]. Spray Forming was first put forward by Prof. Singer, Swansea University UK in 1969[7]. Under the development of Osprey Metals Ltd, it became industrial scale maturity in the late 1990s[8]. The principle underlying spray forming process is the transition of the materials from liquid phase to solid phase during solidification by extremely rapid cooling and the simultaneous shaping into billets, tubes and plates. It allows the production of near net shaped components with enhanced mechanical properties that result from fine-grained and non-segregated structure. The spray forming process differs from the PM technology in that both the atomizing and consolidation process are combined in a single operation. This new technology is very attractive, since the reduction in the number of manufacturing steps can lead to significant economic savings without the prohibitive cost of PM technology. Recently high strength as well as heating-resistant and wear-resistant Al-Si alloys produced by this process have been used in the engines of Daimlar-Benze and Mazda cars[9]; high strength Al-Zn alloys have been used to produced the rotors of ultrahigh speed centrifugal machines and couples of high speed trains[10]. With the development of social economics the need for high property Al-Zn alloys is more and more urgent, but the products produced by conventional methods cannot meet the more and more strict requirements. Under this condition the emphasis of current research work is placed on the production of high strength Al-Zn alloys by spray forming process.

2 EXPERIMENTAL

The experiments were carried out on the SF-200 spray forming pilot equipment. About 40 kg Al-8.6Zn-2.6Mg-2.2Cu ingot was melted in an induction furnace and poured into a tundish with a refractory nozzle. The molten metal coming from the nozzle at the rate of 2~ 3 kg/min was atomized by free-fall nitrogen gas atomizer. The gas pressure was controlled under 0.5 and 0.6 MPa in the experiments. The melt temperature was 800 ℃ to 850 ℃ and did not drop below 780 ℃ during spray forming process. The substrate was a rotating stainless steel disc. The distance of nozzle to the substrate was 400~ 500 mm so that the majority of the particles was in a particularly state upon impingement and did not run off the substrate.

Round billets measuring 170 mm in diameter and 700 mm in length were produced and machined off to 124 mm in diameter and subsequently hot extruded to the form of bars at different extrusion rates of 7∶1, 14∶1 and 28∶1, respectively. T7 heat treatment was selected: quenching at 460 ℃+ 120 ℃, 6 h+ 160 ℃, 1 h.

The microstructure of the materials was observed by optical microscopy (Neophot-2) and scanning electron microscopy (Cambridge S360) and analyzed by

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XRD diffractometer with CuK_{α} (Philips).

The mechanical properties were tested by evaluating the tensile strength, yield strength, fracture elongation and elastic modulus on MTS810 tester.

3 RESULTS AND DISCUSSION

3.1 Production technology and microstructure of as-deposited preform

Porosity is the typical feature of the spray forming products. In order to obtain massive solid preforms with low porosity and fine-grained microstructure, a careful selection and check of many operative parameters are needed, such as melt superheat, metal flow rate, atomizing gas pressure and flight distance.

The emphasis of current research work is determined mainly paying regard to the influence of gas pressures on the microstructure of as-deposited preforms, because regulating the gas pressure can change the gas flow rate and gas speed[11, 12], and affect the heat extracted from the molten particles during their flight[13], which will directly determine microstructure of the as-deposited preform and mechanical properties of the as-deposited preform.

The microstructures in Fig. 1 show that increasing the gas pressure while keeping the metal flow rate stable namely increasing the G/S ratio is effective in refining the size of the grains ($d_{0.5MPa} \cong 5\ \mu m$, $d_{0.6MPa} \cong 3\ \mu m$), but a higher porosity exhibits, leading to a greater amount of gas inclusion in the as-deposited billets. So a higher deformation rate is needed to eliminate the porosity without forming defects in the extruded bars, that stems from the incomplete weld of the inner faces of the gas holes[14]. Furthermore, with the increase of gas pressure the yield of as-deposited billets dropped dramatically from 70% to 60% resulting from the low target efficiency and sticking efficiency[15]. For the reasons mentioned above, it is necessary to place exceptional emphasis on the gas pressures when selecting the parameters for spray forming.

