Elevated-Temperature Al-Ti-Fe-Cr Alloys with High Ductility at High-Strain-Rates[†]

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The rapidly solidified powder metallurgy (RS P/M) $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloys were found to have high elevated-temperature strength, high thermal stability and good high-strain-rate workability. These RS P/M alloys have been indicated as the promising candidate aluminum alloy for elevated-temperature applications. These RS P/M alloys exhibited ambient-temperature tensile strength ranging from 530 to 730 MPa and elongation ranging from 1 to 7%, which were dependent on extrusion temperature. The elevated-temperature strength was in excess of 300 MPa at 573 K. Especially, the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy exhibited about 320 MPa at 573 K. No degradation in the room-temperature hardness was observed for these RS P/M alloys after the isothermal annealing for 100 h at 673 K and for 1000 h at 623 K. The $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy, moreover, exhibited the elongation of more than 100% at high strain-rates ranging from 10^{-1} to 10^0 s^{-1} and at 823 K.

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I. Introduction

Rapidly solidification (RS) is the most effective process for the development of elevated-temperature aluminum alloys⁽¹⁾⁻⁽³⁾. Tensile strength of 300 MPa and more at 573 K is desired for the elevated-temperature aluminum alloys. Good workability that enables to work the alloys with maintaining the original mechanical properties is, moreover, required in the practical use. We have previously reported that $\text{Al}_{93}\text{Ti}_{3.5}\text{Fe}_{3.5}$ RS powder metallurgy (P/M) alloy exhibited high tensile strength of 786 MPa, reasonable plastic elongation of 3.2%, high thermal stability up to 600 K, low density of 2.90 kg/m^3 , high Young's modulus of 91 GPa and low coefficient of thermal expansion of $20.2 \times 10^{-6} \text{ K}^{-1}$ ⁽⁴⁾⁽⁵⁾. The Al-Ti-Fe P/M alloy is expected to be applied as elevated-temperature materials such as Al-Fe-Ce, Al-Fe-Mo, Al-Fe-V-Si and Al-Cr-Zr RS P/M alloys, because the Ti and Fe elements exhibit limited solid solubility and low diffusivity in aluminum⁽³⁾⁽⁶⁾⁻⁽⁹⁾. Recently, we have exhibited that the addition of 1.0 at%Cr and Mo to $\text{Al}_{93}\text{Ti}_{3.5}\text{Fe}_{3.5}$ RS P/M alloy improved effectively its thermal stability⁽¹⁰⁾, elevated-temperature strength⁽¹⁰⁾ and wear resistance⁽¹¹⁾. The elevated-temperature strength was, however, short of the target. On the other hand, although workability is usually inconsistent with the elevated-temperature strength, it has been reported that nanocrystalline aluminum alloys exhibited high-strain-rate superplasticity⁽¹²⁾. The further investigation of the Al-Ti-Fe-(Cr, Mo) RS P/M alloys with nanocrystalline structure is, therefore, expected to obtain good workability and high

elevated-temperature strength. In this paper, we will report the development of elevated-temperature Al-Ti-Fe-(Cr, Mo) P/M alloys with a high strength of more than 300 MPa at 573 K and good high-strain-rate workability.

II. Experimental Procedure

RS powders were produced by a high-pressure helium-gas atomization, where the dynamic gas-pressure was 9.8 MPa. The powders that were sieved to less than $25 \mu\text{m}$ were first packed into a copper can with an inner diameter of 20 mm and an outer diameter of 23 mm, and then were degassed for 900 s at the same temperature as the extrusion temperature. The extrusion was performed at an extrusion ratio of 10, temperatures ranging from 623 to 823 K, and a ram speed of 2.5 mm/s. The structure of the extruded bulk alloys was investigated by X-ray diffractometry (XRD) and transmission electron microscopy (TEM). Tensile strength and elongation were investigated at a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$ using an Instron testing machine. The strain-rate and temperature dependence of the tensile properties was investigated for the evaluation of the deformation behavior under conditions of temperatures ranging from 473 to 823 K and strain rates ranging from 5×10^{-4} to $8 \times 10^{-1} \text{ s}^{-1}$. The thermal stability was estimated by the change in ambient-temperature hardness, that was measured using a Vickers hardness tester, after the annealing at temperatures ranging from 573 K to 823 K.

III. Results and Discussion

Figure 1 shows the relationship between the tensile strength and the plastic elongation for

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Fig. 1 Relationship between tensile strength and elongation of $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys extruded at various temperatures.

$\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys that were consolidated at various extrusion temperatures. These RS P/M alloys exhibited tensile strength ranging from 530 to 730 MPa and elongation ranging from 1 to 7% at ambient temperature. The strength decreased linearly with increasing elongation, which was dependent on the extrusion temperature. The $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$ RS P/M alloy exhibited higher strength and larger elongation than the $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys. It should be noticed that the $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys have high strength of more than 600 MPa even at a high consolidation temperature of 823 K.

Figure 2 shows the elevated-temperature tensile strength of the $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys extruded at 773 K. The elevated-temperature strength was compared for the P/M alloys with a room-temperature strength of about 650 MPa because P/M alloys with higher ambient-temperature strength usually exhibit higher elevated-temperature strength. The elevated-temperature strength of these alloys exceeded 300 MPa at 573 K, which was higher than that (about 280 MPa) of the $\text{Al}_{92}\text{Ti}_{3.5}\text{Fe}_{3.5}(\text{Cr or Mo})_1$ RS P/M alloys⁽¹⁰⁾. Especially, the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy exhibited about 320 MPa at 573 K. The elevated-temperature strength of these RS P/M alloys exceeded the target that is desired for elevated-temperature aluminum alloys.

