The Effect of Al Content on Tensile and Fatigue Properties of Solution-Treated and Quenched Ti-13Cr-1Fe Alloys

Michiharu Ogawa¹, Tetsuya Shimizu¹, Toshiharu Noda¹ and Masahiko Ikeda²

¹Research & Development Lab., Daido Steel Co., Ltd., Nagoya 457-8545, Japan

²Department of Materials Science and Engineering, Faculty of Engineering, FSC, Kansai University, Suita 564-8680, Japan

The effect of Al content on tensile and fatigue properties of Ti-13Cr-1Fe alloys was investigated by measurement of electrical resistivity and Vickers hardness, X-ray diffractometry (XRD), and tensile and fatigue tests. Only β reflection was detected by XRD in all alloys quenched from 1173 K. Resistivity at room and liquid nitrogen temperatures increased monotonically with Al content. Vickers hardness slightly increased with Al content up to 4.5 mass%. In 6.0 mass%Al, the Vickers hardness increased dramatically. In 0 mass%Al and 3.0 mass%Al, the tensile strength (σ_B) and 0.2% proof stress ($\sigma_{0.2}$) remained almost constant. Above 4.5 mass%, σ_B and $\sigma_{0.2}$ increased with increasing Al content. S-N curves in high cycle fatigue test of 0 mass%Al and 3.0 mass%Al showed almost the same behavior. The stress at 10^7 cycles, i.e. the fatigue strength, was around 460 MPa. [doi:10.2320/matertrans.48.390]

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1. Introduction

In countries like the UK, France, and Japan, the elderly population increases every year.¹⁾ In particular, in Japan, the proportion of the elderly population surpassed 20% in 2005. Thus, it is very important to develop welfare goods with higher performance, such as wheelchairs, for elders. This requires the development of new materials, especially metallic materials having higher performance, higher specific strength, higher corrosion resistance, good biocompatibility²⁾ and reasonable cost. One attractive class of metallic materials is titanium and its alloys owing to their high specific strength and corrosion resistance and good biocompatibility. Unfortunately, their high cost constitutes a barrier to the use of titanium alloys in welfare goods. Thus, it is important to develop reasonably low-cost titanium alloys. To lower the cost β titanium alloys, low-cost alloying elements such as Cr and Fe, and 2nd grade sponge titanium, have been employed. So far, Ti-13 mass%Cr-1 mass%Fe alloy has been developed as a promising candidate alloy substituting for conventional β titanium alloys.³⁾ Unfortunately, it has high possibility that this system alloys become brittle through isothermal ω precipitation.⁴⁾ It is well-known that Al addition to β titanium alloys suppresses isothermal ω precipitation and have an effect of solution-hardening. Therefore, it is important to investigate that the influence of Al content on mechanical properties of Ti-Cr-Fe system.

In the present study, the effect of Al addition on the tensile and fatigue properties of Ti-13Cr-1Fe alloys quenched from a temperature within the β phase region were investigated to compare the mechanical properties of the present alloys with those of commercial β titanium alloys.

2. Experimental Procedures

The alloys were prepared by a levitation furnace using sponge titanium, chromium, ferro-chromium alloy and aluminum as raw materials. The roughly 10 kg ingots obtained were hot-forged at about 1323 K into about 20 mm

Table 1 Alloy marks and chemical compositions of alloys used in this study.

Alloy marks	Chemical composition (mass%)					
	Cr	Fe	Al	C	N	O
0Al	12.6	1.21	<0.01	0.009	0.008	0.074
3.0Al	12.7	1.19	2.98	0.009	0.007	0.072
4.5Al	12.6	1.18	4.47	0.008	0.006	0.063
6.0Al	13.1	1.37	6.17	0.007	0.005	0.062

Fig. 1 The shapes and dimensions of tensile and fatigue testing specimens.

diameter round bars. The alloy marks and chemical compositions are shown in Table 1. All specimens were prepared from the hot-forged round bars by cutting, grinding and polishing. The shapes and dimensions of tensile and fatigue testing specimens are shown in Fig. 1. Once they were sealed into quartz tubes, all specimens were solution-treated at 1173 K for 3.6 ks and then quenched in water by immersing the tubes in water and immediately breaking the tubes. The tensile and fatigue test samples were also solution-treated at

Fig. 2 X-ray diffraction profiles in the STQed state.

1173 K for 3.6 ks and then quenched in water. This solution treatment will hereafter be abbreviated as STQ. In STQed specimens, the electrical resistivity at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}) and Vickers hardness (HV) were measured. The phase constitution was identified by X-ray diffractometry (XRD). Microstructures were observed by optical microscopy. Tensile tests were performed at room temperature. The fatigue test was performed by rotating the bending-type fatigue testing machine at a rotation speed of 2600 rpm.

3. Results and Discussion

Figure 2 shows X-ray diffraction profiles in the STQed state. In all STQed specimens, XRD revealed only β reflection. Figure 3 shows optical micrographs in the STQed state. A recrystallized structure was observed. The grain size of 0Al to 6.0Al was almost the same, i.e. about 300 μm .

