NRIM SR-93-01

R&D of Structural Intermetallic Compound TiAl

by

Tokuzou TSUJIMOTO

NRIM Special Report
(Research Report)
No. 93-01

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Contents

Part I General Remarks

Part II Particulars

Part III Concluding Remarks

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Abstruct

NRIM is well known in the world as a research institute which has triggered the present active R & D for light heat-resisting TiAl-base alloys and which has continued to be one of excellent nuclei for progress of this material field up to date. This overview describes how NRIM surmounted for the first time two principal drawbacks of TiAl, deficiency of room temperature ductility and difficulty of hot working and how NRIM has brought out fascinating properties and multifarious potentialities of TiAl-base alloys. The main subjects are improvement of room temperature ductility by composition adjustment, especially addition of manganese; development of isothermal forging techniques issued from study on deformation properties at high temperatures; microstructure control by heat treatment and thermomechanical treatment; superplasticity occurring in TiAl alloys with fine equiaxed $\alpha+\gamma$ structure which is obtained by elaborate thermomechanical treatment; development of handy melting process by means of a high frequency vacuum furnace using Ca0 crucibles.

Keywo: *Intermetallic compound TiAl, Alloy design, Room temperature ductility, Hot working, Alloying, Microstructure control, heat treatment, Thermomechanical treatment, Superplasticity, Twin deformation*

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Part I General Remarks

1. Introduction

This overview describes a research on TiAl-base alloys done in National Research Institute for Metals (hereinafter referered to as NRIM). Here, TiAl is the intermetallic compound which had not regarded as a structural material until about 10 years ago. This research was begun in 1978 and has been still in progress as an important research project in NRIM. At the biginning of this research nobody expected that the compound TiAl would have become an important substance as a light heat-resisting material after the decade except researchers in NRIM. This venturous research in NRIM, however, has yielded a number of important results which open up possibilities of TiAl as a structural material. The results obtained at the early stage of the study gave a strong impact on researchers who had known limits of convertional metallic materials. Thus, a research boom for TiAl-base alloys (hereinafter abbreviated to TiAl alloys) occurred not only in Japan but also in the whole world, and TiAl alloys have regarded as a new material with which human beings can convert their dreams on technology into reality. At present, the research on TiAl alloys is becoming more active year by year and involving wider fields of science and technology.

Reports about TiAl alloys amount to a half of total papers for structural intermetallic compounds submitted at the meeting of Japan Institute of Metals. The reasons why the study on TiAl alloys is so prevalent are as follows. TiAl alloys has epoch-making characteristics as a light heat-resisting metallic material$^{1)}$. TiAl alloys are producible without any complicated equipment or processes, that is, in large scale with basically conventional equipment for metallic alloys. This implies that TiAl alloys have potentialities to be used widely as an industrial material. TiAl alloys afford a wide margin of aspiring research activities, because TiAl alloys belong to a new material of a green field full of new findings and originality.

Two kinds of works done in NRIM are described in details in Part II. One is how two serious drawbacks of TiAl, that is, deficienty of room temperature ductility and difficulty of hot working have been remedied. The other is recent important findings which have given further values for TiAl alloys. These are microstructure control by heat treatment and thermomechanical treatment, and occurrence of superplasticity. Other results are depicted briefly in Chapter 3.

In this overview, the intermetallic compound TiAl of the stoichiometric composition is seldom mentioned. The reason is that the materials used are always so designed upon the base of TiAl-phase as to get any merits in their properties, even in Ti-Al binary alloys. The abbreviated word "TiAl alloys" is used to represent "TiAl-base alloys". In this paper the TiAl alloys are distinguished from the compound TiAl. The word of "TiAl" is used when the original nature of the compound TiAl is described. In this paper the atomic percent is used to represent alloy composition.

2. Background of the Research

2.1 Historical position of the study

It was 1960's that the first attention was paid for properties of intermetallic compounds and active studies were made. The study of intermetallic compounds as structural material became out of vogue in 1970's, because any means to rectify brittleness of intermetallic compounds could not find$^{2)}$. At this period a peculiar property in plasticity of intermetallic compounds which is profitable as high temperature materials has been found. That is reverse temperature dependence of strength, and excellent articles studying causes of this abnormal behavior have been published$^{3-5)}$. These results, however, have been of academic value unless the brittleness is not improved. Such the situation was broken through by Aoki and Izumi in 1979$^{6)}$. They found that boron addition of a small amount made grain boundary brittleness of an intermetallic compound of Ni_3Al disappear at a stretch. This work has revived the hope of researchers on structural intermetallics, and has constituted an important factor for resurrecting active studies for these materials.

On the other hand, a comprehensive study for aluminides and silicides, especially TiAl alloys was carried out in the Air Force of USA from strong needs for high temperature materials of high performance. This semiempirical study was continued indefatigably from 1960 to 1986, and afforded us only a light for structural intermetallics of practical use especially in 1970's.

It was reported in 1956 by McAndrew and Kessler that TiAl has promising properties as a light heat-resisting material7). After that, TiAl alloys had been studied mainly for military use in the USA, as mentioned in the above paragraph. Especially, the research sponsored by the US Air Force from late in the 1970's to early in the 1980's was a large-scale project conducted in strict secrecy8). In this project model turbine-engines were made using TiAl alloys and were tested, which did not accomplish satisfactory results. Researches for TiAl alloys in the USA had been interrupted after this project, until Kim and Huang make the researches restart by influence of the research in NRIM. During this blank period studies for Ti_3Al alloys have become prevalent in the USA.

The research for TiAl alloys in NRIM was begun from 1978 and has been continued without any interruption up to date. Another contributor in around 1980 in Japan was Izumi's group of Research Institute for Iron, Steel and Other Metals of Tohoku University. They have found an interesting fact that TiAl single crystals display positive temperature dependence of flow stress9). However, the interest of this group had remained in the study of the mechanism about this abnormal plasticity in those days, because they had believed that the compound TiAl is too brittle to be regarded as a candidate of structural materials. After the progress of research for TiAl alloys in NRIM, this group has participated in development of TiAl alloys.