Figure 3 shows the change in the ambient-temperature Vickers hardness as a function of the isothermal annealing time for the $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys extruded at 773 K. The thermal stability was compared for the P/M alloys consolidated at the same temperature because P/M al-

Fig. 2 Elevated-temperature tensile strength of $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys extruded at 773 K. The room-temperature tensile strength of these RS P/M alloys was about 650 MPa.

Fig. 3 Isothermal annealing effect on room-temperature hardness in $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys. The room-temperature tensile strength of these RS P/M alloys was around 650 MPa in as-consolidated state.

loys consolidated at higher temperature apparently exhibit higher thermal stability. The change in the hardness after 100 h of exposure at 673 K was small. No degradation in the room-temperature hardness was, moreover, observed after the isothermal annealing for 1000 h at 623 K. The thermal stability is enough to put the RS P/M alloys to practical use as elevated-temperature structural materials.

Figure 4 shows the elevated-temperature tensile strength and elongation for the $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$, $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys extruded at 773 K. The strain-rate used in the tensile tests was $5 \times 10^{-4} \text{ s}^{-1}$. The elongation was in the range from 3 to 5% at temperatures below 573 K and drastically increased at about 600 K and more. On the other hand, the

Fig. 4 Elevated-temperature tensile properties of $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys as a function of test temperature. The room-temperature tensile strength of these RS P/M alloys was about 650 MPa in as-consolidated state.

Fig. 5 Strain-rate dependence of tensile strength and elongation to failure in $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy consolidated at 773 K. The room-temperature tensile strength of this RS P/M alloy was about 650 MPa in as-consolidated state.

strength decreased continuously with increasing temperature. These RS P/M alloys, that had high strength of more than 300 MPa at 573 K, exhibited about 470 MPa at 473 K and about 160 MPa even at relatively high temperature of 673 K. **Figure 5** shows the strain-rate dependence of the tensile strength and elongation to failure for the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy that was extruded at 773 K. The strength increased with increasing strain rate. The maximum elongation of 120% was

Fig. 6 Bright-field electron micrograph of $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy consolidated at 773 K.

obtained at a high strain-rate of about 10^{-1} s^{-1} . Strain-rate sensitivity exponent, namely, m value is usually represented by $m = \Delta \log \sigma / \Delta \log \dot{\epsilon}$. The m value of the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy was estimated to be 0.26. Superplastic materials usually exhibit large elongation in excess of 200% for the deformation in uniaxial tension, and high m values of more than 0.3⁽¹³⁾. Especially, the superplasticity that is observed at strain rates of more than $1.0 \times 10^{-2} \text{ s}^{-1}$ is termed high-strain-rate superplasticity⁽¹⁴⁾. In the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy, the m value was less than 0.3 and the elongation was below 200%. However, the maximum elongation of 120% was obtained at high strain-rates ranging from 10^{-1} to 10^0 s^{-1} . Although the superplasticity was not observed in the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy, the deformability enables to work the P/M alloy at industrial speeds. The tensile strength of the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy that was extruded at 823 K was 615 MPa, which was shown in Fig. 1. Moreover, the room-temperature hardness of the RS P/M alloy extruded at 773 K decreased by about 15% after the isothermal annealing for 5 h at 823 K. It is possible to work the P/M alloy at high strain-rates with keeping the ambient-temperature tensile strength of more than 550 MPa. The high-strain-rate superplasticity is expected to appear by further structural refinement of the RS P/M alloy. Rapid heating of the P/M alloy and lowering of the consolidation temperature are considered as the method of the structural refinement.

X-ray diffraction study showed that the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy predominantly contained fcc-Al and intermetallic compounds of $\text{Al}_{13}\text{Cr}_2$ and Al_3Ti . In addition, some of the peaks could not be indexed to any known binary or ternary compound present in this system. **Figure 6** shows the bright-field electron micrograph of the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy extruded at 773 K. The structure of this P/M alloy consisted of fine intermetallic compounds with a size from 20 to 150 nm and fcc-Al with a size from 100 to 200 nm. Hence, the high tensile strength was obtained presumably due to both the refinement of grain size and the homogeneous dispersion of various phases. Moreover, the good thermal stability is presumably a result of low diffusion rates of Cr, Fe and Ti elements in aluminum.

IV. Conclusions

We have developed $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_1\text{Mo}_1$, $\text{Al}_{92}\text{Ti}_3\text{Fe}_3\text{Cr}_2$ and $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloys that had high elevated-temperature strength, high thermal stability and good high-strain-rate workability. These RS P/M alloys had ambient-temperature tensile strength ranging from 530 to 730 MPa and elongation ranging from 1 to 7%. The elevated-temperature strength of these RS P/M alloys exceeded 300 MPa at 573 K. Especially, the $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ alloy exhibited about 320 MPa at 573 K. No change in the room-temperature hardness of these alloys was observed after the isothermal annealing for 100 h at 673 K and for 1000 h at 623 K. The $\text{Al}_{92.5}\text{Ti}_{2.5}\text{Fe}_{2.5}\text{Cr}_{2.5}$ RS P/M alloy exhibited the elongation of more than 100% at high strain-rates ranging from 10^{-1} to 10^0 s^{-1} at 823 K. Although the RS P/M alloy didn't exhibit superplasticity, the deformability was enough to work the P/M alloy into near-net shaped products industrially. The newly developed Al-Ti-Fe-(Cr, Mo) RS P/M alloys are the promising candidate materials for elevated-temperature applications.

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