Special Feature: Metallic Materials

Research Report

High Specific Strength Aluminum Alloys

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ABSTRACT In the present report, the mechanical properties and microstructures of base alloys, Al-Zr-Ti and Al-Zr-Ti-Fe, and a new powder metallurgical aluminum alloy, *ULMat* (Ultra Strong Material), developed by Toyota Central R&D Labs., Inc., were investigated in detail through analytical transmission electron microscopy and strength tests. Base alloys cast at a cooling rate of 3×10^2 K/s were hardened significantly by aging at 673 K and 723 K for 1 hour because the $L1_2$-Al_3(Zr, Ti) phase consistent with the matrix was dispersed with proeutectic Al_6Fe compounds. *ULMat* was developed based on the hardening mechanism of Al-Zr-Ti and Al-Zr-Ti-Fe alloys by the application of the rapid solidification technique. *ULMat* exhibits a specific tensile strength of 257 MPa/Mgm^{-3} and a fatigue strength of 280 MPa, which eliminates the need for heat treatment. *ULMat* also has high thermal stability up to 723 K and a high Young's modulus, as compared to that of conventional aluminum alloys, of 75 GPa. These excellent properties appear to be due to the thermal stability of coherent $L1_2$-Al_3(Zr, Ti) compound, which precipitates during hot extrusion. *ULMat* is considered to be a promising candidate for improving fuel consumption in automobiles.

KEYWORDS Aluminum Alloy, Powder Metallurgy, Hot Extrusion, High Specific Strength, Thermal Stability

1. Introduction

In order to reduce CO_2 emissions, which are a key factor in global warning, fuel consumption in automobiles should be improved immediately.[1] Weight reduction of automobiles is one promising candidate for improving their fuel consumption. However, the average weight of automobiles has increased with the continuing need to develop new models with enhanced safety, convenience, and luxury. In particular, safety equipment, such as air bags, body structures, and antiskid braking systems, have increased the weight of automobiles. New powertrains, such as hybrid systems, have also resulted in increased vehicle weight. Therefore, in order to diminish vehicle weight increases, new lightweight materials, such as aluminum alloys and fiber-reinforced plastics, are needed.[2,3]

Aluminum alloys are known to have low density, high specific strength, high corrosion resistance, and good formability and are widely used in lightweight structural components of aircraft and trains. In the automobile industry in Europe, the use of aluminum for body and chassis components is expanding, resulting in improved fuel consumption. However, in order to conserve the environment, the properties of conventional aluminum alloys are insufficient for expansion of the applicability to automobile parts, and so the properties of aluminum alloys must be further enhanced.

Therefore, we developed new high specific strength aluminum alloys for lighter, more functional automobile components. The alloy is given a fine microstructure by optimization of the chemical composition and the rapid solidification technique in order to enhance the strength and thermal stability of the alloy. The goal of the present paper is to develop new powder metallurgical aluminum alloys. First, the hardness and microstructure of base alloys, Al-Zr-Ti and Al-Zr-Ti-Fe, were investigated, the optimal range of chemical composition and the aging temperature to obtain high strength and high thermal stability were determined. Next, we reported the mechanical properties of *ULMat* (Ultra Strong Material). The development of *ULMat* is based on the chemical composition with the application of the rapid solidification technique. The extruded alloy exhibited high strength and superior thermal stability compared to conventional aluminum alloys.

2. Experimental Procedure

2. 1 Basic Research on Base Alloys, Al-Zr-Ti and Al-Zr-Ti-Fe

The microstructures and hardening behaviors of Al-1mass%Zr-0.8mass%Ti and Al-1mass%Zr-0.8mass%Ti-4mass%Fe alloys were investigated. These alloys were gravity-cast with pure Al, Al-10mass%Zr, Al-10mass%Ti, and Al-10mass%Fe master alloys. A copper mold was used, and specimens were obtained from a parallel part of 1.2 mm in thickness, as shown in **Fig. 1**. Here, the cooling rate of the parallel part is 3×10^2 K/s. The alloys were aged at temperatures between 573 K and 773 K for 1 hour in atmosphere.