During the first half of the period where NRIM was only a main participant for alloy developement in Japan, NRIM has succeeded to relieve the drawbacks of TiAl alloys. With the progress of the research in NRIM the possibility was increased that TiAl alloys would be used on a large scale as an industrial material in future technology. Thus a research boom for TiAl alloys has begun in Japan from about 1984. This boom was conveyed to USA with some time lag, and then to Europe and China.

MRIM has continued to develop excellent characteristics and various processing techniques of TiAl alloys, and the research boom has grown prosperous year by year. As the consequence many research facilities and organizations have participated in the research of TiAl alloys. At present vast studies are being done in official research institutes, universities and private enterprises from basic researches to processing techniques, and furthermore for applying techniques for practical use.

Use of light heat-resisting TiAl alloys for parts of automobile engines and aircraft engines, or of electric generators will heighten the performance ability of these machines or equipment. Private enterprises are considered to make their efforts to put to practical application of TiAl alloys in these fields. Other application of TiAl alloys is for wings and fuselage of high-speed aircrafts and of space-vehicles. For the purpose of developing materials technology for the latter use, a national research project organized by the Agency of Industrial Science and Technology, MITI, was started in 1989. This project named "High performance materials for severe environments" is in progress as the 8-year plan.

Furthermore, a new national project named "Evaluation and analysis based on modeling for forecasting physical and chemical properties" has been begun from this year, which is organized by Science and Technology Agency (Hereinafter abbreviated to STA). In this project evaluation of properties in TiAl alloys are being studied, reflecting the fact that TiAl alloys has been becoming to the material of practical use.

2.2 Aim and progress of the study

The research in NRIM was begun with the author's own view. Why were the TiAl alloys chosen as the target of the research in 1978 in NRIM? One of the reasons is that the author had been interested in this compound during his research works on Ti-alloys about 10 years ago10), and had made some trials for the TiAl alloys. The other is that Aoki and Izumi have shown the first example of ductilizing a brittle intermetallic compound Ni_3Al by alloying6. This work has given the prospect that selected ones among other intermetallic compounds being brittle might be ductilized. Here, the selected ones mean intermetallic compound of metallic character as aluminides with simple crystal structure. If the ductilization could be achieved in a compound, in what compound would the highest merit be obtained as a high temperature material? It has been believed by the author that the TiAl alloy is the top candidate.

The research in NRIM has started from a preliminary experiment in a current research. In this experiment we have obtained an important indication that Ti-rich TiAl alloys may grow as a valuable heat-resisting material[11)]. The research scale has been enlarged to a specified research from 1981, and then to a special research from 1983 to 1987. At the initial stage of the special research it has been found that the room temperature ductility of TiAl alloys can be improved by Mn addition[12–16)]. At the later stage of the special research fundamental data which prove feasibility of isothermal forging have been accumlated[17)]. In this period our purpose was to make TiAl alloys grow up to a level under which we can aim at an industrial material. For this target we tried to bring out all latent possibilities of merits and to find any techniques getting around difficulties on processing.

During the period of the special research the research boom for TiAl alloys has occurred in Japan, and many researchers began to study TiAl alloys. Until those days NRIM was the trigger for this material. The incoming of the boom implied that the role of trigger had ended. NRIM had to change someone else.

In order to take a measure to meet the situation, a research group which studies mainly TiAl alloys has been built up in 1988 in NRIM, by assembling specialists of various research fields. This group has taken charge of the designated research "Production and character evaluation of functional intermetallic compound". After that, this group has been charged with the two national projects above mentioned. Under support of these funds and collabolation of the experts, NRIM has obtained a lot of valuable findings which had not been expected at the beginning stage of the research.

3. List of main results in NRIM

The research project in NRIM on TiAl alloys has progressed satisfactorily including various new findings up to date, and has obtained numerous results which are useful and well-known to the world. The chronicles of the main results reported by NRIM are listed in Table 1.

The first item in the table was the most important finding and the starting point for a full-scale study on TiAl alloys in NRIM[11)], because TiAl alloys had been believed to be too brittle for use as a structural material in those days. The obtained data are shown in Chapter 5.

It has become clear at the initial stage of the research that TiAl alloys can be handled with the same way as usual metallic materials. TiAl alloys are

Table 1. Chronological Results for TiAl-Base Alloys done by NRIM.

1. **Finding the fact that TiAl of low Al content is not so brittle at room temperature. (1980): The best composition is an alloy with about 48at%Al.**
2. **Reporting feasibility for machining. (1981)**
3. **Reporting a success in hot extrusion with lateral pressure. (1982)**
4. **Reporting on melting by vacuum high frequency furnace with CaO crucible. (1983)**
5. **Finding room-temperature ductility of about 5% by bend test in Ti-48at%Al-1at%Mn alloy (containing Ti_3Al). (1984)**
6. **Reporting on active twin deformation at room-temperature in the above alloy. (1985)**
7. **Establishing an isothermal forging technique. (1986)**
8. **Improving oxidation property by addition of Si. (1987)**
9. **Confirming a positive temperature dependence of fatigue strength. (1988)**
10. **Finding fine grain superplasticity and dynamic superplasticity. (1989)**
11. **Establishing thermomechanical processing techniques for structure control to get fine equiaxed $TiAl+Ti_3Al$ alloys. (1990)**
12. **Improving room temperature ductility by directional solidification. (1991)**
13. **Finding a technique which dissolves only TiAl phase in TiAl alloys consisting of $TiAl+Ti_3Al$. (1991)**
14. **Throwing light on environmental effects on room temperature ductility of TiAl alloys in relation to phase constitution. (1992)**

cut, polished and etched for microscopic observation. Test specimens of TiAl alloys are shaped by machining and grinding. The second item is mentioned as a representation of handling capability. Later, Yamamoto has studied the machining properties and cutting mechanisms in detail$^{18)}$.

