Microstructure and Mechanical Properties of P/M Al–V–Fe and Al–Fe–M–Ti (M = V, Cr, Mn) Alloys Containing Dispersed Quasicrystalline Particles

Hisamichi Kimura, Akihisa Inoue and Kenichiro Sasamori

Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

By using the conventional powder metallurgy technique, P/M Al–V–Fe and Al–Fe–M–Ti (M = V, Cr, Mn) alloys with a diameter of 8 mm and a length of 300 mm were prepared by extrusion of the atomized powders at an extrusion ratio of 10 and extrusion temperatures (Te) of 623, 673 and 723 K. The structure of the P/M Al86V4Fe2 alloys is identified as fcc-Al (Al) + icosahedral quasicrystal (Q.C.) at Te = 623 K, Al + Q.C. + Al13V at Te = 673 K and 723 K. The structure of the P/M Al86Fe13Cr2Ti2 alloys is Al + Q.C. + Al12Ti5 at Te = 673 K. The ultimate tensile strength (σUTS), 0.2% proof stress (σ0.2), plastic elongation (εp), Young’s moduli (E), Vickers hardness (HV) and specific strength (σUTS/E) of the P/M Al86Fe13Cr2Ti2 alloy at room temperature are 660 MPa, 550 MPa, 4.4%, 85 GPa, 192 and 2.20 × 10^3 N m kg^-1, respectively. After heating for 300 s at 573 K, the σUTS, σ0.2 and εp are 360 MPa, 330 MPa and 1.5%, respectively. The Q.C. structure in the P/M Al86Fe13Cr2Ti2 alloy remains almost unchanged even after annealing for 720 ks at 573 K and the good wear resistance against S50C steel is also maintained for the extruded alloy tested at the sliding velocity of 0.5 to 2 m/s.

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1. Introduction

Since an icosahedral phase was found in a melt-spun Al86Mn14 alloy in 1984, 1 a number of icosahedral alloys in Al-, Mg-, Pd-, Ti-, V- and Zr-based systems have been synthesized in melt-spun ribbon and arc-melted ingot forms. It is generally known that the icosahedral alloys have an extremely brittle nature combined with high Vickers hardness (HV), for example, HV is 755 for the Q.C. Al86V14 alloy 2 and 710 for the Q.C. Al85.6Cr15.4 alloy 3 and 1010 for the Q.C. Al77.5Mn22.5 alloy. 4 These alloys have also been reported to have high thermal stability. 5, 6 There is a high possibility of synthesizing a new material with high specific strength, high elevated-temperature strength and high wear resistance by dispersing Q.C. particles into fcc-Al phase. Inoue et al. have found that a mixed microstructure consisting of nanoscale icosahedral or nanoscale amorphous and fcc-Al phases is formed for the melt-spun Al85Mn5Ce2 (5) and Al84.5Cr1Ce2Co1.5 (6) and Al82V7Fe2 (7), and Al82Fe3Ti4 (7) alloys which exhibit high tensile fracture strength exceeding 1000 MPa combined with good ductility. The mixed microstructure consisting of nanoscale amorphous and fcc-Al phases was also observed for the melt-spun Al82Fe3Ti4 Ti4 alloys (8) substituted M (M = V, Cr, Mn) of 2 at% for Ti of Al82Fe3Ti4 alloy which exhibit tensile fracture strength exceeding 800 MPa combined with good ductility. This paper presents the microstructure, mechanical properties at room temperature, elevated-temperature strength and wear resistance for the P/M Al–V–Fe and Al–Fe–M–Ti (M = V, Cr, Mn) alloys produced by powder metallurgy.

