JOURNAL OF MATERIALS SCIENCE 32 (1997) 829–832

Microstructures and tensile properties of spray-deposited high-strength aluminium alloys

JEN SHEN, RONGHUA LIU*, YING LIU**, ZULING JIANG, QINGCHUN LI
School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, People's Republic of China
** Department of Technology and ** Institute for Iron and Steel Research, Shanghai Fifth Iron and Steel Works, Shanghai, People's Republic of China*

Spray deposition is a new rapid solidification technique which produces bulk preforms directly from the melt metals. A spray deposition process was used to develop several high-strength aluminium alloys based on their commercial chemical compositions. These alloys include 2024 alloy, 7075 alloy and 7075 alloy modified with 1.0% Fe and 1.0% Ni. The deposits possessed rapid solidification microstructure with grain size of about 20 μm and a relative density of over 94%. The hardening phases of the materials in T4 or T6 conditions consisted of supersatured solid solution, stable and unstable ageing precipitates and disperse phases. The formation of the fine distributed disperse phases was due to the addition of iron and nickel to the 7075 alloy. The spray-deposited materials exhibited substantial improvement in tensile strengths and maintained acceptable ductility when compared to the corresponding ingot metallurgy processed materials.

1. Introduction

Aluminium alloys have been widely used as structural materials in many applications for their particular properties in terms of high specific modulus, tensile strength and ductility at room and elevated temperatures, great resistance to fatigue, corrosion and stress corrosion, etc. However, the conventional manufacturing technology has proved itself to be limited in developing the potential properties of structural aluminium alloys. Over the last decades, many rapid solidification processes have been shown to be employable to improve further the engineering performances of aluminium alloys as well as other ferrous and non-ferrous alloys. Among the rapid solidification techniques, the spray deposition process is considered one of the most attractive and promising alternatives for producing advanced materials. Spray deposition involves atomization of molten metals to create dispersive droplets and deposition of these droplets on to a static or movable substrate to form rapidly solidified deposits; see Fig. 1.

Spray deposition, because it features fewer production steps, lower oxide contamination and the absence of a prior particle boundary, all of which are associated with powder metallurgy, has attracted much attention and been applied to develop a variety of advanced materials [1–13].

In the present work, several high-strength aluminium alloys were produced via spray-deposition processing, and the resulting microstructures and tensile properties were analysed and evaluated.

2. Experimental procedure

Commercial 2024 and 7075 alloy bars were used as the master materials. To study the effect of transit metals on the microstructures and properties of rapidly solidified aluminium alloys, a small amount of iron and nickel was added to a 7075 alloy. The chemical compositions of the materials are shown in Table I.

The master alloy was mounted into a graphite crucible which was situated in the top part of a supersonic atomization and deposition apparatus. Details of the equipment were described elsewhere [14]. Prior to atomization, the chamber was evacuated to a vacuum of approximately 10 Pa and subsequently backfilled with nitrogen to a presure slightly higher than that of the ambient atmosphere. Nitrogen with purity of 99.98% was used as the atomization medium at a pressure of 2.5 MPa. When the alloy was heated to a superheat of 200 °C, the melt was released through an annular slit atomizer where the high-energy gas disintegrates the metal stream into droplets. Then the droplets were accelerated by the atomizing gas and deposited on a static substrate. The nozzle to substrate distance was 400 mm. The as-deposited microstructure was examined using scanning electron microscopy (SEM). The sample was taken along the axial direction of the preform. The density of the preform was measured based on Archimedes' principle.

Hot extrusion was employed for further densification of the deposits. The hot extrusion samples were held for 1 h at 400 °C and extruded on a 450 ton hydraulic press. The extrusion ratio used was 25:1.