Although the room temperature ductility attaining 25% was measured by compression test in the first item, tensile elongation of the binary TiAl alloys was not enough as a metallic structure material. Therefore, improvement of tensile ductility of TiAl alloys was an essenstial requisite in those days. The fifth item was the first definite work in the world that the room temperature ductility in TiAl alloys was improved by alloying$^{12),13),14)}$. The research boom for TiAl alloys have begun from this work in Japan. The sixth item shows that the ductilization of this alloy is taken place by special deformation mechanism$^{15),16)}$. This finding attracted attention of materials scientists because it leads to a new concept of deformation mode design to improve the poor ductility of intermetallic compounds. The fifth and the sixth items are described in details in Chapter 6. At present it is not rare for TiAl alloys to have tensile elongation of several percent at ambient temperature as the results of recent development.

Hot working of TiAl had been believed to be far more difficult than we know it today. The third item was the first work in Japan which showed that hot working of TiAl alloys was possible$^{19)}$. In this case a rather special method was used in anticipation of the severe difficulty. Later, isothermal forging was developed as a more general method as cited in the seventh item$^{20),21)}$. Using a slow deformation rate was inevitable, because the flow stress of TiAl increases rapidly with strain rate, and this reflects strongly upon the attainable fracture strain$^{17),22-25)}$.

Superplasticity is a very useful phenomenon which can be used for secondary forming. Occurrence of superplasticity has been found first in NRIM as cited in the tenth item. The origin of the fine grain superplasticity is in slowness of diffusion in the intermetallic compound TiAl, and the origin of the dynamic superplasticity is in difference of deformation mechanism between high temperatures and low temperatures$^{26)}$. This is a surprising phenomenon which could not be expected at all at the time when the research was begun. Details of the third, the seventh and the tenth items are described in Chapter 8.

It is becoming clear that microstructure in TiAl alloys changes considerably with heat-treatment or thermomechanical processing as described in Chaper 7, and that mechanical properties of the alloys change remarkably with microstructure. We can see prospects in this technical field. It may be stated that the front work of development for the alloys is changing from composition control to microstructure control. A strong endeavor is being made now for the establishment of structure control technique of TiAl alloys in NRIM. A successful example is the eleventh item. We have obtained TiAl alloys with a special configuration and distribution of T_3Al by thermomechanical treatment$^{22),23),24)}$. This structure is especially effective for obtaining superplasticity at high temperatures, and has a beneficial effect on ductility at room temperature$^{28)}$. Furthermore, we are developing various microstructures$^{29),30)}$: structures with excellent creep resistance, structures with toughness to impact, structures with good ductility at room temperature, and so on.

Molten TiAl is not so active as molten Ti-alloys, because the titanium content in TiAl is only half that of Ti-alloys. Utilizing this difference, melting using a CaO crucible has been studied as given in the fourth item$^{31),32),33)}$. As a vacuum high frequency melting furnace is conventional equipment, this fabrication method is very economical and easily applicable. It has been concluded that inclusion of oxygen of 0.13 wt% is inevitable with the CaO crucible, which is the equilibrium value of molten TiAl to CaO. Although TiAl alloys melted by this method have limited elongation at ambient temperature, various studies have been done to improve the ductility. They have also been used widely as a substitute of TiAl alloys produced by standard method when processing techniques are studied on a large scale.

The thirteen item is a useful technique for observing in three dimensions figures of the constituent phases, of inclusions, and of ternary intermetallic compounds in TiAl alloys34). In this method the polished surface of the specimen is deeply etched electrolytically using methanol solution containing 1% tetramethyl ammonium chloride and 10% acetyle acetone in volume %. A current density of 0.1 A cm^{-2}, with a stainless steel plate cathod at a distance of approximately 4 cm from the specimen is used for the etching, and the etching time is 1200 s.

The fourteen item is the first result showing that room temperature ductility of TiAl alloys is subjected to influence of atomospheres on tension test35),36). Although a Cr-added TiAl alloy has, for example, elongation of 4.3% in vacuum, it decreases to 0.6% in air. On the other hand, a Mn-added TiAl alloy has elongation of 2.4% in vacuum, and it decreases hardly in air. At present, effects of third elements and constitution phases on environmental brittlenss are being studied systematically37).

Some items are listed in Table 1 besides mentioned above. These were fresh topics once in respective period, and the following literatures have been published: (38) in the reference number for oxidation, (39) for fatigue and (40) for directional solidification.

Futhermore, occupation sites of the third elements in TiAl-phase have been studied as basically important problem which determines properties of intermetallics. The results have been published in the reference number (41) and (42).

4. Scientific Fundamentals

4.1 Characteristics of intermetallic compounds

In the Periodic Table the elements are arranged in order of metallic elements, semimetallic elements, and metalloid elements from the left side to the right side. An intermetallic compound is defined to be a compound which consists of a combination of only plural metallic elements. On the other hand, a ceramic is defined to be a compound consisting of metallic elements and metalloid elements. Metallurgists want to classify semimetallic elements into metallic elements in argument on intermetallic compounds, while ceramists classify them into metalloid elements in their argument. Regardless of the classification, metalloid properties of the elements increase with going to the right in the Periodic Table in the vicinity of semimetallic elements.

An intermetallic compound consisting of typical metallic elements is of metallic character which is derived from existence of conduction electrons. With increasing metalloid properties of the elements a tendency to form covalent or ionic bonding in intermetallic compounds is strengthened, and with the further increase intermetallic compounds change to ceramics with no conduction electrons. This means that intermetallic compounds are a group of substances located between metals and ceramics, and cover a wide range of properties. Metallic bonding brings goods malleability, while covalent bonding brings high strength at high temperatures which comes from strong binding between the nearest atoms. This situation is depicted in Fig. 1. From the viewpoint of compatibility between ductility and strength, we can choose an intermetallic compound of appropriate metalloid properties. Aluminides are usualy chosen as objects of study for structure materials. Aluminides can be treated by processing techniques for metals and are expected to possess some merits of metalloid. For silicides we are not tractable only by processing techniques for metals.

