Title	Microstructure in Weld Heat-affected Zone of Beta Titanium Alloy(Materials, Metallugy & Weldability)
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Citation	Transactions of JWRI. 1990, 19(1), p. 79-86
Version Type	VoR
URL	https://doi.org/10.18910/12078
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Microstructure in Weld Heat-affected Zone of Beta Titanium Alloy†

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Abstract

Relation between microstructure and hardness of β titanium Ti-15V-3Cr-3Sn-3Al alloy and its welds was investigated by means of transmission electron microscopy and X-ray diffraction technique.

As the aged Ti-15V-3Cr-3Sn-3Al alloy was welded by using DCSP-TIG welding procedure, the decrease of the hardness occurs in the heat-affected zone, because of the solution of α phase. The hardness in the weld heat-affected zone is considerably higher than that of the base metal, as the welded sample was aged at 773K after welding. This phenomena was mainly due to the increase of the precipitation amounts of fine α phase.

Maximum hardness after aging treatment increases with increasing solution treatment temperature. The precipitation of α phase occurs, as the specimens were aged at 573K, 673K and 773K after solution treatment. The precipitation amount of α phase increases with increasing solution temperature.

The increase of the solution treatment temperature also causes the decrease of the lattice parameter αc_0 during aging by X-ray diffraction technique, and causes homogeneous precipitation and fine precipitation of α phase during aging by means of transmission electron microscopy.

KEY WORDS : (Beta titanium alloy) (HAZ) (Microstructure) (X ray diffraction) (Transmission electron microscopy) (Solution temperature) (Age hardening)

1. Introduction

β titanium alloy such as Ti-15V-3Cr-3Sn-3Al has been characterized by a good formability in a solution treatment conditon[1,2], which consisting of β phase in microstructure. Consequently, complicated shapes and forms can be easily performed in low costs for requests of users and planners. In this alloy, α phase precipitates in the β phase and high hardness can be obtained, as the aging treatment after solution treatment was carried out. As a result, the aged β titanium alloy can have ultra high tensile strength of 1.4GPa[1]. Then this alloy is noteworthy as materials for airplane and aerospace structural applications.

The other way, as the aged β titanium alloy was welded, the strength of the heat-affected zones becomes lower than that of the base metal[3,4].

Generally, β titanium alloy solution-treated hardly occured hydrogen induced cracking[5], because of the high solution content of hydrogen in the β phase. But, the aged β titanium alloy has consisting of α + β micro-structure such as Ti-6Al-4V alloy. Consequently, it is expected that hydrogen induced cracking may occurs.

In this paper, the microstructure of the weld heat-affected zone of aged β titanium Ti-15V-3Cr-3Sn-3Al alloy has investigated and the relation between microstructure and hardness was evaluated by means of X-ray diffraction techniques and transmission electron microscopy. And the mechanism of age hardening was discussed.

2. Experimental procedures

Ti-15V-3Cr-3Sn-3Al alloy plate was received in a solution state. The thickness was 5 mm, the chemical compositions are shown in **Table 1**. Welding was carried out using DCSP TIG by bead-on-plate condition. In order to discuss the age hardening mechanism, the heat treatment was carried out, which was performed in a vacuum furnace. The specimens were heated at 1073K to

Table 1 Chemical compositions of Ti-15V-3Cr-3Sn-3Al alloy(mass%)