2. Experimental Procedure

The P/M Al–V–Fe and Al–Fe–M–Ti (M = V, Cr, Mn) alloys were prepared in the present study. The alloy ingots were prepared by arc melting Al, V and Cr metals in an argon gas atmosphere. From the ingots, alloy ribbons with a cross section of 0.02 x 1 mm2 were produced by a melt spinning technique. The ingots of P/M (powder metallurgy) alloys were prepared by induction melting pre-atomized ingots of Al–52.18 mass%V, Al–4.82 mass%Ti, Al–4.89 mass%Mn, Al–10.1 mass%Mn and Al–51.09 mass%Fe and Al and Cr metals in an argon atmosphere. Rapidly solidified powders were produced by high pressure gas atomization (9) and then sieved into different particle size fractions. By using the conventional powder metallurgy technique, P/M Al–V–Fe and Al–Fe–M–Ti (M = V, Cr, Mn) alloys with a diameter of 8 mm and a length of 300 mm were produced by extrusion of the atomized powders at an extrusion ratio of 10 and extrusion temperatures (Te) of 623, 673 and 723 K. The structures of as-quenched and extruded alloys were examined by X-ray diffraction and transmission electron microscopy (TEM). Thermal stability was examined by differential scanning calorimetry at a heating rate of 0.67 K/s. Mechanical properties were measured at a strain rate of 5.0 × 10^-4 s^-1 in the temperature range from room temperature to 573 K with an Instron testing machine. Hardness was measured with a Vickers microhardness tester under a load of 9.8 N for the P/M alloy. Wear rate against case hardened steel S50C (HV = 680) was measured in the sliding velocity range from 0.5 to 2 m/s with a wear testing machine.

3. Results and Discussion

3.1 Microstructure

The gas-atomized powder has a spherical shape with an average diameter of about 31 μm. Figure 1 shows an X-ray diffraction pattern of the Al86V4Fe2 powder with a particle size smaller than 26 μm, together with the data of the melt-spun Al86V14 alloy with a nearly single icosahedral quasicrystal (Q.C.) phase. 10 The structure of the as-atomized powder is
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Fig. 1 X-ray diffraction pattern of an Al_{94}V_{4}Fe_{2} alloy powder with the size smaller than 26 μm. The pattern of a melt-spun (MS) Al_{96}V_{14} ribbon is also shown for comparison.

Fig. 2 X-ray diffraction patterns of P/M Al_{94}V_{4}Fe_{2} alloys extruded at extrusion temperatures (T_e) of 623, 673 and 723 K.

identified as fcc-Al (Al) + Q.C. + Al_{11}V. The diffraction peaks of the Q.C. agree with those for the Al-V alloy. Figure 2 shows the X-ray diffraction patterns of the P/M Al_{94}V_{4}Fe_{2} alloys produced by extruding atomized powders with the size smaller than 26 μm at extrusion temperatures (T_e) of 623, 673 and 523 K and an extrusion ratio of 10. The structure is Al + Q.C. at T_e = 623 K, Al + Q.C. + Al_{11}V at T_e = 673 K and 723 K. However, the peak intensity of the Al_{11}V compound is rather weak and hence the main constituent phases appear to be Al and Q.C. phases. Figure 3 shows a bright-field image of an electron micrograph (a) and selected-area electron diffraction patterns (b, c, d) of the P/M Al_{94}V_{4}Fe_{2} alloy extruded at T_e = 673 K. The diffraction patterns of the sphere particles with a size of about 400 nm show the five-, three- and two-fold symmetries revealing the precipitation of Q.C..

Fig. 3 Bright-field electron micrograph (a) and selected area diffraction patterns of a P/M Al_{94}V_{4}Fe_{2} alloy extruded at 673 K.

Figure 4 shows X-ray diffraction patterns of the P/M Al_{92}Fe_{2}Cr_{5}Ti_{2} alloy and the melt-spun Al_{96}Cr_{4}, Al_{94}Cr_{6} and Al_{92}Cr_{8} alloys. The diffraction patterns of the melt-spun Al_{96}Cr_{4}, Al_{94}Cr_{6} and Al_{92}Cr_{8} alloys are identified as Al for the Al_{96}Cr_{4} alloy and Q.C. + Al for the Al_{94}Cr_{6} and Al_{92}Cr_{8} alloys. The X-ray diffraction pattern of the P/M Al_{92}Fe_{2}Cr_{5}Ti_{2} alloy is identified as Q.C. + Al + Al_{12}Ti_{9}. The structure of the Q.C. phase was examined by TEM. The diffraction patterns show reflection spots of Al for the Al_{96}Cr_{4} alloy and five- and three-fold symmetries for the Al_{94}Cr_{6} and Al_{92}Cr_{8} alloys. Figure 5 shows bright-field TEM images (a to c) and selected-area electron diffraction patterns (d to g) of the P/M Al_{92}Fe_{2}Cr_{5}Ti_{2} alloys produced by extrusion of atomized powders with the size smaller than 75 μm. The diffraction patterns of the nearly spherical precipitated particles have the five-, three- and two-fold symmetries of the Q.C. phase. The particle size and interparticle spacing in the Q.C. phase are about 600 nm and about 400 nm, respectively.