The other factor that we take into consideration for structural intermetallics is symmetry of crystal structure. For compounds whose crystal symmetry is not good, we can not expect plasticity from the viewpoint of deformation mechanism. Thus structural intermetallics are restricted to aluminides with good crystal symmetry. Such the compounds are Fe$_3$Al, FeAl,

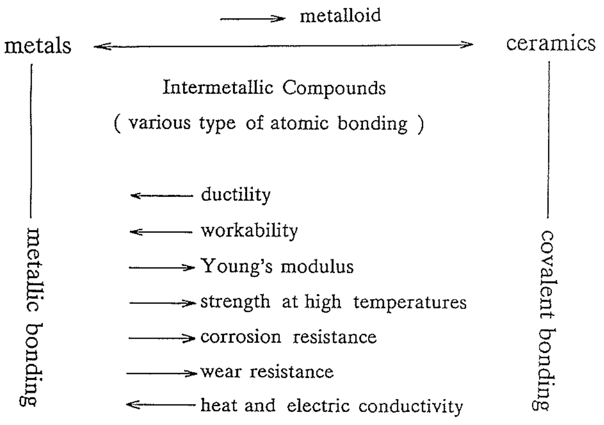


Fig. 1 Schematic illustration about properties of intermetallic compounds. The property is better toward the arrow.

Ni_3Al, Ti_3Al and TiAl. Among these, Ti_3Al and Fe_3Al soften at low temperatures because of order-disorder transformation. When the other three kinds of compounds are compared, TiAl has the highest melting point and is the lightest. This is the scientific reason why we chose TiAl as the best object of the study.

4.2 Intermetallic compounds in Ti-Al binary system

The Ti-Al binary phase diagram, which is considered to be the most reliable at the present, is shown in Fig. 2[43-45]. The compound TiAl, which is called γ phase, has a wide solubility range in the high Al side from the stoichiometric composition. The adjacent compound in the Ti-rich side is Ti_3Al, which is formed by ordering of α Ti and is called α_2 phase. The ordering reaction from the α phase to the α_2 phase cannot be suppressed on normal cooling[46]. In the scope of this paper discrimination between α and α_2 is not important, so α and α_2 are written α to avoid complexity arising from the trivial difference in the notation, though the α phase is ductile while the α_2 phase is brittle. It should be memorized that the properties of the phase written as α in this paper is entirely different between high temperatures and room temperature.

Strong temperature dependence in compositions of $\alpha/\alpha+\gamma/\gamma$ phase boundaries should be noted. It is becoming clear recently that this dependence and similarity of the crystal structures in the α and γ phases enable various methods of heat treatment and thermomechanical treatment.

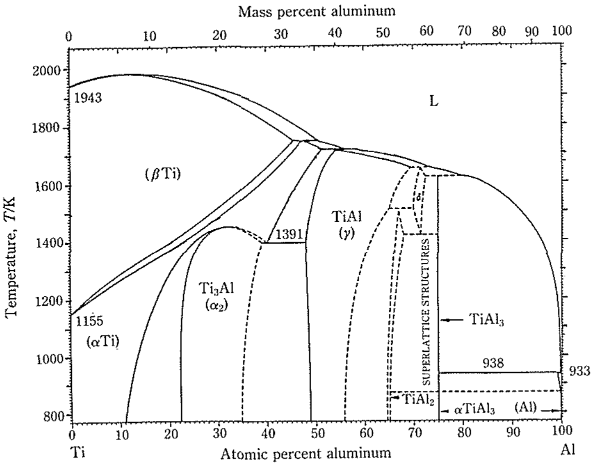


Fig. 2 Ti-Al binary equilibrium phase diagram. The diagram is composed based on the Ref. (44) and (45) for the composition range of 35–55%Al, and on the Ref. (43) in the other range.

It should be noted that Ti is the transition element with non-filled 3d electrons, and that Al is the normal element with one 3p electron. Al which is contiguous to Si in the Periodic Table behaves as a metal or, on the contrary, as a non-metal. The ability of the 3p electron in Al to absorb other electrons makes covalent-like bonding of a p-d hybrid in TiAl[47], and this bonding gives various benefits and drawbacks to TiAl

The crystal structure of TiAl is $L1_0$ with the axial ratio *(c/a)* of 1.02, and that of Ti_3Al is $D0_{19}$. The crystal structures of TiAl and Ti_3Al are shown in Fig. 3. The deviations from the stoichiometric compositions in TiAl and Ti_3Al are adjusted not by introducing vacancies but by changing the kind of the atom in the sublattice[48]. The axial ratio of $L1_0$ crystal is generally less than 1.0, like in AuCu which is the representative $L1_0$-type intermetallic compound. The reason why the axial ratio of TiAl is larger than 1.0 is attributed to the formation of the covalent-like bonding of the p-d hybrid, and this anisotropy in the crystal structure has a strong relationship with the low ductility of TiAl at ambient temperature. TiAl has the specific gravity of 3.7, the yield strength of 150 MPa and the Young's modulus of 180 GPa at 1270 K, the excellent oxidation resistance up to 1070 K, and the crystal structure of tolerably good symmetry. These characteristics suggest that the compound TiAl can become an epoch-making material.