V	Cr	Sn	Al	Fe	O	N	H
15.27	3.05	3.03	3.06	0.165	0.112	0.0055	< 0.0010

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

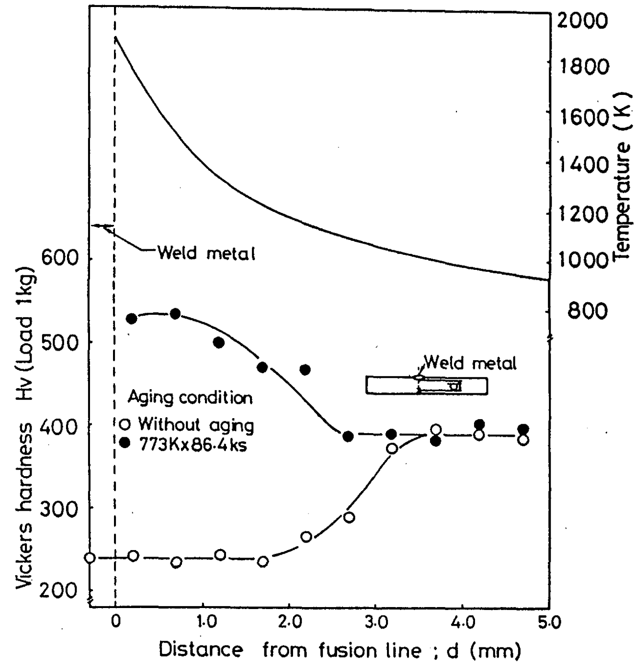
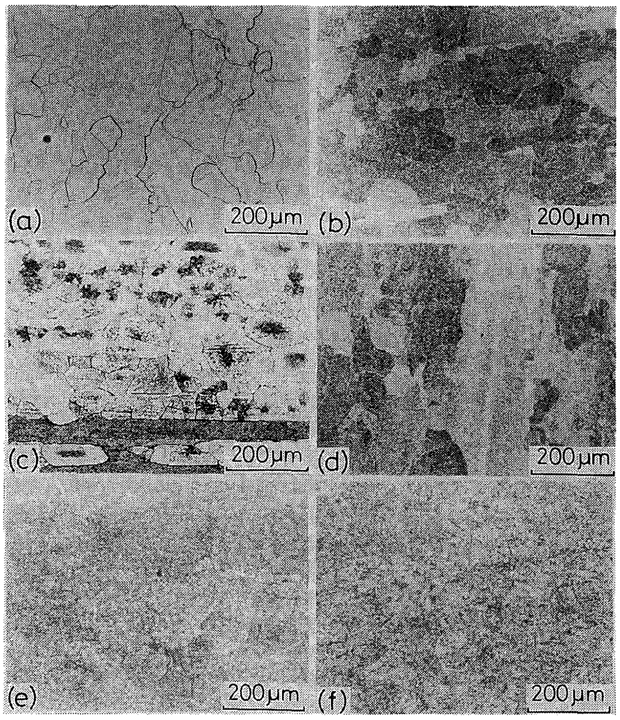


Fig. 1 Hardness distributions of as-welded sample and aged sample after welding for Ti-15V-3Cr-3Sn-3Al alloy.



(a): 1 mm from fusion line (As weld),
(b): 1 mm from fusion line (Aging),
(c): 2.5 mm from fusion line (As weld),
(d): 2.5 mm from fusion line (Aging),
(e): Base metal (As-weld),
(f): Base metal (Aging).

Fig. 2 Optical microstructures of weld heat-affected zone of as-welded sample and aged sample after welding.
Aging condition: 773K, 86.4ks.

1573K for 3.6ks, water quenched, and then aged at 573K, 673K and 773K for various times. The microstructure was studied using transmission electron microscopy, the specimen was prepared by jet polishing in electrolyte consisting of perchrolic acid, butyl alchol and methanol at 14.5V and below 233K. The precipitation amount and size of the α phase was evaluated by the volume fraction and lattice parameter using X-ray diffraction technique with Cu radiation filtered by Ni.

3. Results and Discussion

3.1 Microstructure and hardness distribution of weld heat affected zone.

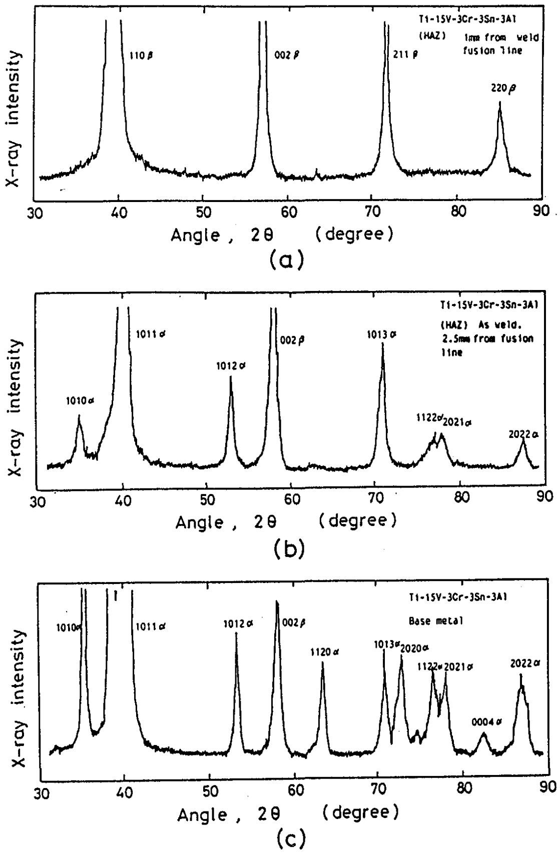
Generally, β titanium alloy has been aged at 773K after solution treatment at 1073K and obtained high strength[6-9]. In this study, the samples prior welding were solution-treated at 1073K for 3.6ks, water quenched and then aged at 773K for 86.4ks.

Figure 1 indicates the hardness distributions of the weld heat-affected zones, as the samples were welded and aged after welding. For as-welded sample, the hardness of the base metal is Hv 400 and the hardness decreases with approaching near the fusion line. The hardness near the fusion line is low such as Hv 230. The softening zone may causes cracks and fracture, if the weldment was applied tensile stress. Then, the welded samples were aged at 773K for 86.4ks after welding. As the results, the hardness in the heat-affected zone becomes very high in comparison with that of the base metal. Especially, the hardness in the region near the weld fusion line is Hv 530.

