MICROSTRUCTURES AND MECHANICAL PROPERTIES OF RAPIDLY SOLIDIFIED Al-Fe-Cr-Zr-V-Si ALLOY AND THEIR THERMAL STABILITY①

Xiao Yude, Li Songrui, Li Wenxian and Wang Richu
Department of Materials Science and Engineering,
Central South University of Technology, Changsha 410083, P. R. China

ABSTRACT The rapidly solidified powder of Al-Fe-Cr-Zr-V-Si alloy was prepared using multi-stage atomization rapid solidification device and then consolidated by hot extrusion after cold isostatic pressing and vacuum degassing. The microstructures, room- and elevated-temperature mechanical properties of the consolidated material and their thermal stability were studied by optical microscopy, transmission electron microscopy, hardness test and tensile test. The results show that this alloy has excellent mechanical properties at room and high temperatures and good thermal stability, and it exhibits good heat-resistance at least below 400 ℃. The main second phases that strengthen this alloy are $Al_{12}(Fe, Cr, V)_3Si$ and Al_3Zr, of which the $Al_{12}(Fe, Cr, V)_3Si$ silicide is of bcc structure (a= 12.6 Å) and has excellent thermal stability and coarsening resistance.

Key words rapid solidification powder metallurgy heat-resistant aluminium alloy Al-Fe-Cr-Zr-V-Si

1 INTRODUCTION

The mechanical properties of the conventional aeronautical high-strength aluminium alloys degenerate rapidly when the temperature is higher than 0.5T_m (T_m denotes melting point, K), thus these alloys cannot satisfy the requirement for increasing development of the aviation and space technologies. In the recent years, great efforts have been made to develop rapidly solidified (RS) aluminium alloys which can be used at high temperatures, and the emphases have been placed on the Al-Fe system and Al-Cr system[1].

The rapidly solidified Al-Fe-Cr-Zr-V-Si system can be regarded as a valuable system[2, 3], but its ductility and heat-resistance leave room for improvement yet. This paper aims to further improve the mechanical properties and thermal stability through forming fine $Al_{12}(Fe, X)_3Si$(X = Mo, V, Cr, W) silicide particles[4].

2 EXPERIMENTAL

The test alloy Al-7.03Fe-3.75Cr-1.5Zr-1.25V-1.7Si was prepared using multi-stage rapid solidification atomization device. After sizing (- 140 mesh), cold isostatic pressing and vacuum degassing, the powder was extruded into d 12 mm bars (extrusion temperature: 480 ℃, extrusion ratio: 28).

The tensile tests were performed using Instron 8032 tensile tester at room temperature, 250 ℃, 350 ℃ and 400 ℃ at a rate of 0.2 mm/min after holding at these temperatures for 7 min. The optical microstructure observations were carried out with Neophot-2 optical microscope. The TEM morphologies were observed with H800 transmission electron microscope.

3 RESULTS AND DISCUSSION

As shown in Fig. 1, the room temperature strengths of the test alloy are σ_b= 398 MPa and

① Project supported by the Advanced Materials Committee of China
Received Jun. 3, 1997; accepted Sep. 22, 1997

$\sigma_{0.2}$ = 348 MPa; with increasing temperature, the strengths decrease progressively in the range of 25~ 400 ℃. The strengths at 350 ℃ are σ_b = 195 MPa and $\sigma_{0.2}$ = 180 MPa, and at 400 ℃ are σ_b = 154 MPa and $\sigma_{0.2}$ = 134 MPa. This can be attributed to the much higher recrystallization temperature caused by excessive additions of transition metals such as Fe, Cr and V. It can also be seen from Fig. 1 that the test alloy has good room- and high-temperature ductility which reaches 6. 2% and 9. 3% at room temperature and 400 ℃ respectively. But the ductility value near 200 ℃ is very low, i. e. there is a middle temperature ductility valley which maybe caused by dynamic strain ageing[5, 6]. Although the dynamic strain ageing can alleviate the decrease of the strength, it seriously affects the ductility of the alloy, which is not favourable to working and service of the test alloy in this temperature range.