The microstructure was investigated by transmission electron microscopy (TEM; Hitachi HF-2200). Transmission electron microscopy samples were prepared by mechanically thinning sections to a thickness of approximately 100 µm. Discs of 3 mm in diameter were obtained from these sections and were thinned to perforation by twin-jet electro polishing using a solution of 70% methanol and 30% nitric acid. The thin foils were examined by a transmission electron microscope equipped with an energy dispersive X-ray spectroscopy (EDX; Thermo Scientific NORAN) detector.

The hardening behaviors of the as-cast and aged samples were evaluated by Vickers hardness tests. The hardness was measured on polished samples and then determined using the average value of seven independent measurements.

2. 2 Development of *ULMat*, a New Powder Metallurgical Aluminum Alloy

The mechanical properties and thermal stability of *ULMat*, a new powder metallurgical aluminum alloy, were investigated. The powders used here were produced by high-pressure air atomization of molten aluminum alloy at 1,373 K and a dynamic pressure of 3 MPa were sieved to under 106 µm. The cooling rate of atomization was estimated to be at least 1×10^4 K/s. The powders were formed to a packing density of 80% by cold isostatic pressing. After degassing, the compact piece was hot-extruded at 723 K using extrusion dies, as shown in **Fig. 2**. In the present study, the extrusion ratio was 11.

The tensile and fatigue strengths of the extrusion samples were evaluated using the specimens shown in **Fig. 3**. The longitudinal direction of the specimens matched the extrusion direction. The tensile test was conducted using a tensile and compression machine (Minebea TG-50KN) at a tensile rate of 2 mm/min in atmosphere.

3. Results and Discussion

3. 1 Hardening Behaviors and Microstructures of Al-Zr-Ti and Al-Zr-Ti-Fe Base Alloys

Figure 4 shows the results of the Vickers hardness test on the Al-Zr-Ti and Al-Zr-Ti-Fe alloys after the isochronal aging step (1 h at each temperature). As shown in Fig. 4, the hardening behavior of the Al-Zr-Ti and Al-Zr-Ti-Fe alloys has three periods: (a)

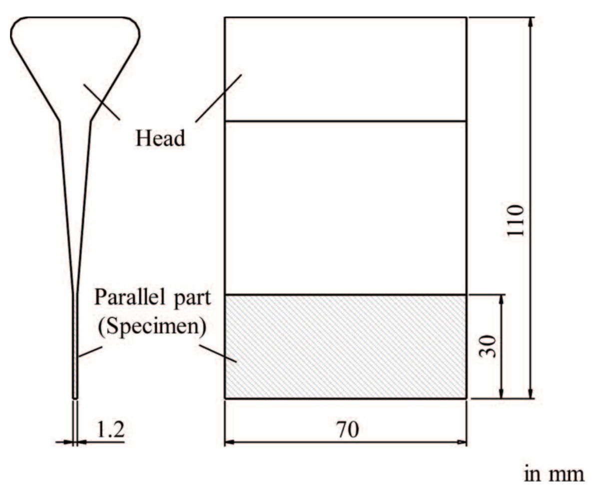

Fig. 1 Shape and dimensions of the sample cast in copper mold.

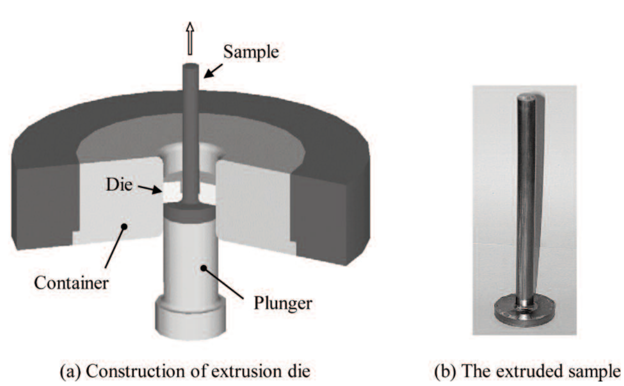

Fig. 2 Schematic illustration of extrusion dies (a) and an extruded sample (b).

an incubation period, (b) a transient period with an increase in hardness at 673 K, and (c) a plateau period at high hardness. When the aging temperature was controlled at 673 K and 723 K, the mechanical properties of the Al-Zr-Ti base alloy was significantly improved. The addition of Fe to the Al-Zr-Ti alloy caused a remarkable increase in hardness, whereas the hardness of the Al-Zr-Ti-Fe alloy decreased when aged at 773 K. Therefore, the range of the aging temperature for strengthening is comparable to temperatures for hot forming, such as extrusion and forging. Note that shape forming and strengthening are accomplished simultaneously.