Figure 2 indicates optical microstructures of the weld heat-affected zone of as-welded sample and aged sample after welding. For the base metal shown in Fig. 2-(e), fine α phases are present in the β phase. For the region of 2.5 mm from the fusion line as shown in Fig. 2-(c), α phases observed as dark particles are partially solutionized. For the region of 1 mm from fusion line as shown in Fig. 2-(a), α phase are fully solutionized. Consequently, the softening zone in weld heat-affected zone is considered to have occured due to the solution of α phase.

As the welded samples were aged at 773K for 86.4ks, the microstructures are consisting of fine α phase in the β phase at any region. As shown in Fig. 1, the hardness of the sample aged after welding in the heat-affected zone is higher than that of the base metal. In order to evaluate this cause, X-ray diffraction technique was carried out and the volume fraction of α phase and the lattice parameter were measured.

Figure 3 shows X-ray diffraction patterns in the heat-affected zone of as-welded sample. For the base metal



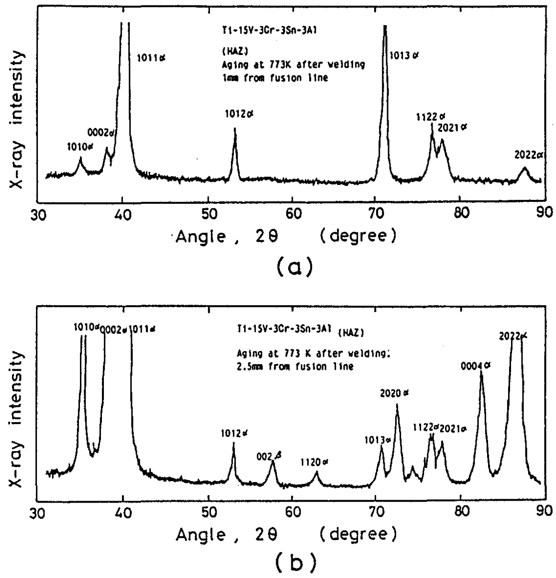
(a): 1 mm from fusion line.
(b): 2.5 mm from fusion line.
(c): Base metal.

Fig. 3 X-ray diffraction patterns of as-welded sample.

shown in Fig. 3-(c), the peaks due to 200_β and many peaks generated due to the α phase. For the region of 2.5 mm from fusuion line, the peak height of α phase decreases. For the region of 1 mm from fusion line, the peak due to α phase precipitation is hardly observed, and the peaks due to β phase are observed more.

Figure 4 shows X-ray diffraction patterns in the heat-affected zone of aged samples after welding. For any region, the diffraction peak due to the α phase are observed much, it means that α phase precipitates in the β phase by the aging treatment. In these diffraction patterns, the volume fractions of α phase were measured on the basis of integrated intensity of the peak 1012_α, or 1120_α and 002_β.

Figure 5 indicates the volume fraction of α phase by X-ray diffraction technique in the weld heat-affected zones for as-welded samples and aged samples after welding. In this figure, "without aging" sample shows as-welded sample, and "773K for 86.4ks aging" sample shows aged sample after welding. For as-welded sample without aging, the volume fraction of α phase is about 35%, and that of the β phase is about 65%. For the



(a): 1 mm from fusion line.
(b): 2.5 mm from fusion line.

Fig. 4 X-ray diffraction patterns of aged sample after welding.

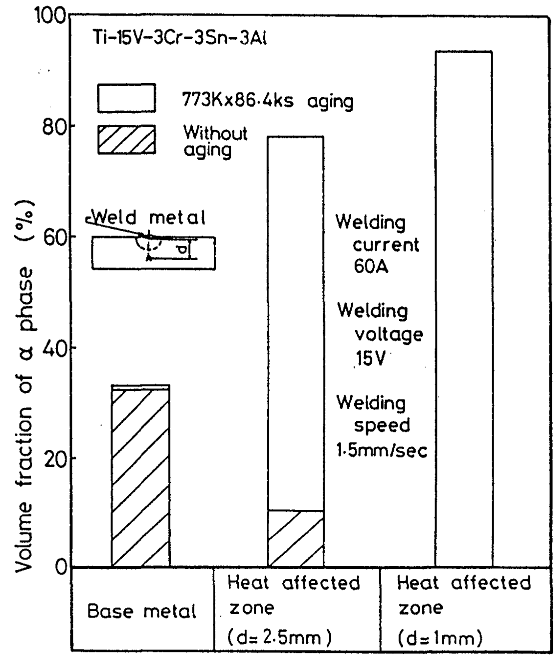


Fig. 5 Volume fraction of α phase in weld heat-affected zone for as-welded samples and aged samples after welding.

region 2.5 mm from fusion line, the volume fraction of α phase is about 10%. For the region 1 mm from fusion line, α phase are fully solutionized and the volume fraction of β phase is near 100%.