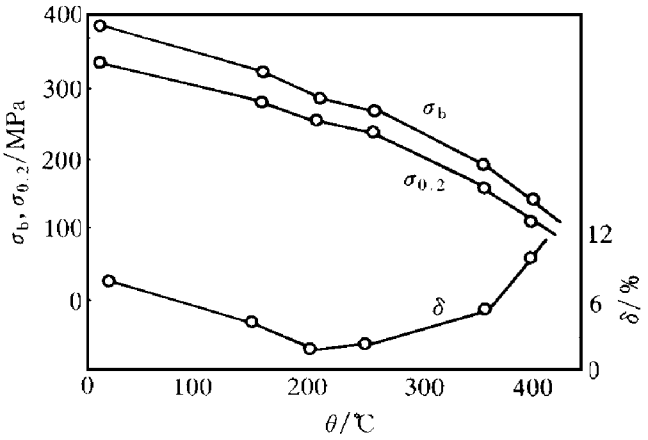

Fig. 1 Variation of tensile properties with temperature of as-extruded bar

It can be seen from Fig. 2 that the grains of the test alloy are fine, and their mean size is about 800 nm. The second phases are mainly 20 ~ 80 nm spheroids whose mean size is about 36 nm. The second phases are predominantly $Al_{12}(Fe, Cr, V)_3Si$ (bcc, a = 12. 61 Å) and Al_3Zr (DO_{23} tetragonal, a = 4. 02 Å, c = 17. 32 Å) determined by selected area electron diffraction and energy dispersive spectrum. The amount of the second phases is estimated to be 20%; most of them are distributed along the grain boundaries and some of them are distributed on the matrix. Compared with the microstructures of AlFeCrZr alloys with similar compositions in Refs. [2, 3], it can be known that the additions of V and Si under rapid cooling conditions suppress the precipitations of $Al_3(Fe, Cr)$ and $Al_{13}Cr_2$ phases and promote the formation of fine metastable $Al_{12}(Fe, Cr, V)_3Si$ spheroids. The metastable $Al_{12}(Fe, Cr, V)_3Si$ and the DO_{23} Al_3Zr phases are of high elastic modulii, high thermal stability and good coarsening-resistance. The uniform distribution of stable fine spherical hardening phases can strengthen the matrix and check the migration of the boundaries, and can make it difficult to produce stress concentration which will accelerate the fracture of the material. Therefore, compared with the Al-Fe-Cr-Zr alloy[2], although the test alloy has no obvious advantage in low-temperature strength, it has much higher ductility and high-temperature strength.

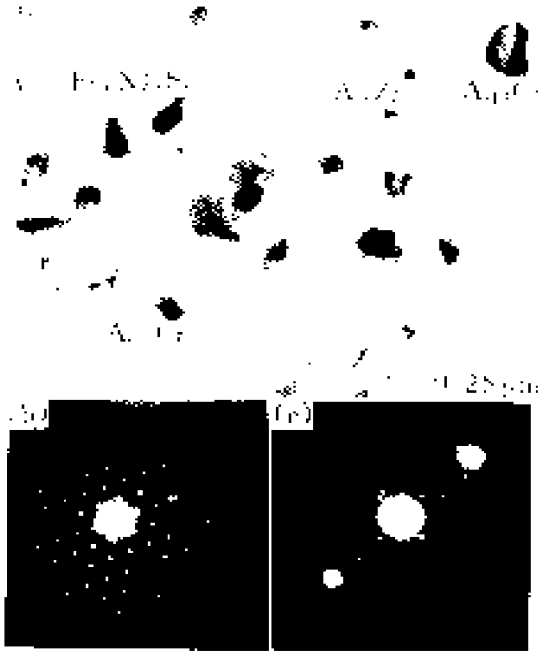

Fig. 2 TEM micrograph of as-extruded bar(a), SAD patterns of $Al_{12}(Fe, X)_3Si$(b) and Al_3Zr(c)

Fig. 3 shows the variation of hardness with time at different temperatures, and Fig. 4 shows the microstructures at different annealing temperatures. After annealing at 400 ℃ for a long time, the hardness of the test alloy is almost

unchanged and the microstructure is still like the as-extruded microstructure with dispersive, uniform and fine second phase particles. After annealing at 450 ℃ for a short time, the hardness increases somewhat, then decreases significantly with increasing time. This is maybe due to the fact that the as-extruded alloy is still oversaturated solid solution, and it will precipitate fine hardening phase particles, thus increasing the amount of the hardening phase(Fig. 4(b)). Especially the precipitation of the metastable Ll_2 Al_3Zr (fcc, a = 4.053~4.071 Å) can produce remarkable ageing precipitation hardening effect. With increasing annealing time, the second phase particles will coarsen (Fig. 4(c)), and the metastable Ll_2 Al_3Zr phase will transform into equilibrium DO_{23} Al_3Zr phase, consequently, the strengthening effect of the second phase will be weaken[7]. With increasing annealing temperature, the second phase particles will further coarsen (Fig. 4(d)) and thus the hardness will decrease more obviously, especially the hardness decreases sharply after annealing at 600 ℃ for a short time. This is related with the rapid coarsening of the second phase particles and the unfavourable transformation of metastable $Al_{12}(Fe, Cr, V)_3Si$ phase into the equilibrium