3.2 Hot extrusion

3.2.1 Microstructure of hot extruded bar

Fig. 2 shows microstructures after extruded with different extrusion rates. The as-deposited preforms which were originally completely porous were totally compacted with fine-grained microstructure after hot extrusion. This result has been verified by a large number of hot extrusion tests that hot extrusion is effective in eliminating porosity in as-deposited preforms. A great number of precipitated particles are

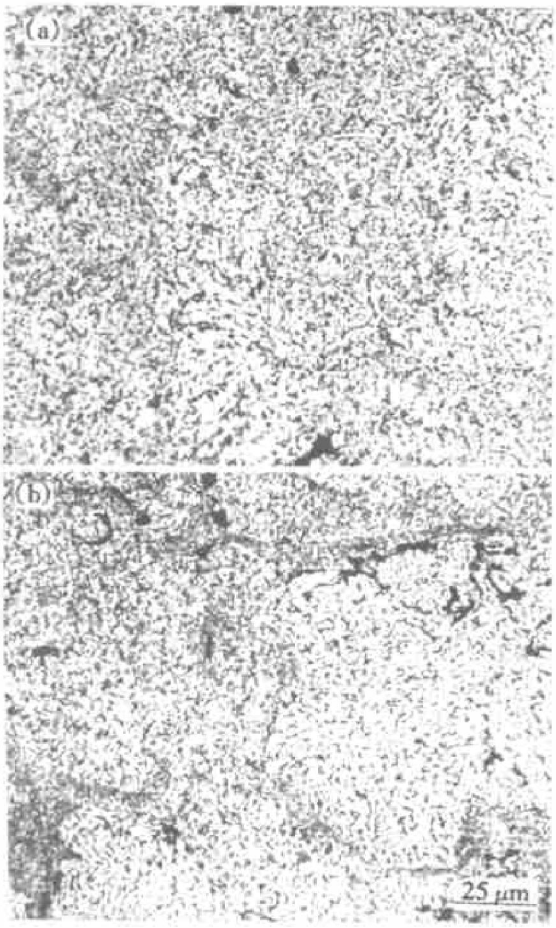

Fig. 1 As-deposited microstructures with different gas pressures
(a) —P = 0.5 MPa; (b) —P = 0.6 MPa

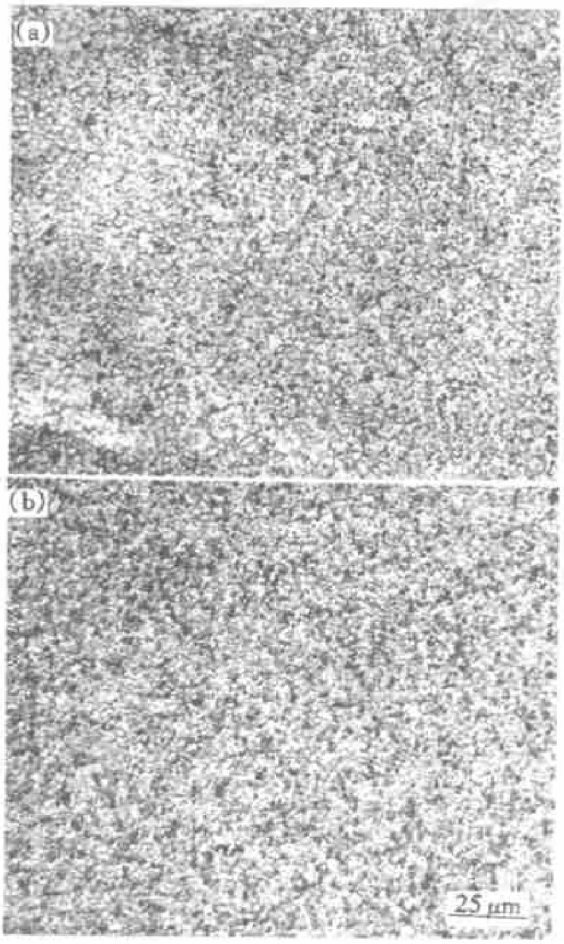

Fig. 2 As-extruded microstructures with different extrusion rates
(a) —14∶1; (b) —28∶1