It is thus concluded that the Q.C. structure of the P/M alloy...
Fig. 4 X-ray diffraction pattern of a P/M Al<sub>92</sub>Fe<sub>3</sub>Cr<sub>5</sub>Ti<sub>2</sub> alloy extruded at 673 K. The data of the melt-spun (MS) Al<sub>92</sub>Cr<sub>5</sub>, Al<sub>92</sub>Cr<sub>6</sub> and Al<sub>92</sub>Cr<sub>8</sub> ribbons are also shown for comparison.

was produced at the lower cooling rate of about 10<sup>2</sup> K/s<sup>2</sup> as compared with the melt-spun alloys.

3.2 Mechanical properties

Table 1 summarizes the ultimate tensile strength (σ<sub>UTS</sub>), 0.2% proof stress (σ<sub>0.2</sub>) and plastic elongation (ε<sub>p</sub>) at room temperature of the P/M Al<sub>92</sub>V<sub>4</sub>Fe<sub>2</sub> and Al<sub>93</sub>Fe<sub>3</sub>M<sub>2</sub>Ti<sub>2</sub> alloys produced by extrusion of atomized powders with the size smaller than 26 and 125 μm and the P/M Al<sub>92</sub>Fe<sub>3</sub>M<sub>2</sub>Ti<sub>2</sub> (M = V, Cr or Mn) alloys produced by extrusion of atomized powders with the size smaller than 75 μm, together with the data of the commercial 7075-T6 aluminum alloy. The σ<sub>UTS</sub>, σ<sub>0.2</sub> and ε<sub>p</sub> of the P/M Al–V–Fe alloys containing dispersed Q.C. particles are smaller than those for the commercial 7075-T6 aluminum alloy, while their Young’s moduli are higher. For the P/M Al<sub>92</sub>Fe<sub>3</sub>M<sub>2</sub>Ti<sub>2</sub> and Al<sub>92</sub>Fe<sub>3</sub>M<sub>2</sub>Ti<sub>2</sub> (M = V, Cr or Mn) alloys, the σ<sub>UTS</sub> for the powder with the size smaller than 26 μm is higher than that for the powder with the size smaller than 125 μm and tends to increase in the order of Cr > Mn > V. On the other hand, the ε<sub>p</sub> shows an opposite tendency to that for σ<sub>UTS</sub> and σ<sub>0.2</sub>. The best mechanical properties of 660 MPa for σ<sub>UTS</sub>, 550 MPa for σ<sub>0.2</sub> and 4.5% for ε<sub>p</sub> are obtained for the Al<sub>92</sub>Fe<sub>3</sub>Cr<sub>5</sub>Ti<sub>2</sub> alloy produced by extrusion of atomized powder with the size smaller than

![Diagram](image-url)

Table 1 Mechanical properties of the P/M alloys tested at room temperature. The data of the commercial 7075-T6 aluminum alloy also shown for comparison.