Figure 4 shows the variation with Al content of the resistivity at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}), the resistivity ratio (ρ_{LN}/ρ_{RT}), and the Vickers hardness (HV) in the STQed state. Resistivity at room and liquid nitrogen temperatures increased monotonically with Al content. These increases were due to the dissolution of Al in matrix. The resistivity at liquid nitrogen temperature was higher than that at room temperature. The resistivity ratios increased with increasing Al content up to 3.0 mass% and then decreased with increasing Al content. It was reported⁵⁾ that the selected area electron diffraction (SAED) patterns changed with increasing Al addition. According to the report, weak diffuse scattering reflections which were attributed to athermal ω were observed in Ti-13 mass%Cr-1 mass%Fe and Ti-13 mass%Cr-1 mass%Fe-3 mass%Al, and it didn't exist in Ti-13 mass%Cr-1 mass%Fe-6 mass%Al, higher Al content alloy. Those results imply that the volume fraction of athermal ω decreases with increasing α stabilizing elements, e.g. Al in the β phase. Furthermore, it is thought that the reason the resistivity ratio of β titanium alloys decreases is due to decrease of volume fraction of athermal ω .⁶⁻⁸⁾ It is considered that athermal ω is not observed by XRD because

Fig. 3 Optical micrographs in the STQed state.

the volume fraction of athermal ω is too low to detect it. The same phenomenon is observed in Ti-V-Al alloys.⁶⁾ It has been reported that with increasing Al addition, the starting temperature of athermal ω formation is lowered and the volume fraction of athermal ω at room temperature is reduced.⁶⁾ Vickers hardness slightly increased with Al content up to 4.5 mass%. In 6.0 mass%Al, the Vickers hardness increased dramatically. It is considered that cause of hardness change is due to change in balance between

Fig. 4 The variation with Al content of the resistivity at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}), the resistivity ratio (ρ_{LN}/ρ_{RT}) and the Vickers hardness (HV) in the STQed state.

Fig. 5 The variation with Al content of the tensile strength (σ_B), 0.2% proof stress ($\sigma_{0.2}$), elongation (δ) and reduction in area (ϕ) in the STQed state.

decrease of hardness with decreasing of athermal ω and increasing of solution-hardening with Al addition.⁹⁾

Figure 5 shows the variation with Al content of the tensile strength (σ_B), 0.2% proof stress ($\sigma_{0.2}$), elongation (δ) and

Fig. 6 SEM micrographs of fracture surfaces after tensile testing.

reduction in area (ϕ) in the STQed state. In 0Al and 3.0Al, σ_B and $\sigma_{0.2}$ remained almost constant. In the 0Al, σ_B and $\sigma_{0.2}$ were roughly 930 and 900 MPa, respectively. The δ and ϕ of the 0Al were about 20% and 60%, respectively. Above 4.5 mass%, σ_B and $\sigma_{0.2}$ increased with Al content. The increase in both was due to the solution-hardening by Al. The δ and ϕ of both 0Al and 3.0Al remained almost constant up to 4.5Al. In the 6.0Al, σ_B and $\sigma_{0.2}$ increased slightly, while δ and ϕ decreased slightly. These alloys in STQed state show good balance between strength and ductility. For example, the σ_B , δ and ϕ of Ti-22%V-4%Al, a commercial β titanium alloy, are about 760 MPa, 22% and 65%.¹⁰⁾ Figure 6 shows SEM micrographs of fracture surfaces after tensile testing. Dim-

ples were observed in all specimens. The fracture surfaces of these specimens were almost entirely covered with dimples whose shape and size hardly varied with alloy composition.

Figure 7 shows S-N curves of high cycle fatigue test. S-N curves of 0Al and 3.0Al exhibited almost the same behavior, and the fatigue limit of these alloys was almost the same value. Above 4.5 massAl%, S-N curves slightly shifted toward low stress. To reveal cause of change of S-N curve, a further investigation about fatigue test is necessary. The stress at 10^7 cycles, i.e. the fatigue strength of 0Al, was around 460 MPa. For example, the stress at 10^7 cycles of Ti-22%V-4%Al alloy was reported to be around 300 MPa.¹¹⁾ Figure 8 shows SEM micrographs of fracture surfaces of 0Al to 6.0Al after fatigue testing. The fatigue crack initiation site was observed at near surface. From Fig. 4, it is considered that volume fraction of athermal ω of 3.0Al is lower than that

Fig. 7 S-N curves of high cycle fatigue test.

0Al 466MPa 5.31x10 ⁴ cycles	2mm	100 μ m
3.0Al 461MPa 7.43x10 ⁴ cycles	2mm	100 μ m
4.5Al 431MPa 10.92x10 ⁴ cycles	2mm	100 μ m
6.0Al 422MPa 85.56x10 ⁴ cycles	2mm	100 μ m

Fig. 8 SEM micrographs of fracture surfaces of 0Al to 6.0Al after fatigue testing.

of 0Al. However, tensile and fatigue properties of 3.0Al were almost the same as those of 0Al. Thus, it is considered that athermal ω hardly influences the tensile and fatigue properties in alloys below 3.0Al.

4. Conclusions

The effect of Al content on tensile and fatigue properties of Ti-13Cr-1Fe alloys was investigated by measurement of electrical resistivity and Vickers hardness, X-ray diffractometry (XRD), and tensile and fatigue tests. Only β reflection was detected by XRD in all alloys quenched from 1173 K. Resistivity at room and liquid nitrogen temperatures increased monotonically with Al content. Vickers hardness slightly increased with Al content up to 4.5 mass%. In 6.0 mass%Al, the Vickers hardness increased dramatically. In 0 mass%Al and 3.0 mass%Al, the tensile strength (σ_B) and 0.2% proof stress ($\sigma_{0.2}$) remained almost constant. Above 4.5 mass%, σ_B and $\sigma_{0.2}$ increased with increasing Al content. S-N curves in high cycle fatigue test of 0 mass%Al and 3.0 mass%Al showed almost the same behavior. The stress at 10^7 cycles, i.e. the fatigue strength, was around 460 MPa.

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