For as-welded sample, the hardness decrease in the weld heat-affected zone as shown in Fig. 1 is considered to be due to the solution of the α phase in the β phase. In case of the sample aged at 773K for 86.4ks after welding, the volume fraction of α phase in the heat-affected zone becomes higher than that of the base metal. Consequently, the hardness mainly depends on the volume fraction of α phase.

Figure 6 indicates lattice parameters in the weld heat-affected zones for as-welded samples and aged samples after welding. In case of as-welded samples without aging, lattice parameters of $\alpha\, c_0$ and $\alpha\, a_0$ at 2.5 mm from fusion line are higher a little than that of the base metal. It means that the partial solution of the α phase causes the increase of the parameters $\alpha\, c_0$ and $\alpha\, a_0$. In case of aged samples with 773K for 86.4ks aging, the lattice parameter of $\alpha\, c_0$ and $\alpha\, a_0$ in the heat-affected zone is lower than that of the base metal. Consequently, the increase of the hardness in the heat-affected zone for aged sample after welding is considered to be due to the decrease of the $\alpha\, c_0$ and $\alpha\, a_0$.

For the lattice parameter of the β phase $\beta\, a_0$, the parameter increases with increasing solution of α phase in the heat-affected zone of as-welded sample without aging. And the parameter, $\beta\, a_0$ decreases with increasing precipitation of α phase. Consequently, the precipitation or solution behavior of the α phase causes the change in the lattice parameters such as $\alpha\, a_0$, $\alpha\, c_0$ and affects the change in the lattice parameter, $\beta\, a_0$.

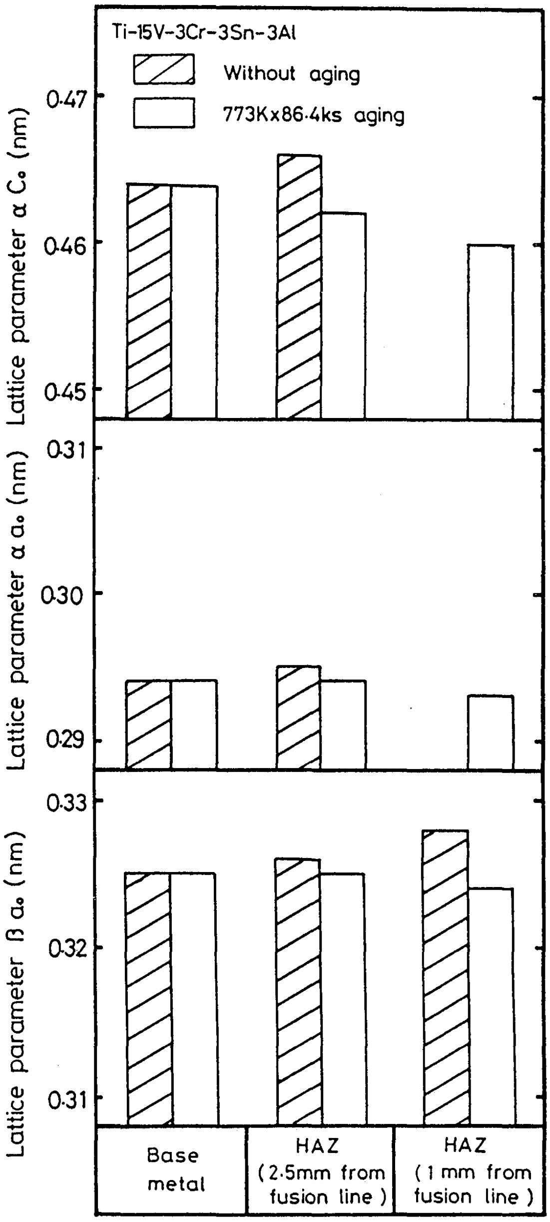


Fig. 6 Lattice parameters in weld heat-affected zones for as-welded samples and aged samples after welding.

3.2 Effect of solution temperature on age hardening characteristics

In the 3.1 section, it was shown that age hardening characteristics is extremely accelerated in the weld heat-affected zone, especially bond region, by the aging treatment at 773K after welding. In this section, the effect of solution treatment temperature on age-hardening characteristics was investigated in details.