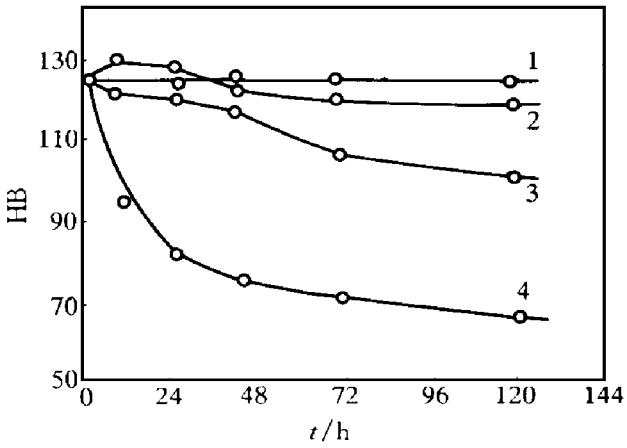

Fig. 3 Variation of HB of test alloy with time at different temperatures
1—400 ℃; 2—450 ℃;
3—550 ℃; 4—600 ℃

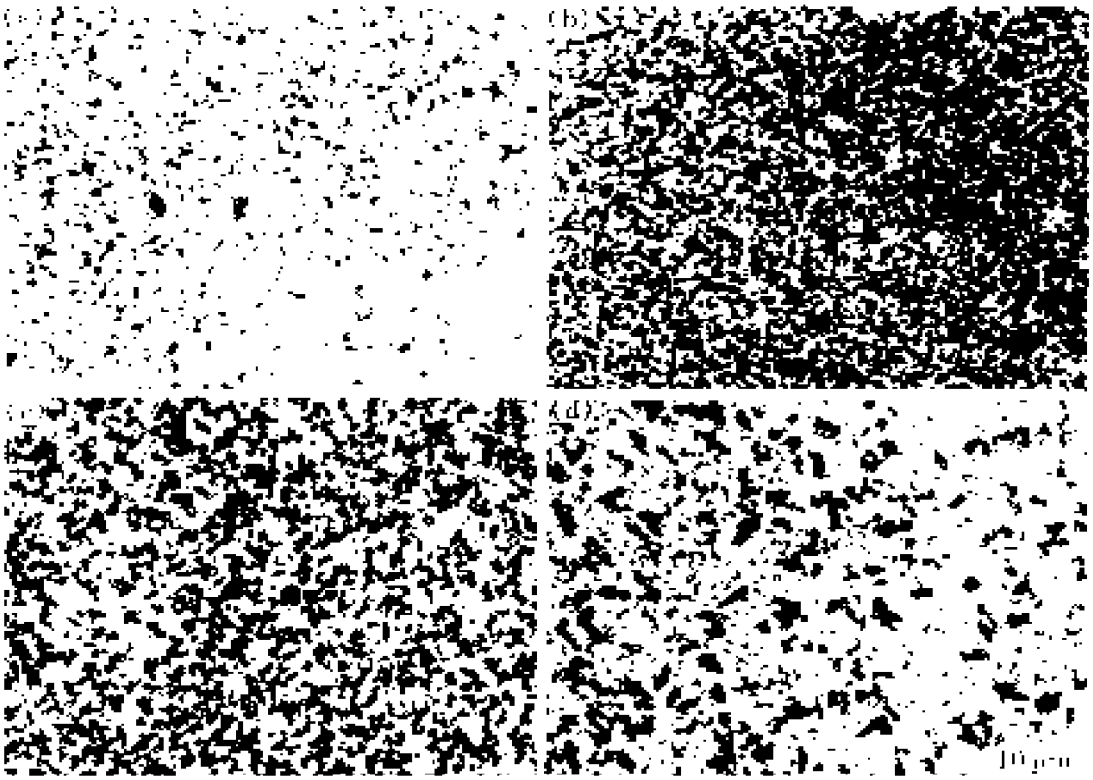

Fig. 4 Optical microstructures of test alloy after different annealing treatment
(a) —400 ℃, 120 h; (b) —450 ℃, 8 h; (c) —450 ℃, 120 h; (d) —600 ℃, 8 h

$Al_{13}Fe_4$ phase (Fig. 5).