The drawbacks of TiAl are the lack of ductility at room temperature and difficulty of hot working at elevated temperatures. The origin of the deficiency in these properties is phenomenologically in planarity of slip which comes basically from the fact that the slip to the ***b*** direction in Fig, 3(c) is more difficult than that to the ***a*** direction. It was believed around 1975 in Japan that TiAl is too brittle to be regarded as a condidate of structural material. The fracture mode was known to be not of the grain boundary type but of the cleavage type. The cleavage planes are not specified, i.e., the cleavage occurs on various planes such as (100), (001),

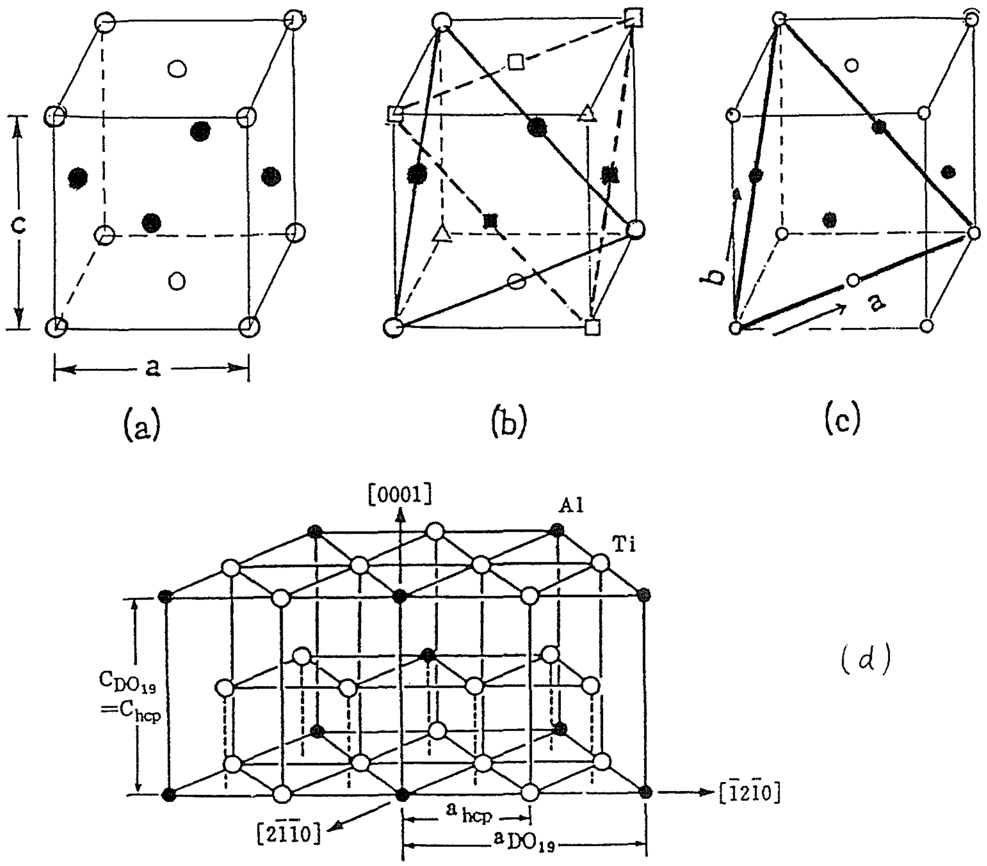


Fig. 3 Crystal structure of TiAl (γ) and Ti_3Al (α_2). (a)-(c) are for γ and (d) for α_2. (a): $L1_0$ structure of TiAl with axial ratio *(c/a)* of 1.02. (b): abcabc stacking of close-packed planes $\{111\}_\gamma$ (○, ● a-plane; □, ■ b-plane; △ c-plane). (c): Slip plane (broad lines) and slip direction (*a*, *b*). (d): $D0_{19}$ structure of Ti_3Al which is the same as hcp in the disordered state (α-phase). ababab stacking of close-packed planes $(0001)_\alpha$.

(110), (111) and so on[49].

Part II Particulars

5. Preliminary Experiment

From a viewpoint that TiAl is very brittle, the first research plan in NRIM has been to design TiAl alloys as a two-phase material in which TiAl coexists with any metallic phase in the equilibrium state. In other words, the aim of the preliminary study is to get a material like Ni-base heat resisting alloys which consist of Ni terminal solid solution and the intermetallic compound Ni_3Al. After some tests at room temperature for TiAl alloys with various additional elements, it has been found that the alloys containing Ag are exclusively metallic compared with the other alloys. In the alloys containing Ag, TiAl is equilibrated with the terminal solid solution of Ag. The obtained ternary equilibrium phase diagram of Ti-Al-Ag is shown in Fig. 4[50].

Ductilities of the TiAl alloys containing Ag and the binary TiAl alloys have been compared by a compression test in the preliminary study. The authors have experienced a great surprise in this experiment. It is a fact that the binary TiAl alloys are not so brittle at room temperature as one's conviction in those days. The obtained data are shown in Table 2[11]. This table tells us that the ductility depends strongly on Al-content in the binary alloys. It has been concluded that the Al-rich TiAl is brittle, while the Ti-rich TiAl is not brittle. It has been supposed that most researchers had studied the Al-rich TiAl to ensure single phase of TiAl and found TiAl to be brittle.