shown in Fig. 3. These regular shape particles with close size indicate that solid solute decomposed during hot extrusion. XRD diffraction pattern is shown in Fig. 4. From Fig. 4 it is known that the main phase compositions of hot extruded bars are α(Al) and Mg_2Zn_3. There were strong preferential orientations within the extruded products namely ⟨111⟩ Al parallel to the hot extrusion direction.

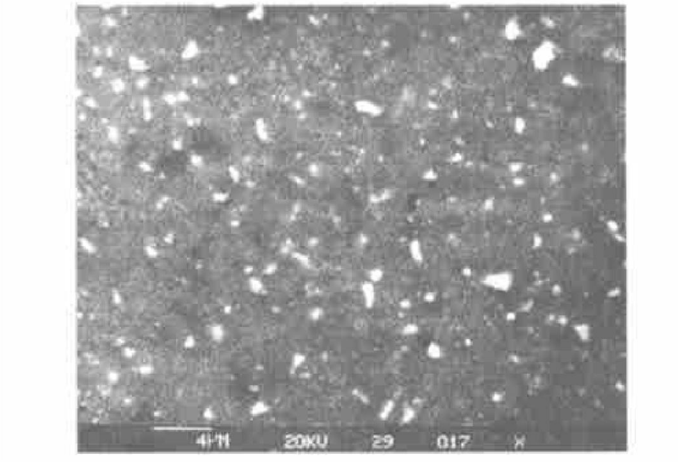

Fig. 3 SEM micrograph of hot extruded preform

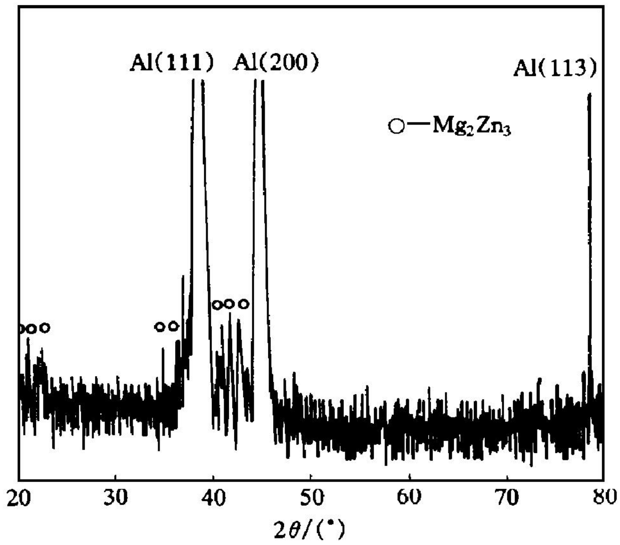

Fig. 4 XRD pattern of hot extrusion preform

3.2.2 Hot extrusion temperature

Before hot extrusion the deposited materials were preheated in an open muffle furnace to the expected temperature and kept for 1 h. The relationship between temperature and piercing pressure in Fig. 5 shows that piercing pressure rapidly increases with decreasing temperature. Fig. 6 shows that the elongation increases with increasing temperature and reaches peak value at 400 ℃. After that the deforming ability of the materials begins to decrease. The hot extrusion tests showed that Al-Zn-Mg-Cu alloys should be hot extruded at the temperature of 350 ℃ to 450 ℃.