Figure 5 shows a TEM bright-field micrograph of Al-Zr-Ti-Fe alloy aged at 723 K corresponding to the temperature exhibiting the peak hardness shown in Fig. 4. Rod-shaped Al-Fe compounds with diameters of between 100 and 300 nm and with lengths of several micrometers were observed in the eutectic regions.

Figure 6 shows TEM images and EDX analysis results of the primary α-Al phase of the Al-Zr-Ti-Fe alloy aged at 723 K. Spherical precipitates with diameters of several nanometers were observed in the primary α-Al phase, as shown in Fig. 6(a). The SADP in Fig. 6(b) indicates a face-centered cubic α-Al matrix and $L1_2$ ordered structure. It is clear that coherent precipitates form, so that there is a definite relationship between the structures of the matrix and the precipitate, as indicated in Fig. 6(d). Al, Zr, and Ti were detected in the precipitates, as shown in Fig. 6(e). Therefore, the precipitates are confirmed to be a composite $L1_2$-type Al_3(Zr, Ti). Small amount of Fe were detected, this was attributed to impurity Fe in the sample.

Figure 7 shows the results of TEM observation in the eutectic regions shown in Fig. 5(b). Based on the results of SADP (Fig. 7(b)) and EDX (Fig. 7(c))

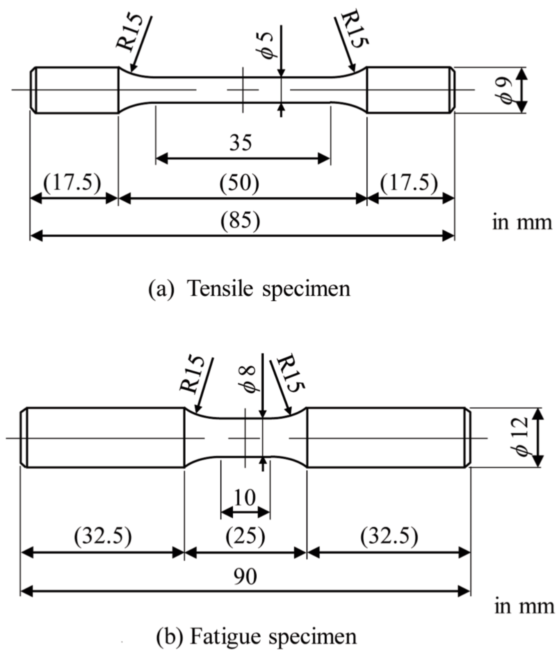

Fig. 3 Shapes and dimensions of the tensile and fatigue specimens.

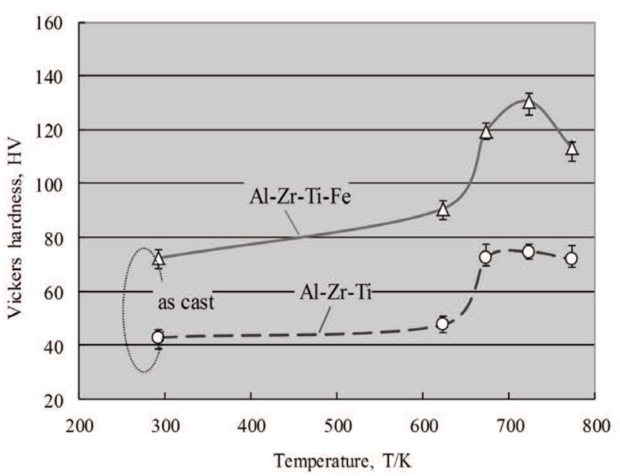

Fig. 4 Relationship between Vickers hardness and aged temperature of Al-Zr-Ti and Al-Zr-Ti-Fe alloys.