This finding has been an important turning point in

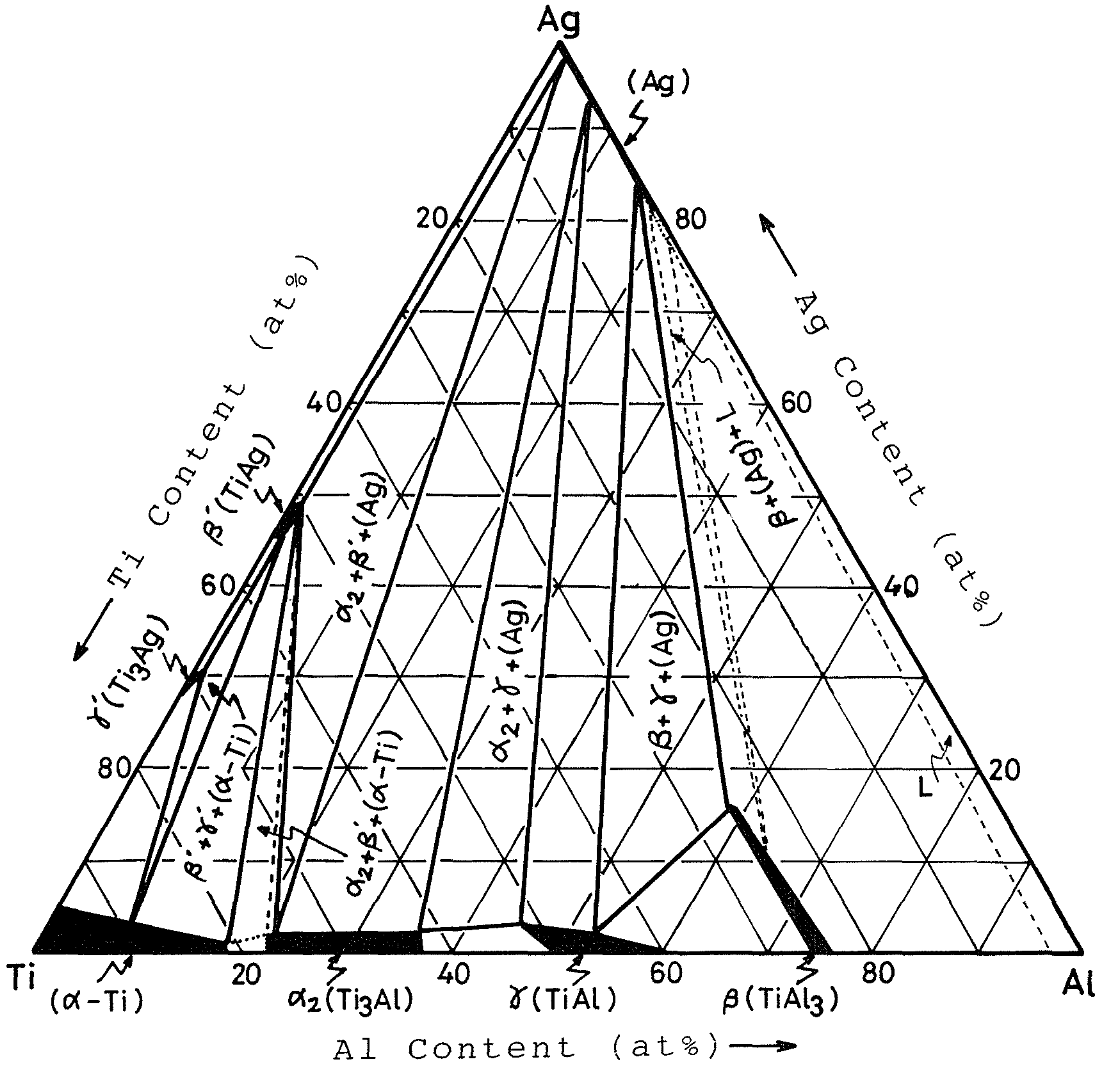


Fig. 4 Isothermal section at 1073 K of the Ti-Al-Ag ternary phase diagram.

the research of TiAl alloys. Necessity for the coexistence of any metallic phases disappeared, and all we have to do became to drag out ductility from TiAl itself or the TiAl-Ti_3Al mixture. It has been concluded to be required that the Al content in γ phase should be the lowest, because the ductility at room temperature increases with decreasing Al content in γ phase. This principle agrees with a concept that the p-d hybrid in TiAl is generated from the Al-atom and, therefore, the p-d hybrid is weakened with lowering of Al content in γ phase. For purpose of guaranteeing that the γ phase contains the poorest Al content, coexistence of α phase is valid in the binary alloys. Also, dispersion of a small amount of α phase is beneficial from a viewpoint of fineness of microstructure in TiAl alloys, which would play a role in preventing the generation of cleavage cracks due to stress concentration51).

6. Improvement of room temperature ductility by alloying

Room temperature elongation of 3% is requested as the minimum requirement for metallic structural materials by machine designers. Although the ductility by compression is large enough in Ti-rich TiAl alloys as shown in Table 2, the tensile elongation in these alloys is below 1% at ambient temperature. Accordingly, the tensile ductility of TiAl alloys should

Table 2. Results of preliminary compression test for Ti-Al binary alloys at a strain rate of 1.34×10^{-2} s^{-1}.

(a) Ti-50.0%Al alloy as cast.

Temperature (K)	Proof stress (MPs)	Compression strength (MPa)	Strain at failure (%)
R. T.	384	1413	22.0
573	377	1544	21.9
773	362	>1216	>25.9
973	353	> 880	>52.4

(b) Ti-50.0%Al alloy annealed at 1573 K for 7.2 ks.

Temperature (K)	Proof stress (MPa)	Compression strength (MPa)	Strain at failure (%)
R. T.	341	>1385	>25.8
573	292	1432	25.2
773	280	>1340	>30.5
973	341	>1069	>41.7
R.T.*	288	1575	26.2

*at a strain rate of 2.68×10^{-2} s^{-1}

(c) Ti-50.0%Al alloy annealed at 1573 K for 3.6 ks.

Temperature (K)	Proof stress (MPs)	Compression strength (MPs)	Strain at failure (%)
R. T.	320	379	0.4
573	308	349	0.5
773	265	450	2.2
973	309	441	1.1

be improved.

With regard to the ductilization of brittle intermetallic compounds, there had been only a precedent done in Japan at the time when the research in NRIM was begun. Its study showed that a small addition of boron eliminates drastically the intergranular brittleness of the compound Ni$_3$Al[6]. Therefore, a natural policy for the improvement of ductility in TiAl was alloying in those days.

6.1 Change of structure and mechanical properties by alloying

Effects of third elements added to TiAl alloys on the crystal structure, microstructures and mechanical properties at room temperature were studied. Mn, V, Nb and Zr were chosen as the third elements, in which the atomic sizes of Mn and V are smaller than of Ti and Al, while those of Zr and Nb are larger.