Figure 7 indicates the relation between hardness and aging time, as the specimens were solution-treated at 1073K, 1273K and 1573K for 3.6ks, water quenched, and then aged at 573K, 673K and 773K for various times. The hardness increases with increasing aging time for any

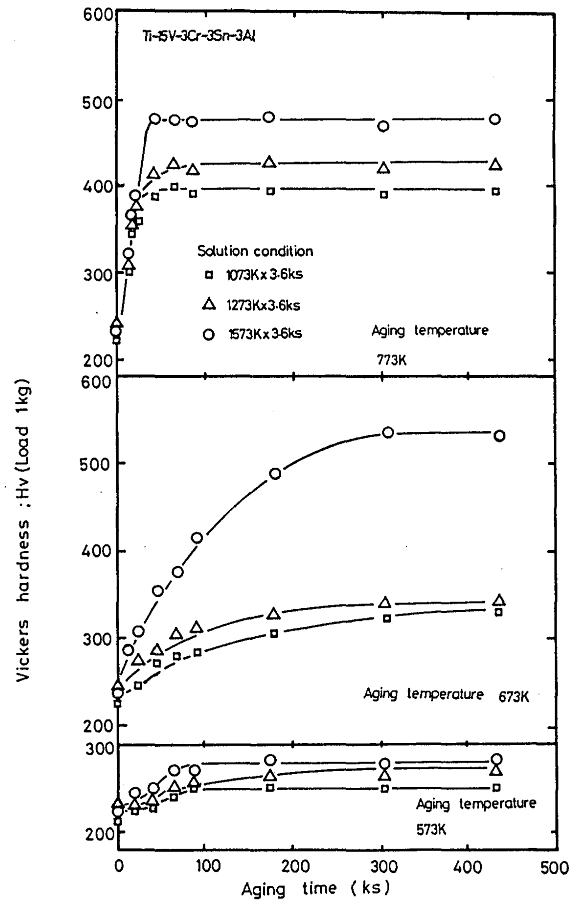


Fig. 7 Relation between hardness and aging time.

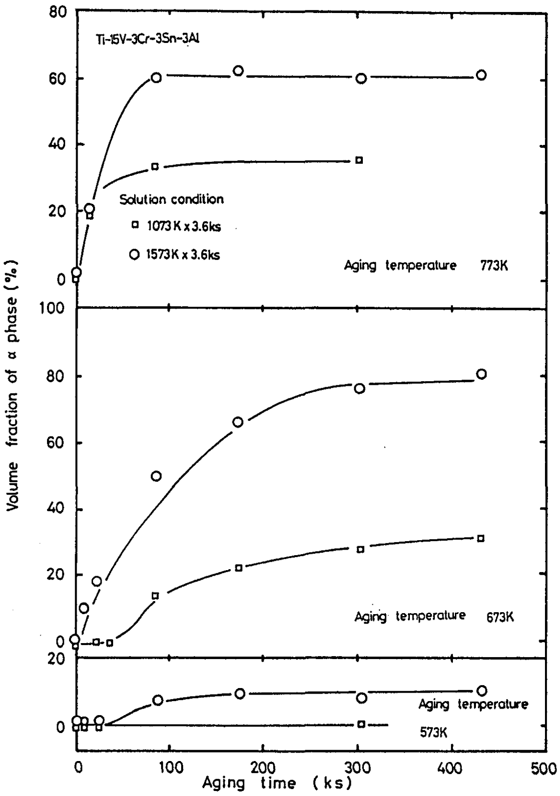


Fig. 8 Relation between volume fraction of α phase and aging time.

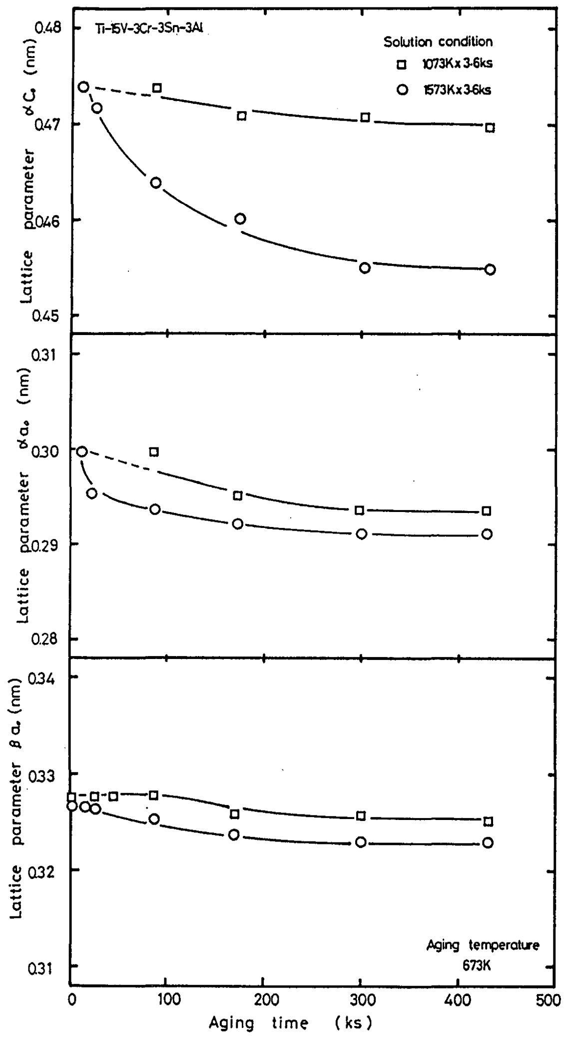


Fig. 9 Relation between lattice parameter and aging time at 673K.

solution temperature and aging temperature.