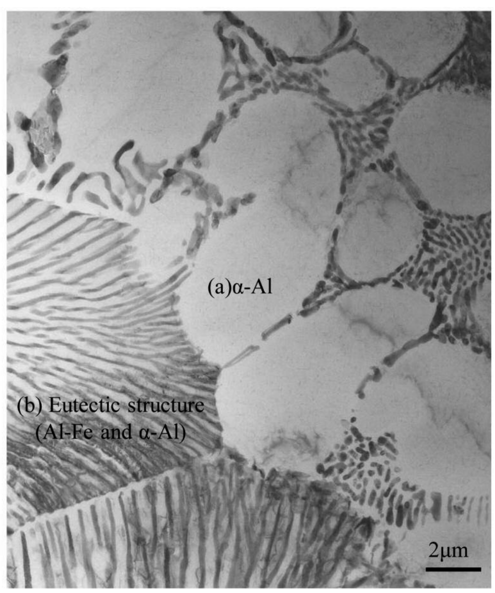

Fig. 5 TEM bright-field micrograph of Al-Zr-Ti-Fe alloy aged at 723 K. The regions marked (a) and (b) indicate the α-Al and the eutectic structure consisting of Al and Al-Fe compound, respectively.

analysis, the Al-Fe compound was metastable Al_6Fe (orthorhombic).[4,5] Therefore, the increase in hardness with the heating of the Al-Zr-Ti-Fe alloy was attributed to the dispersion strengthening by $L1_2$-Al_3(Zr, Ti) and Al_6Fe compounds. On the other hand, the hardness decrease in the Al-Zr-Ti-Fe alloy aged at 773 K was probably caused by phase transformation from the metastable Al_6Fe phase to the stable Al_3Fe phase.[6,7]

Based on the above results, the increase in hardness with high-temperature aging of the cast Al-Zr-Ti and Al-Zr-Ti-Fe alloys was attributed to the dispersion strengthening by coherent precipitation of $L1_2$-Al_3(Zr, Ti) structure and proeutectic Al_6Fe compounds.

3. 2 Mechanical Properties of *ULMat*, a New Aluminum Alloy

The chemical composition of the new powder metallurgical alloy, *ULMat*, was determined based on the evaluation results for the hardening behavior of samples that were prepared by casting. The optimum composition of *ULMat*, which has high specific strength and thermal stability, is Al-0.6mass%Zr-0.2mass%Ti-2.5mass%Fe-7.5mass%Mg-1.1mass%Co-0.8mass%Mo-0.5mass%Cu. The density of *ULMat* is 2.7 Mgm^{-3}, which is comparable to pure aluminum.

Figure 8 summarizes the results of hardness evaluation in each process. The sample that was extruded at 723 K exhibited a higher hardness than that of raw alloy powder. Nearly identical hardness was

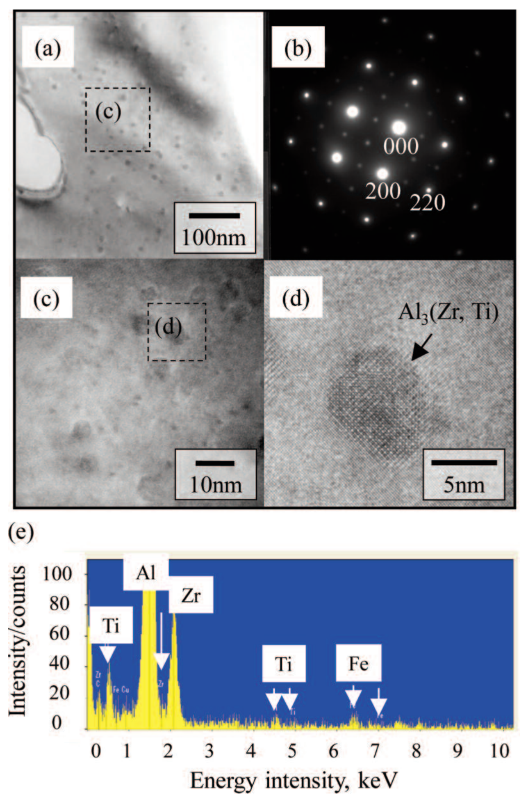

Fig. 6 TEM micrograph of Al-Zr-Ti-Fe alloy aged at 723 K. (a) TEM bright-field image, (b) SADP of (a), (c) and (d) HREM micrographs, (e) EDX analysis of the Al_3(Zr, Ti) precipitates indicated by the arrow in (d).