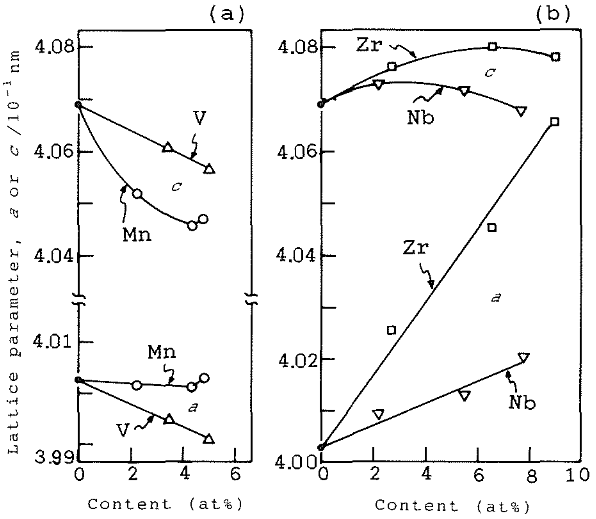


Fig. 5 Effect of third elements on lattice parameters, *a* and *c*, of $L1_0$ structure of γ phase in alloys keeping atom ratio of *Al/(Ti+Al)* at 47.8%, where *Ti* or *Al* is the composition of each element in at % in the alloys.

Buttons were arc-melted using a tungsten electrode under an argon atomosphere, annealed for 1 week at 1270 K, and then quenched into water. Examination was carried out for these specimens. Alloy compositions were chosen so that γ single phase alloys and $\alpha+\gamma$ two-phase alloys could be obtained after annealing. The crystal structure of the γ-phase were examined by powder X-ray analysis. Mechanical properties were measured by a compression test and a bend test. The compression test was carried out at a rate of 10^{-3} s^{-1} using specimens of 3×3×7.5 mm. The bend test was carried out by means of 3-point bending for the specimens of 2.5×5×26 mm. The moving speed of the loading rod was 10^{-5} m/s and the span between the supporting rods was 16 mm[13].

The lattice parameters and the axial ratios obtained for the γ-phase in the $\alpha+\gamma$ two-phase alloys are shown in Figs. 5 and 6[14]. No direct relationship between the atomic sizes of the third elements and the axial ratios is found. The axial ratio decreases with Zr or Mn content, but the causes of the decreases are completely different in both the alloys. In the alloys containing Zr the axial ratio is decreased by an increase of the *a* value, while in the alloys containing Mn it is decreased by a decrease of the *c* value. The decrease of the *c*

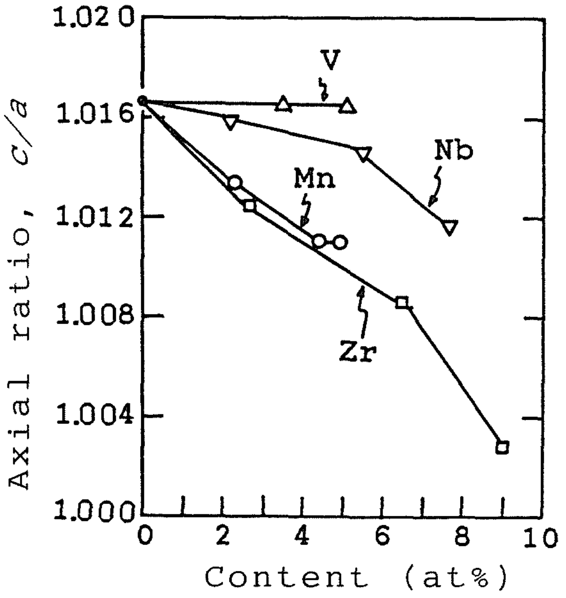


Fig. 6 Effect of third elements on axial ratio *(c/a)* of the γ phase in the same alloys as shown in Fig. 5.

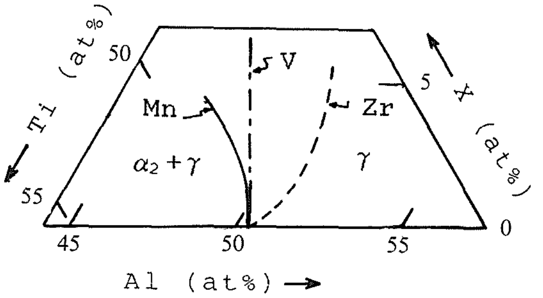


Fig. 7 Effect of third elements X (:Mn, V, Zr) on the $\alpha+\gamma/\gamma$ phase boundaries at 1270 K.

value implies an important meaning because it suggests that the covalent-like bonding is weakened. In the alloys containing V, the axial ratio remains constant because both the *a* and the *c* value decrease.

Figure 7 shows $\alpha+\gamma/\gamma$ phase boundaries at 1273 K obtained for four kinds of the alloying elements. Although the complete equilibrium state cannot be