0022–2461

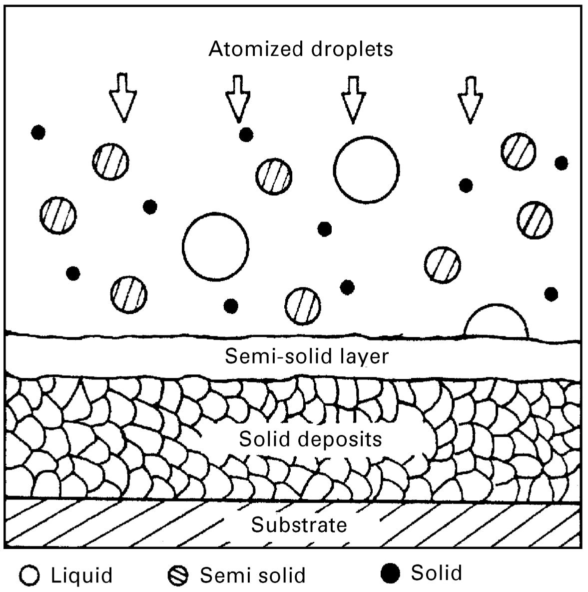


Figure 1. Schematic illustration of the spray deposition process.

TABLE I Chemical compositions of the high-strength aluminium alloys

Alloy	Element (wt %)							
	Cu	Mg	Zn	Mn	Fe	Ni	Si	Al
2024	4.48	1.45	–	0.61	0.31	–	0.15	Bal.
7075	1.30	2.55	5.60	0.11	0.42	–	0.20	Bal.
7075 + Fe + Ni	1.32	2.56	5.59	0.12	0.98	0.91	0.18	Bal.

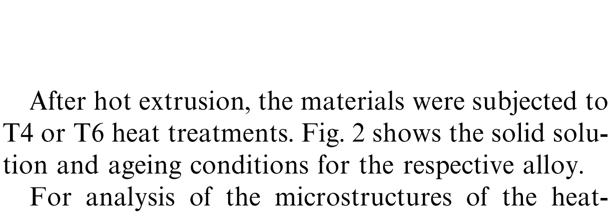


Figure 2. Schematic maps of the heat treatments subjected to the alloy (a) 2024-T6, (b) 2024-T4, (c) 7075-T6 and 7075 + Fe + Ni-T6.

After hot extrusion, the materials were subjected to T4 or T6 heat treatments. Fig. 2 shows the solid solution and ageing conditions for the respective alloy.

For analysis of the microstructures of the heat-treated alloys, thin areas were prepared at $-40\,^{\circ}C$ using a dual jet polishing unit. The electrolyte consisted of 30 vol % nitric acid and 70 vol % methanol. The prepared samples were examined in a Phillips/CM12 TEM at 120 kV.

Tensile properties were tested at room temperature on an Instron-type machine. And the fracture surfaces of the tensile samples were characterized using SEM.

3. Results and discussion

The as-deposited densities of both the 2024 alloy and the 7075 alloy were determined to be over 94% theoretical. Furthermore, no striking difference in densification was detected along the axial and the radial directions of the preforms. That is, the optimized operative parameters can be used to produce densified aluminium alloy preforms.

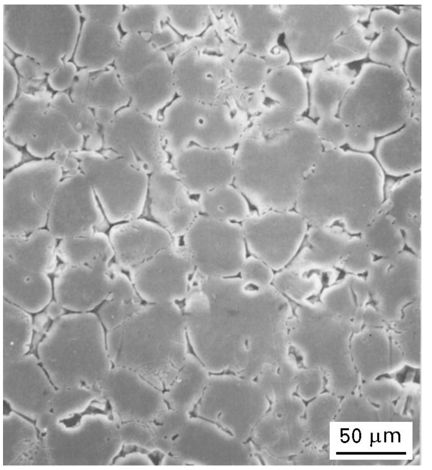


Figure 3. Scanning electron micrograph showing the microstructure of the as-deposited 2024 alloy.

Fig. 3 shows a view of the as-deposited microstructure of the 2024 alloy. It is clearly seen that the deposit possesses a very fine grain structure of about 20 μm, and a small amount of non-interconnected and irregular-shaped pores with a size of less than 5 μm are preferentially located at grain boundaries. The origin of the porosity in spray-deposited materials can be traced to three possible sources, as suggested by Lavernia [15], i.e. gas entrapment, solidification shrinkage and interstitial porosity.