For the aging temperature at 573K, the effect of solution temperature on age hardening characteristics is hardly recognized. For the aging temperature at 673K, the hardness remarkably increases with increasing aging time for the specimens solution-treated at 1573K. For the aging temperature at 773K, the hardness is remarkably high for the specimens solution-treated at 1573K. The age hardening rate is high at the aging temperature of 773K. Thus, the solution temperature strongly affects the age hardening characteristics. The age hardening characteristics are accelerated with increasing solution temperature, and the age hardening finishes up to 50ks of aging time and after that, the hardness remains a constant value.

Figure 8 indicates the relation between volume fraction of α phase and aging time, by means of X-ray diffraction technique. The volume fraction of α phase increases with increasing aging time at any solution temperature and aging temperature. The precipitation rate of α phase for the specimens solution-treated at 1573K is higher than that at 1073K at any aging temperature. For the specimen aged at 773K, the volume fraction of α phase for the specimen solution-treated at 1573K is about 60%, in comparison with that for the specimen solution-treated at 1073K, which is about 30%. Thus, the solution treatment temperature is accelerates the precipitation of α phase, namely causes the increase of the volume fraction of α phase. In these three aging temperatures, the precipitation rate of α phase is highest at the aging temperature of 773K. The precipitation characteristics of α phase in Fig. 8 is corresponded to the age hardening characteristics. Consequently, the volume fraction of α phase affects strongly the increase of the hardness. The solution treatment temperature also affects the precipitation rate at the aging process. The volume fraction of α phase shows total precipitation amount of the α phase, the size and shape of the α phase is not considered. Then, the concept of the lattice parameter was introduced. Lattice parameter of α phase is shown by the αa_0 and αc_0. αa_0 is lattice parameter on the basal plane, and αc_0 is the lattice parameter in the prismatic plane. The size of the lattice can be evaluated by the lattice parameter.

3.3 Effect of solution temperature on α and β lattice parameters during aging.

Figure 9 indicates the relation between lattice parameter and aging time at 673K. The lattice parameters decreases with increasing aging time at any solution temperature. In case of the lattice parameter αc_0, the lattice parameter for the specimen solution-treated at 1573K is lower than that at 1073K. α phase is consisting of h.c.p. structure, the c axis is contracted by the aging treatment.

Generally, interstitial atoms such as hydrogen, nitrogen and oxygen are introduced in the lattice, the lattice parameter always increases. But, as shown in Fig. 9, the lattice parameter decreases with increasing aging time. This means that substitutional atoms replaces with Ti atoms in the α lattice. In this alloy, various elements are contained, that is, Sn, Al and Cr are α stabilized elements, and V is a β stabilized element. These elements are replaced with Ti atoms as substitutional atoms. Generally, the lattice expands or contracts by the size of substitutional atoms. The discussion will be made in another report.

As the solution treatment temperature is high, vacancy concentration in equilibrium is high, the vacancies at the room temperature remain vacancy concentration at the solution treatment temperature by rapid cooling. Then, vacancy concentration is high, the precipitation nucleation increases, and the precipitation of the α phase is accelerated. The phenomena is shown in Fig. 8. But, concerning lattice parameter, vacancy concentration contracts the αc_0 lattice parameter. Consequently, an interaction of vacancy and substitutional atoms must be considered, for example, binding energy of vacancy and

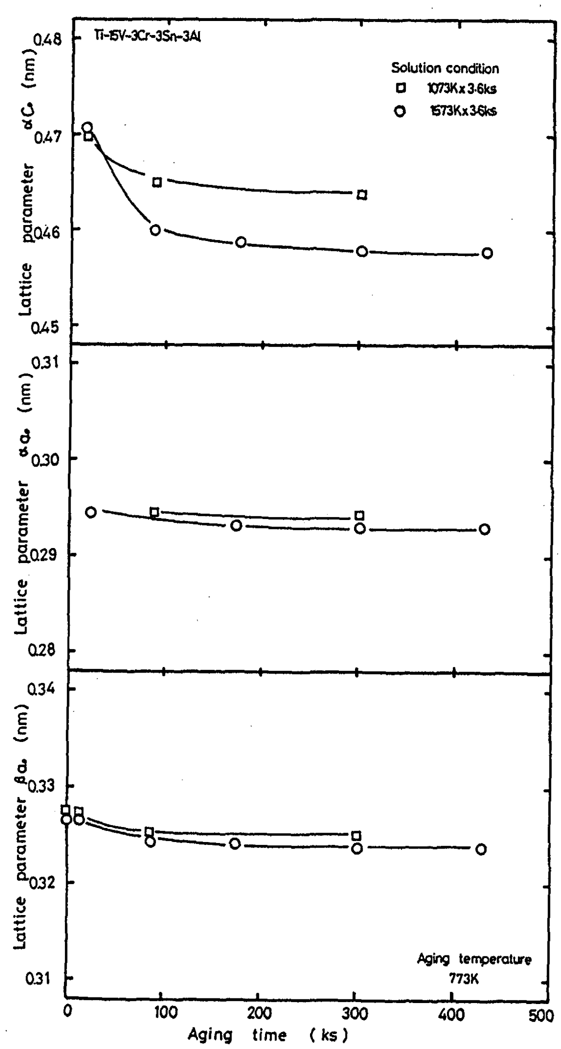


Fig. 10 Relation between lattice parameter and aging time at 773K.