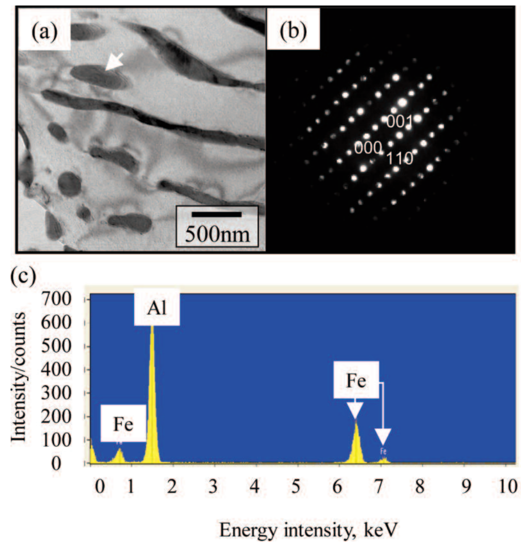

Fig. 7 TEM micrograph of Al-Zr-Ti-Fe alloy aged at 723 K. (a) TEM bright-field image, (b) micro-beam diffraction pattern obtained from the Al-Fe compound, (c) EDX analysis of the Al-Fe compound indicated by the arrow in (b).

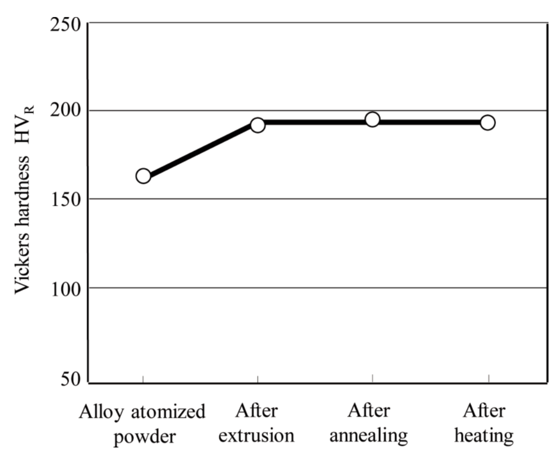

Fig. 8 Changes in Vickers hardness of the developed material after annealing at 723 K for 3.6 ks, and heating at 573 K for 360 ks.

achieved in the extruded sample and the reheated samples at 723 K for 1 hour and at 573 K for 100 hours. *ULMat* was found to be able to enhance the mechanical properties simultaneously with hot extrusion, eliminating the need for the heat treatment required for heat-treatable alloys. *ULMat* also has superior thermal stability after exposure at high temperatures of up to 723 K. This is due to the structural stability of coherent $L1_2$-Al_3(Zr, Ti) phase and low diffusion rates of Zr and Ti in aluminum.

The tensile properties of *ULMat* are shown in **Table 1**. The specific strength as determined from the tensile strength (designated σ_B) and density was 257 MPa/Mgm^{-3}, which was higher than the values reported for titanium alloys, such as Ti-6Al-4V, and high-tensile-strength steel. **Figure 9** shows the S-N curves of *ULMat* and conventional aluminum alloys. *ULMat* exhibited a fatigue strength (designated σ_w) of 280 MPa, which is 30% higher than the corresponding strength of commercial 7050-T76 alloy at the same rupture life. **Figure 10** summarizes the relationship between σ_B and σ_W for *ULMat* and for various aluminum alloys. The relationship between σ_B and σ_W for conventional aluminum alloys can be expressed by following empirical formula[(8)]:

$$\sigma_W = a\sigma_B^{\ b} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where coefficients *a* and *b* are 2.86 and 0.66, respectively. The fatigue ratio, σ_W/σ_B, of conventional alloys tends to decrease with increasing σ_B, as shown in Fig. 10. On the other hand, σ_W/σ_B of *ULMat*, as determined in the present study was 0.4, which is higher than that of the high-strength aluminum alloys with tensile strengths of 500 MPa or more. This result suggests that the variation of σ_W/σ_B is attributed to the difference of the precipitation structures that are dispersed in the matrix of *ULMat* and conventional alloys, such as heat-treatable Al-Zn-Mg(-Cu) and Al-Cu(-Mg) system alloys.