Fig. 4a–d show the typical bright-field images of spray-deposited high-strength aluminium alloys in the T4 or T6 conditions. In the 2024-T4 alloy, as a sequence of natural ageing, the solute atoms piled up to form extensive coherent Guinier–Preston (GP) zones; see Fig. 4a. For this alloy, the fine solid solutions and the GP zones constituted the dominant strengthening phases. But for the 2024-T6 alloy, dissolution of GP zones gave rise to the formation of partially coherent intermediate phases and incoherent equilibrium phases (usually refered to as S′ and S phase, respectively); see Fig. 4b.

To be similar to the 2024-T6 alloy, the main hardening phases in the 7075-T6 alloys also consisted of solid solution and metastable (η') and stable ($\eta(MgZn_2)$) phases; see Fig. 4c. In the 7075 + Fe + Ni alloy, however, additional very fine hardening phases were detected; see Fig. 4d. These phases are believed to be dispersoid particles which were formed due to the addition of iron and nickel.

Tensile properties of the spray-deposited high-strength aluminium alloys after heat treatments were obtained and are presented in Table II. For the purpose of comparison, tensile data for ingot metallurgy processed 2024 and 7075 alloys are also given in Table II. Both the yield strengths and the tensile strengths of the spray-deposited high-strength aluminium alloys are improved 15%–23% with no obvious

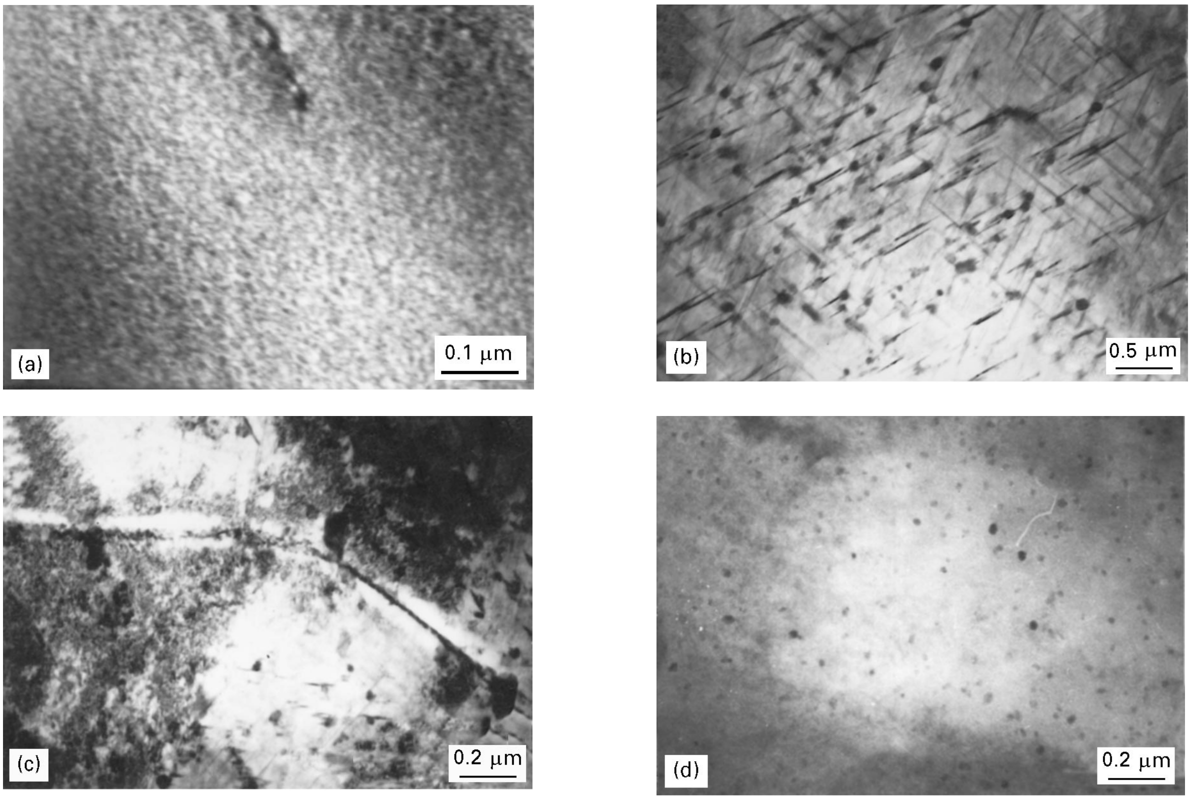


Figure 4. Transmission electron micrographs showing the microstructures of spray-deposited alloy (a) 2024-T4, (b) 2024-T6, (c) 7075-T6, and (d) 7075 + Fe + Ni-T6.