<table>
<thead>
<tr>
<th>P/M alloy</th>
<th>Powder size (μm)</th>
<th>σ&lt;sub&gt;UTS&lt;/sub&gt; (MPa)</th>
<th>σ&lt;sub&gt;0.2&lt;/sub&gt; (MPa)</th>
<th>ε&lt;sub&gt;p&lt;/sub&gt; (%)</th>
<th>E (GPa)</th>
<th>H&lt;sub&gt;v&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;UTS&lt;/sub&gt;/ρ (10&lt;sup&gt;5&lt;/sup&gt; N m kg&lt;sup&gt;-1&lt;/sup&gt;)</th>
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<tr>
<td>Al&lt;sub&gt;94&lt;/sub&gt;V&lt;sub&gt;4&lt;/sub&gt;Fe&lt;sub&gt;2&lt;/sub&gt;</td>
<td>26</td>
<td>585</td>
<td>470</td>
<td>4.5</td>
<td>85</td>
<td>190 ± 3</td>
<td>1.9</td>
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<td>Al&lt;sub&gt;93&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;Cr&lt;sub&gt;5&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>26</td>
<td>658 ± 9</td>
<td>545 ± 14</td>
<td>4.4 ± 0.5</td>
<td>85 ± 2</td>
<td>192 ± 3</td>
<td>2.2</td>
</tr>
<tr>
<td>Al&lt;sub&gt;93&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;M&lt;sub&gt;2&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>125</td>
<td>537 ± 4</td>
<td>464 ± 5</td>
<td>5.4 ± 1.4</td>
<td>90 ± 1</td>
<td>165 ± 3</td>
<td>1.8</td>
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<td>Al&lt;sub&gt;93&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;M&lt;sub&gt;2&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>26</td>
<td>608</td>
<td>490</td>
<td>4.2</td>
<td>87</td>
<td>190 ± 3</td>
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<tr>
<td>Al&lt;sub&gt;92&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;V&lt;sub&gt;4&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>125</td>
<td>497</td>
<td>430</td>
<td>4.8</td>
<td>80</td>
<td>160 ± 4</td>
<td>1.7</td>
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<td>75</td>
<td>494 ± 4</td>
<td>407 ± 49</td>
<td>5.5 ± 0.6</td>
<td>87 ± 1</td>
<td>159 ± 4</td>
<td>—</td>
</tr>
<tr>
<td>Al&lt;sub&gt;92&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;M&lt;sub&gt;2&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>75</td>
<td>581 ± 2</td>
<td>488 ± 8</td>
<td>3.3 ± 0.4</td>
<td>85 ± 2</td>
<td>191 ± 3</td>
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<td>Al&lt;sub&gt;92&lt;/sub&gt;Fe&lt;sub&gt;3&lt;/sub&gt;M&lt;sub&gt;2&lt;/sub&gt;Ti&lt;sub&gt;2&lt;/sub&gt;</td>
<td>75</td>
<td>584 ± 4</td>
<td>491 ± 7</td>
<td>2.7 ± 0.6</td>
<td>89 ± 1</td>
<td>191 ± 5</td>
<td>—</td>
</tr>
<tr>
<td>7075-T6</td>
<td>—</td>
<td>600</td>
<td>550</td>
<td>10.7</td>
<td>70</td>
<td>190 ± 3</td>
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26 μm powder. $\sigma_{UTS}$ and $\sigma_{0.2}$ of the Al–Fe–Cr–Ti alloy are higher than those for the commercial 7075-T6 aluminum alloy, though the $\varepsilon_p$ is lower.

### 3.3 High elevated-temperature strength

We examined the $\sigma_{UTS}$, $\sigma_{0.2}$ and $\varepsilon_p$ after holding time for 30 s and 360 ks at 573 K for the P/M Al$_{94}$V$_4$Fe$_2$, Al$_{93}$V$_4$Fe$_2$Ti$_1$, Al$_{92}$Fe$_2$M$_2$Ti$_2$, and Al$_{92}$Fe$_3$M$_3$Ti$_2$ (M = V, Cr or Mn) alloys. The $\sigma_{UTS}$, $\sigma_{0.2}$ and $\varepsilon_p$ are 305 MPa, 291 MPa and 5.0%, respectively, for P/M Al$_{94}$V$_4$Fe$_2$ alloy and 316 MPa, 298 MPa and 5.5%, respectively, for the P/M Al$_{93}$V$_4$Fe$_2$Ti$_1$ alloy. Figure 6 summarizes the $\sigma_{UTS}$, $\sigma_{0.2}$ and $\varepsilon_p$ of the P/M Al$_{93}$Fe$_2$M$_2$Ti$_2$ and Al$_{92}$Fe$_3$M$_3$Ti$_2$ (M = V, Cr or Mn) alloys. The $\sigma_{UTS}$ and $\sigma_{0.2}$ decrease in the order of Cr > Mn > V, while the $\varepsilon_p$ shows an opposite tendency. Here, it is noticed that high elevated-temperature strength with $\sigma_{UTS}$ of 340 MPa and $\sigma_{0.2}$ of 310 MPa is obtained for the Al$_{92}$Fe$_2$Cr$_2$Ti$_2$ alloy after holding time of 360 ks at 573 K. In addition, these Al-based alloys do not include any expensive element. Owing to these advantage points, the Al–Fe–Cr–Ti alloys with dispersed Q.C. particles are expected to be used as a new high elevated-temperature strength material.

Figure 7 shows a bright-field electron micrograph (a) and selected-area diffraction patterns (b, c, d) taken from 200 to 700 nm particles of the P/M Al$_{94}$Fe$_2$Cr$_2$Ti$_2$ alloy by annealing for 720 ks at 573 K. The diffraction patterns reveal the five-, three- and two-symmetries indicating the existence of the Q.C. phase. It is to be noticed that the Q.C. phase remains unchanged even after annealing for 720 ks at 573 K.