Table 1 Tensile properties of the developed material, *ULMat.*

Tensile strength σ_B／MPa	0.2% proof stress $\sigma_{0.2}$／MPa	Elongation δ／%	Young's modulus E／GPa
690	560	7.3	75

4. Summary

The hardening behaviors and microstructures of Al-Zr-Ti and Al-Zr-Ti-Fe base alloys and of *ULMat*, a new powder metallurgical aluminum alloy developed by Toyota Central R&D Labs., Inc., were investigated. The following results were obtained and discussed:

1) The hardening behavior of the Al-Zr-Ti and Al-Zr-Ti-Fe alloys exhibit three periods: (a) an incubation period, (b) a transient period with increased hardness at 673 K, and (c) a plateau period at high hardness. When the aging temperature was controlled at 673 K and 723 K, the mechanical properties of Al-Zr-Ti base alloy were significantly improved. The addition of Fe to the Al-

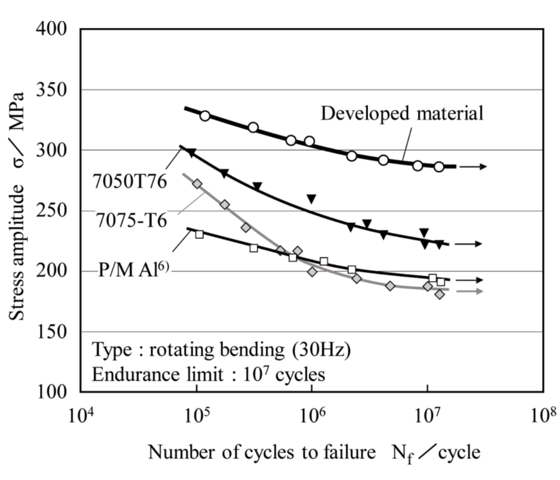

Fig. 9 S-N curves of the developed material, *ULMat*, and some conventional aluminum alloys.

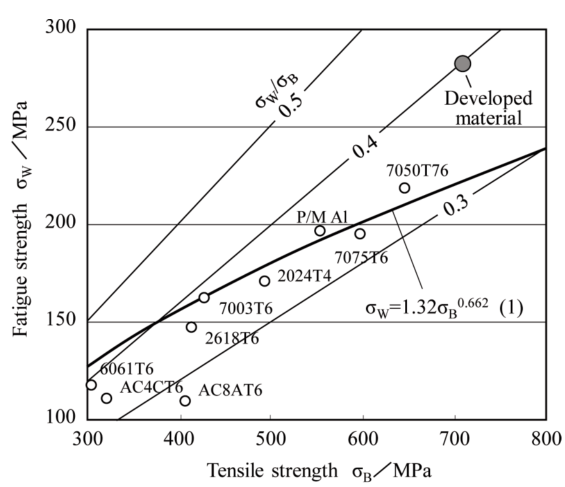

Fig. 10 Relationship between tensile strength and fatigue strength of the developed material, *ULMat*.

Zr-Ti alloy caused a remarkable increase in hardness, whereas the hardness of the Al-Zr-Ti-Fe alloy decreased when aged at 773 K.

2) The chemical composition of *ULMat*, as determined through basic research on the hardening behavior of base alloys is Al 0.6mass%Zr-0.2mass%Ti-2.5mass%Fe-7.5mass%Mg-1.1mass%Co-0.8 mass%Mo-0.5mass%Cu. *ULMat* was found to be able to enhance the mechanical properties simultaneously with hot extrusion, eliminating the need for the heat treatment required for heat-treatable alloys.

3) *ULMat* also has superior thermal stability after exposure at high temperatures of up to 723 K. This is due to the thermal stability of the coherent $L1_2$-$Al_3(Zr,Ti)$ phase and the low diffusion rates of Zr and Ti atoms in aluminum.

4) The density of *ULMat* is 2.7 Mgm^{-3}, which is comparable to that of pure aluminum. The specific strength, Young's modulus, and fatigue strength of *ULMat* are 257 MPa/Mgm^{-3}, 75 GPa, and 280 MPa, respectively. The fatigue ratio of *ULMat* is higher than that of conventional high-strength aluminum alloys.

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