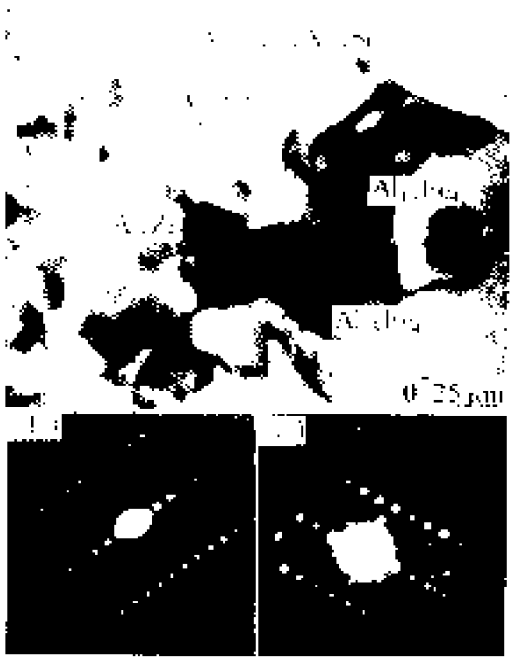

Fig. 5 TEM micrograph of test alloy after annealing at 550 ℃ for 120 h (a) and SAD patterns of θ-$Al_{13}Fe_4$ (b) and $Al_{13}Cr_2$ (c)

Although annealing at 450 ℃ for a short time can increase the hardness of the test alloy to some extent, it cannot improve the comprehensive mechanical properties of the test alloy. As shown in Fig. 6, after annealing at 450 ℃ for a short time, the strength of the test alloy increases somewhat while its ductility obviously decreases, which is due to the fact that in the annealing process the formation of new particles is accompanied by the coarsening of the second phase particles, especially the rapid coarsening of $Al_{13}Cr_2$ phase particles, thus the ductility is seriously affected. Although $Al_{13}Cr_2$ is also a good heat-resistant phase, it begins to coarsen significantly from 375 ℃ and its coarsening rate is 3~4 orders of magnitude larger than that of the $Al_{12}(Fe, X)_3Si$ silicides[8]. As shown in Fig. 5, $Al_{12}(Fe, Cr)_3Si$ and Al_3Zr can maintain as small spheroids, but the $Al_{13}Cr_2$ phase is markedly coarsened and is block-shaped. Therefore the presence of the $Al_{13}Cr_2$ phase is unfavourable to further improve the high-temperature thermal stability of the test alloy, and it is necessary to control the content of Cr. By adjusting the composition, it is possible to form only $Al_{12}(Fe, Cr, V)_3Si$ and DO_{23} Al_3Zr second phase particles, thus eliminating or reducing the harmful effect of the coarse $Al_{13}Cr_2$ phase.

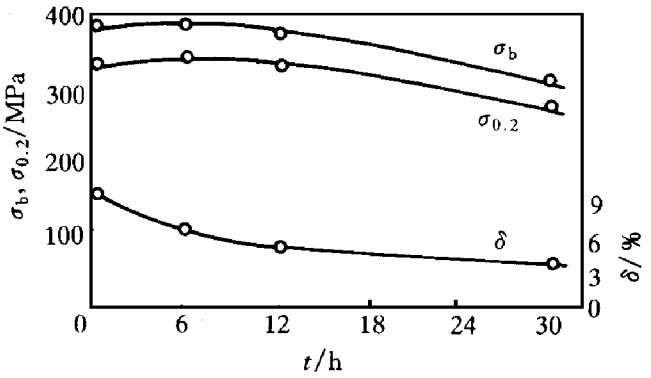

Fig. 6 Variation of tensile properties of test alloy with annealing time (450 ℃)

REFERENCES

1 Ward C M and Froes F H. JOM, 1994, 46(1): 20.
2 Xiao Yude, Li Songrui *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1995, 5(2): 128.
3 Xiao Yude, Li Songrui *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1994, 4(4): 104.
4 Skinner D J. In: Kim Y-W and Liriffith W M eds, Dispersion Strengthened Aluminium Alloys. Morristown: The Minerals, Metals and Materials Society, 1988: 181.
5 Mitra S and Menelley T R. Metall Trans, 1993, 24A (11): 2589.
6 Robinson J M and Shaw M P. International Materials Reviews, 1994, 39(3): 113.
7 Marshall G J, Hughes I R *et al*. Material Science and Technology, 1986, 2(6): 611.
8 Ragharan A, Anger L M *et al*. Metall Trans, 1988, 19A(6): 1645.

(Edited by Peng Chaoqun)