TABLE II Tensile properties of high-strength aluminium alloys

Processing route	Alloy and temper	YS (MPa)	UTS (MPa)	Elongation (%)
Spray deposition	2024-T4	475	543	18.5
Ingot metallurgy*	2024-T4	310	441	20.0
Spray deposition	2024-T6	425	524	19.2
Spray deposition	7075-T6	567	631	10.0
Spray deposition	7075 + Fe + Ni-T6	601	687	8.9
Ingot metallurgy [16]	7075-T6	510	572	13.0

loss of ductility, as compared to the corresponding ingot metallurgy processed materials. It should be noted that the 7075 + Fe + Ni-T6 alloy has much higher strength than the 7075-T6 alloy. This increase in strength of the iron-and nickel-containing alloy can be easily explained by the presence of the extremely fine dispersoid particles embeded in the matrix of the alloy.

The tensile fracture surfaces of the 2024-T4, 2024-T6, 7075-T6 and 7075 + Fe + Ni-T6 alloys are shown in Fig. 5a–d, respectively. On a microscopic scale, the fractures in all the alloys are ductile. The fracture surfaces feature numerous small dimples, in which microsized particles of the secondary phases are situated. The coexistance of the dimples and the secondary phases imply that the cracks are nucleated at the particle–matrix interface in the deformation process of the tensile samples. It should be noted that examination of the fracture surfaces by SEM shows no oxide delaminations which are normally found in the powder metallurgy tensile test specimens [17–19]. This

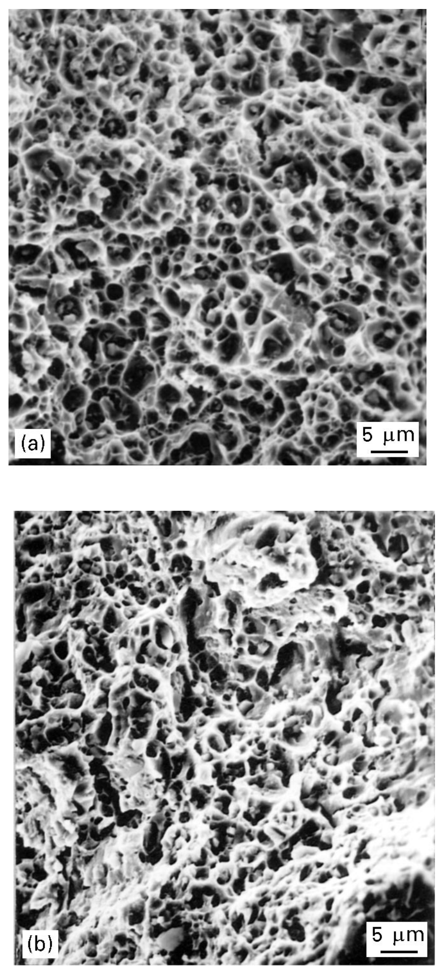
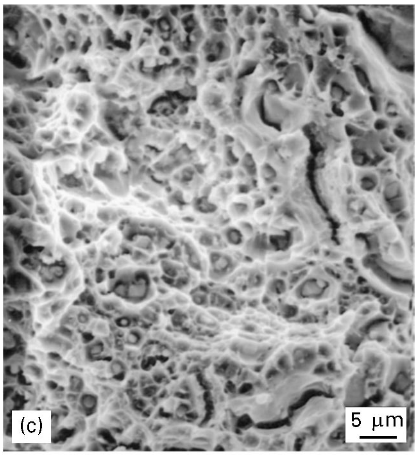


Figure 5. Scanning electron micrographs showing the fracture surfaces of the spray deposited alloy (a) 2024-T4, (b) 2024-T6, (c) 7075-T6, and (d) 7075 + Fe + Ni-T6.