3.2.3 Hot extrusion rate

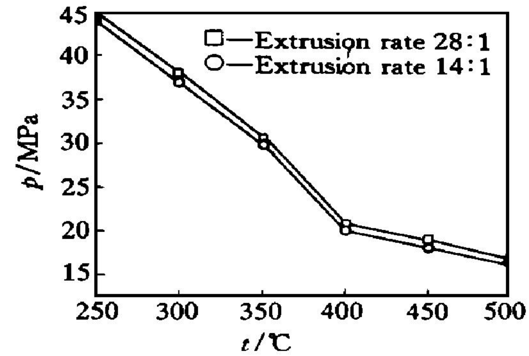

Fig. 5 Relationship between temperature and piercing pressure

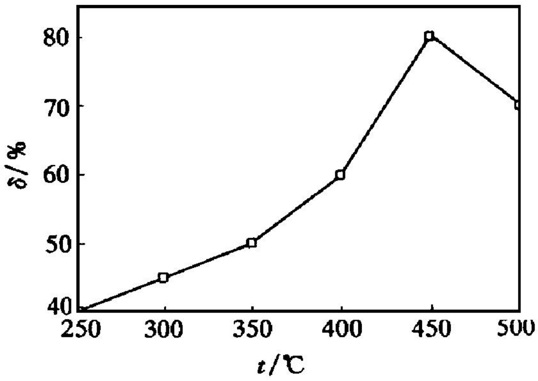

Fig. 6 Relationship between elongation and temperature

Although products obtain compacted microstructure after using different extrusion rates, there are differences in mechanical properties. The differences are mainly associated with the removal of the microcracks in the extruded bars by using higher extrusion rates, which reduces the defects resulting from the incompletely welding of the inner faces of gas holes. Unlike the products extruded at 28∶1 there were blisters forming on the surface of the products extruded at 7∶1 and 14∶1 during heat treatment. The piercing pressure do not increase remarkably with increasing extrusion rate.

4 MECHANICAL PROPERTIES

Table 1 shows that the properties of Al-Zn-Mg-Cu alloys after heat treatment have been improved

Table 1 Mechanical properties of Al-Zn-Mg-Cu alloys at room temperature

Processing condition	σ_b/MPa	$\sigma_{0.2}$/MPa	δ_5/%	E/GPa
Extrusion(28∶1)	372	317	14.0	66.0
Extrusion(14∶1)	300	247	19	66.0
Extrusion(7∶1)	250	200	15	66.0
T7	754	722	8	72.0
Cast (After T6 heat treatment)	610	580	4	70.0

remarkably with tensile strength up to 754 MPa, yield strength up to 722 MPa, fracture elongation up to 8%, elastic modulus up to 72 GPa higher than those of the samples produced by conventional casting. Fig. 7 shows that the fracture is tough fracture along grain boundary.

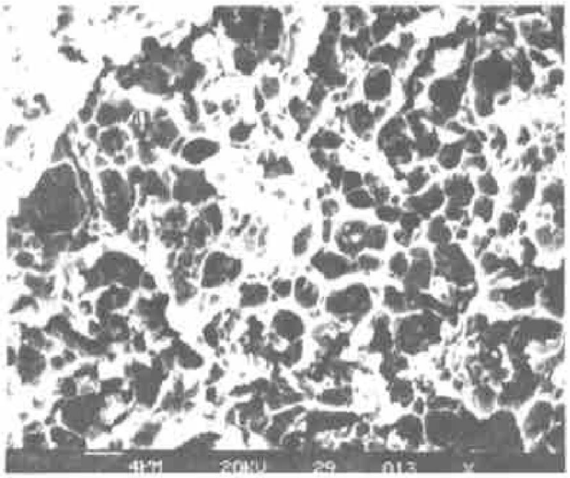

Fig. 7 SEM fractograph of Al-Zn-Mg-Cu alloy

5 CONCLUSIONS

1) The as-deposited billets produced by spray forming have fine-grained microstructure and low porosity.

2) Hot extrusion has effects on eliminating porosity in the as-deposited billets to obtain compacted extruded products with fine-grained microstructure. The best extrusion temperature is 350~ 450 ℃ with extrusion rate higher than 28∶1.

3) After T7 heat treatment, the mechanical properties of Al-Zn-Mg-Cu alloys have been improved remarkably with tensile strength up to 754 MPa, yield strength to 722 MPa, fracture elongation to 8%, elastic modulus to 72 GPa higher than those of the samples produced by conventional casting.

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