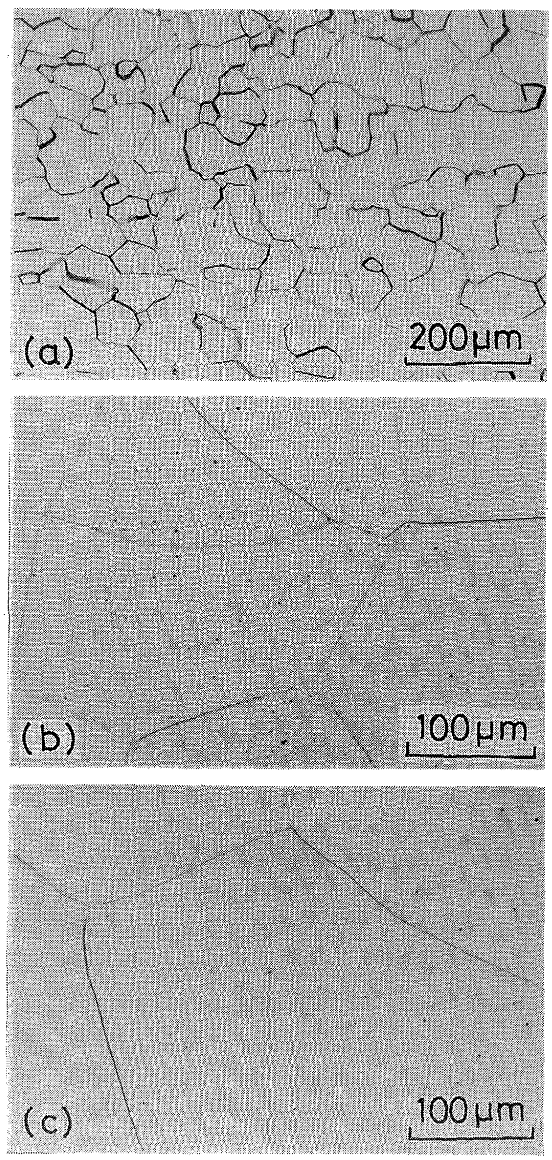


Fig. 11 Optical microstructures for the specimens solution-treated at 1073K(a), 1273K(b) and 1573K(c).

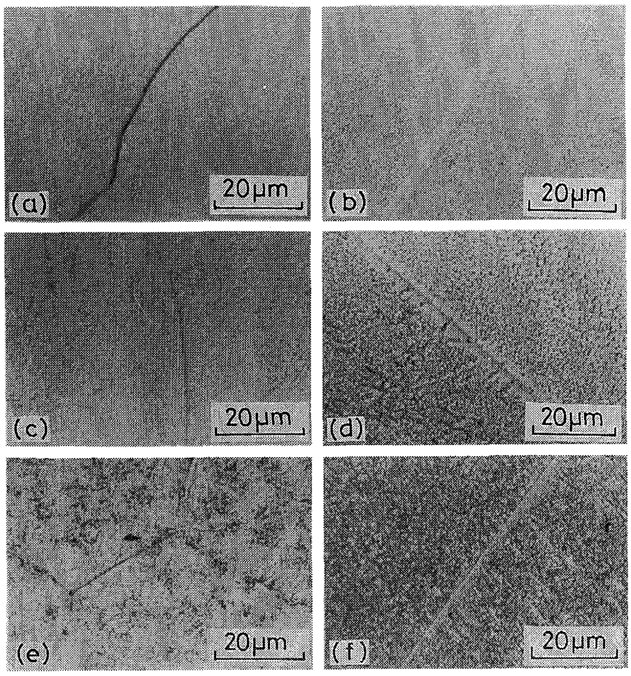


Fig. 12 Optical microstructures for the specimens solution-treated at 1073K(a), (c), (e) and 1573K(b), (d), (f), and aged at 673K for various times.
(a), (b): 21.6ks aging, (c), (d): 86.4ks aging, (e), (f): 302.4ks aging.