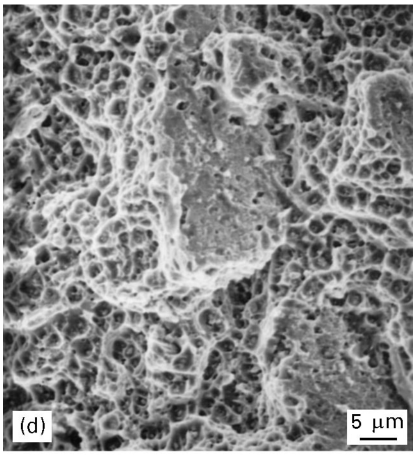


Figure 5. (Continued).

explains the slightly higher ductility of the spray-deposited alloys relative to that of powder metallurgy processed alloys.

4. Conclusions

1. The spray-deposited high-strength aluminium alloys possess the microstructural features of fine grains, less segregation, high density and low oxide content. The hardening phases include supersatured solid solution, stable and unstable precipitates and disperse phases.

2. Increases in yield strength and tensile strength of 15%–23% are observed for the spray-deposited products with excellent ductility maintained when compared to the corresponding ingot metallurgy processed materials. The addition of a small amount of otherwise undesired impurity elements, such as iron and nickel, to rapidly solidified aluminium alloy, is demonstrated to improve further the tensile properties.

Acknowledgement

The authors acknowledge the financial support of the National Science Foundation under grant number 5918002.

References

1. R. H. BRICKNELL *Metall. Trans.* **17A** (1986) 583.
2. T. S. CHIN, Y. HARA, E. J. LAVERNIA, R. C. O. HANDLEY and N. J. GRANT *J. Appl. Phys.* **59** (1986) 1297.
3. W. B. JAMES, *Inter. P/M P/T* **21** (1985) 172.
4. B. A. RICKINSIN, F. A. KIRK and D. R. G. DAVIES, *Powder Metall.* **1** (1981) 1.
5. E. J. LAVERNIA and N. J. GRANT, *Mater. Sci. Eng.* **98** (1988) 381.
6. S. N. OJHA, J. N. JHA and S. N. SINGH, *Scripta Metall. Mater.* **25** (1991) 443.
7. J. ZHOU, J. DUSZCZYK and B. M. KOVEVAAR, *J. Mater. Sci.* **26** (1991) 5275.
8. J. L. ESTRADA and J. DUSZCZYK, *ibid.* **25** (1990) 1381.
9. D. G. MORIS and M. A. MORRIS, *J. Mater. Res.* **6** (1991) 361.
10. E. J. LAVERNIA, J. BARAM and E. GUTIERREZ, *Mater. Sci. Eng.* **A132** (1991) 119.
11. R. MACHLER, P. J. UGGOWITZER, C. SOLENTHALER, R. M. PEDRAZAOLI and M. O. SPEIDEL, *Mater. Sci. Technol.* **7** (1991) 447.
12. M. D. SANCTIS, *Mater. Sci. Eng.* **A141** (1991) 103.
13. P. S. GRANT, W. T. KIM and B. CANTOR, *ibid.* **A134** (1991) 1111.
14. JUN SHEN, DPHIL thesis, Harbin Institute of Technology, Harbin, People's Republic of China (1993).
15. E. J. LAVERNIA, *Int. J. Rapid Solid.* **5** (1989) 47.
16. "Metals Handbook", 8th Edn., Vol. **1** (1961) 881.
17. P. K. DOMALAVAGE, N. J. GRANT and Y. GREEN. *Metall. Trans.* **14A** (1983) 1599.
18. K. K. SANKARAN and N. J. GRANT, *Mater. Sci. Eng.* **44** (1980) 213.
19. M. LEBO and N. J. GRANT, *Metall. Trans.* **5** (1974) 1547.

Received 14 October 1993
and accepted 28 August 1996