### 3.4 Wear resistance

Figure 8 shows the change in the wear resistance against SS30 steel of the P/M Al$_{94}$V$_4$Fe$_2$, Al$_{92}$V$_4$Fe$_2$Si$_1$, and Al$_{92}$Fe$_2$Cr$_2$Ti$_2$ alloys with dispersed Q.C. particles at sliding velocities ranging from 0.5 to 2 m/s, together with the data of the commercial A-390 aluminum alloy. Although the wear loss of the A-390 aluminum alloy increases rapidly at the sliding velocity of 1.5 m/s, the P/M alloys keep lower wear losses below $3 \times 10^{-13}$ m$^3$/kg even at 2 m/s. The good wear resistance of the P/M alloys is considered to result from the dispersion of Q.C. particles with high hardness and high stability into the Al matrix.

### 4. Summary

We examined the possibility of developing a high-strength material in the P/M Al–V–Fe and Al–Fe–M–Ti alloys with dispersed icosahedral quasicrystalline (Q.C.) particles. The results obtained are summarized as follows.

1. The P/M Al$_{94}$V$_4$Fe$_2$ alloy produced at extrusion temperature ($T_e$) of 623 K consists of Q.C. and Al phases. The ultimate tensile strength ($\sigma_{UTS}$), 0.2% proof stress ($\sigma_{0.2}$), plastic elongation ($\varepsilon_p$), Vickers hardness ($H_v$), Young’s modulus ($E$) and specific strength ($\sigma_{UTS}/\rho$) at room temperature are 585 MPa, 470 MPa, 4.5%, 190, 85 GPa and $1.91 \times 10^3$ N m kg$^{-1}$, respectively. The $\sigma_{UTS}$, $\sigma_{0.2}$ and $\varepsilon_p$ after hold-
Fig. 8 Change in the specific wear rate ($c_i$) with sliding velocity ($v_s$) for P/M $\text{Al}_3\text{V}_2\text{Fe}_2$, $\text{Al}_{25.5}\text{V}_7\text{Fe}_3\text{Si}_1\text{S}$, and $\text{Al}_{90}\text{Fe}_7\text{Cr}_2\text{Ti}_2$ alloys with dispersed icosahedral quasicrystal particles produced by powder with the size smaller than 25 $\mu$m. The data of the commercial A390-T6 aluminum alloy are also shown for comparison.

(1) The $\sigma_{\text{UTS}}$ and $\sigma_{0.2}$ of the P/M $\text{Al}_{90}\text{Fe}_7\text{Cr}_2\text{Ti}_2$ and $\text{Al}_{90}\text{Fe}_7\text{M}_{2}\text{Ti}_2$ ($M = V, Cr$ or $\text{Mn}$) alloys increase in the order of $\text{Cr} > \text{Mn} > V$. On the other hand, the $\epsilon_F$ shows an opposite tendency to those for $\sigma_{\text{UTS}}$ and $\sigma_{0.2}$.

(3) By extruding the atomized powders containing Q.C. phase at 673 K and an extrusion ratio of 10, the P/M alloys in a cylindrical rod form were prepared. The P/M $\text{Al}_{90}\text{Fe}_7\text{Cr}_2\text{Ti}_2$ alloys exhibit high tensile strength exceeding 600 MPa for $\sigma_{\text{UTS}}$ and 550 MPa for $\sigma_{0.2}$ at room temperature. In particular, the $\sigma_{\text{UTS}}$ of 340 MPa after holding time of 360 ks at 573 K exceeds 300 MPa which is final target of high elevated-temperature strength.

(4) The Q.C. structure in the P/M $\text{Al}_{90}\text{Fe}_7\text{Cr}_2\text{Ti}_2$ alloy remains almost unchanged even after annealing for 720 ks at 573 K and the good wear resistance against S50C steel is also maintained at the sliding velocity of 0.5 to 2 m/s.

(5) The syntheses of the high elevated-temperature strength materials in the Al-based system by the use of alloy with dispersed Q.C. particles containing Fe, Cr and Ti elements with low atomic diffusivities is important for the future development of a new type of Al-based alloys with high-strength at elevated-temperatures.

REFERENCES