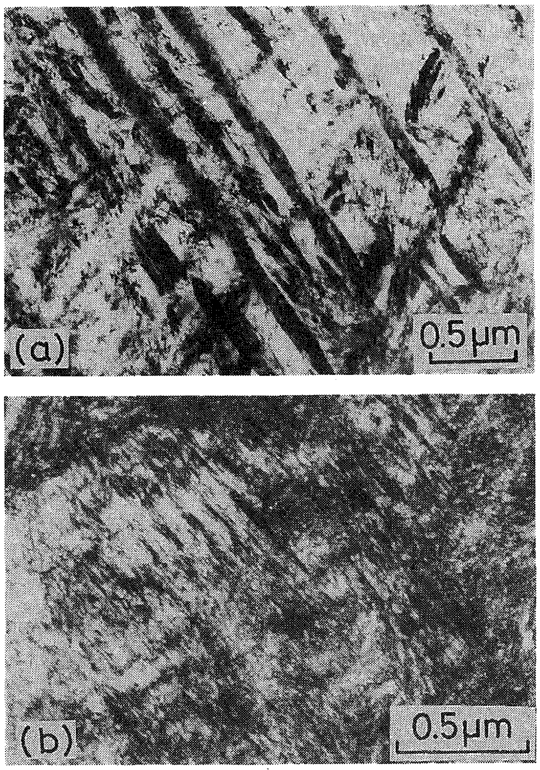


Fig. 13 Transmission electron micrographs of the specimens aged at 773K for 86.4ks(a) and 673K for 302.4ks(b) after solution treatment at 1573K.

substitutional atoms.

Figure 10 indicates the relation between lattice parameter and aging time at 773K. The decrease of the lattice parameter occurs at the short aging time. The effects of the solution treatment temperature on the decrease of the lattice parameter is small at 773K. This phenomena is dependent on the vacancy concentration in equilibrium at 773K and 673K aging. As the difference concentration between vacancy concentration in equilibrium at the aging temperature and that at solution treatment temperature, is high, the precipitation will be accelerated. Consequently, the increase of the aging temperature decrease the effect of the solution temperature. The other way, the lattice parameter of α phase, $\alpha\ a_0$ decreases with increasing aging temperature.

3.4 Effect of solution and aging temperature on precipitation morphology of α phase during aging.

Figure 11 shows optical microstructures for the specimens solution-treated at 1073K, 1273K and 1573K. The grain size increases with increasing solution treatment temperature. The microstructure is only β phase.

Figure 12 shows optical microstructures for the specimens solution-treated at 1073K and 1573K, and aged at 673K for various times. For the specimen solution-treated at 1073K, as shown in Fig. 12-(a), (c), (e), the precipitation of α phase is very little, large amounts of β phase remain in the microstructure. As shown in Fig. 12-(e), the large sizes of the α phase precipitate heterogeneously for prolonged aging time. The other way, for the specimen solution-treated at 1573K as shown in Fig. 12-(b), (d), (e), fine α phase precipitates more with increasing aging time. The width of the precipitation free zones(PFZ) is narrow in comparison with that at solution treatment of 1073K. It seems that vacancy concentration at 1573K is higher than that at 1073K. As shown in Fig. 12-(f), very small sizes of α phase precipitates homogeneously. Consequently, the increase of the solution treatment temperature causes tha increase of the nucleation sites of the precipitates, and causes the homogeneous precipitation, because of the high vacancy concentration[10].

Figure 13 shows transmission electron micrographs of the specimens aged at 773K(a) and 673K(b) after solution treatment at 1573K. The increase of the aging temperature causes the increase of the lath size of α phase, and causes the decrease of the hardness. The lath size is large and the amount of α phase is little for the specimen aged at 773K. But, the decrease of the aging temperature causes the increase of fine α phase precipitation and the increase of the amount of the precipitates. These factors affect the increase of the hardness strongly.

4. Conclusions

Relation between microstructure and hardness of β titanium Ti-15V-3Cr-3Sn-3Al alloy and its welds was investigated by means of transmission electron microscopy and X-ray diffraction technique. The results obtained in the present investigation are summarized as follows.

(1) As the aged Ti-15V-3Cr-3Sn-3Al alloy was welded by using DCSP-TIG welding procedure, the decrease of the hardness occurs in the heat-affected zone, because of the solution of α phase, which was based on the evaluation of the volume fraction of α phase by X-ray diffraction.

(2) The hardness in the weld heat-affected zone is considerably higher than that of the base metal, as the welded sample was aged at 773K after welding. This phenomena was mainly due to the increase of the precipitation amounts of fine α phase.

(3) Maximum hardness after aging treatment increases with increasing solution treatment temperature. The precipitation of α phase occurs, as the specimens were aged at 573K, 673K and 773K after solution treatment. The precipitation amount of α phase increases with increasing solution temperature. The hardness mainly depends on the precipitation amount of α phase, namely the volume fraction of α phase.

(4) The increase of the solution treatment temperature also causes the decrease of the lattice parameter αc_0 during aging by X-ray diffraction technique, and causes homogeneous precipitation and fine precipitation of α phase during aging by means of transmission electron microscopy.

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