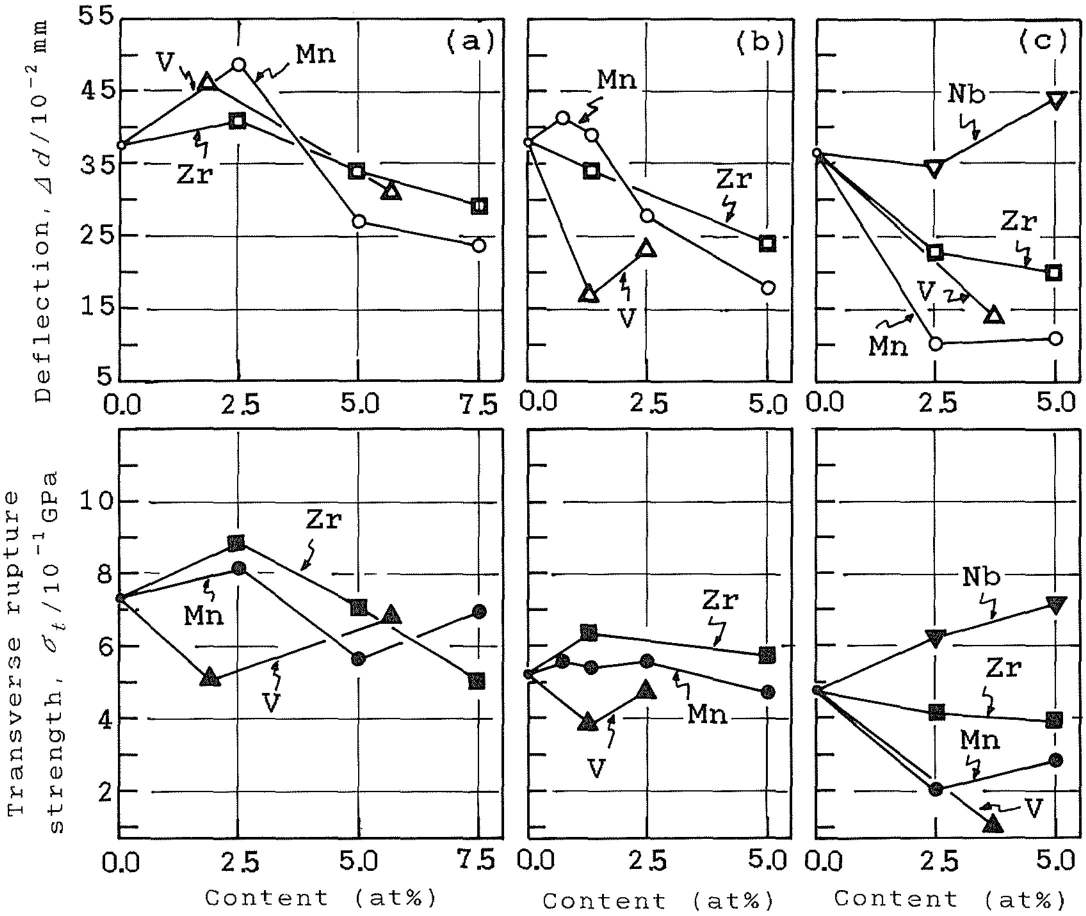


Fig. 8 Effect of third elements on the bending properties. (a) Alloys of 47.8% in *Al/(Ti+Al)*. (b) Alloys of 50.0% in *Al/(Ti+Al)*. (c) Alloys of 52.1% in *Al/(Ti+Al)*.

achieved by the present heat treatment in these alloys systems, the tendency is clear. The Mn atoms occupy the Al-site of the sublattice, the Zr or Nb atoms occupy the Ti-site, and the V atoms replace both sites. It is considered that the decrease of Al content in the γ-phase by Mn addition causes weakening the covalent-like bonding, leading to the decrease of the axial ratio.

A result of the bending test is shown in Fig. 8. A good combination of ductility and strength is obtained for the Mn-added $\alpha+\gamma$ alloys14).

6.2 Ductility improvement by Mn addition

From the results of Fig. 8, the ductility and deformation mechanism of the Mn-added alloys were examined in detail15). In order to determine the optimum composition for good ductility, the alloys shown in Fig. 9 were made and examined at room temperature by the bend test. Here, the solid symbols represent the alloys which have maximum ductility in each series of constant atomic ratio of *Al/Ti*. Here, *Al* and *Ti* represent the content of each element in the alloys. The best ductility is obtained for the alloy indicated by the symbol ⊙. This alloy whose composition is Ti-48.4%Al-1.0%Mn is able to bend at room temperature as shown in Fig. 10(a). Elongation at the tensile surface of this specimen reaches about 5%16).

The microstructure of the polished tension-side surface in the specimen is shown in Fig. 10(b). A plenty of straight lines are observed. These are deformation twins which are not observed absolutely in Al-rich TiAl alloys and found only in a small amount for other Ti-rich TiAl alloys. A clear difference in the amount of deformation twin between the binary alloy and the Mn-added alloy of the same Al content should be noted to be significant15). After all, the addition of Mn promotes the generation of deformation twins which makes the deformation mechanism multifarious.

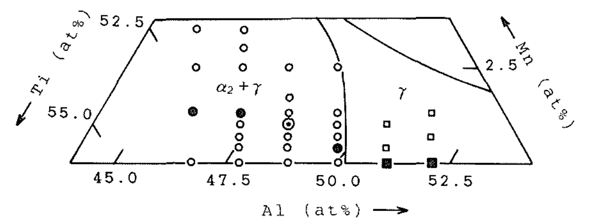


Fig. 9 Ductility of fabricated Ti-Al-Mn ternary alloys. Solid symbols represent alloys whose ductility is best in each series of constant *Al/Ti* ratio. Symbol ⊙ denotes the most ductile composition.

Hardness changes of the γ-phase with Mn-content are shown in Fig. 11 15). Solution softening is observed on a small addition of Mn in the alloys whose atomic ratios of *Al/(Ti+Al)* are 50% and 49%. The increase of hardness at higher Mn content in these alloys is solution hardening. The solution softening is believed to be related with the twin deformation. The absence of solution softening in the off-stoichiometric base alloys seems to be the result of being masked by hardening due to the existence of α phase or the strong defect hardening of excess Al-atoms.

Phenomenal reasoning with regard to "Why is twin deformation promoted in the γ-phase containing Mn?" has been searched by two groups. Hanamura *et al.* have found that twin partial dislocations in the alloys containing Mn are more stable through a pinning effect by Mn segregation than those in binary TiAl alloys52),53). Hug and Veyssiere have found that stacking fault energy is high for the alloys containing Mn54), in contrast to an anticipation of Hanamura *et al.*

At present there are no systematic studies on the relation between the occurrence of deformation twin and the kinds of the third elements in TiAl alloys. One supposition is that the twin deformation is promoted in the order of Mn>Cr>V and the solubilities of the third elements in TiAl are restricted in the same order. To be noted is the above order corresponds to that of the periodic table.

There is a possibility that high temperature strength decreases when the compound is ductilized. To check up this anxiety, the compression test was made16). Figure 12 shows that the ductilized alloy has good high temperature strength, displaying a strong positive temperature dependece of strength in spite of being the fine grained polycrystal alloy.

6.3 Principle of ductilization by Mn addition

Materials fracture when the deformation stress exceeds the fracture stress. In a case of the compound TiAl the cleavage strength should be discussed.

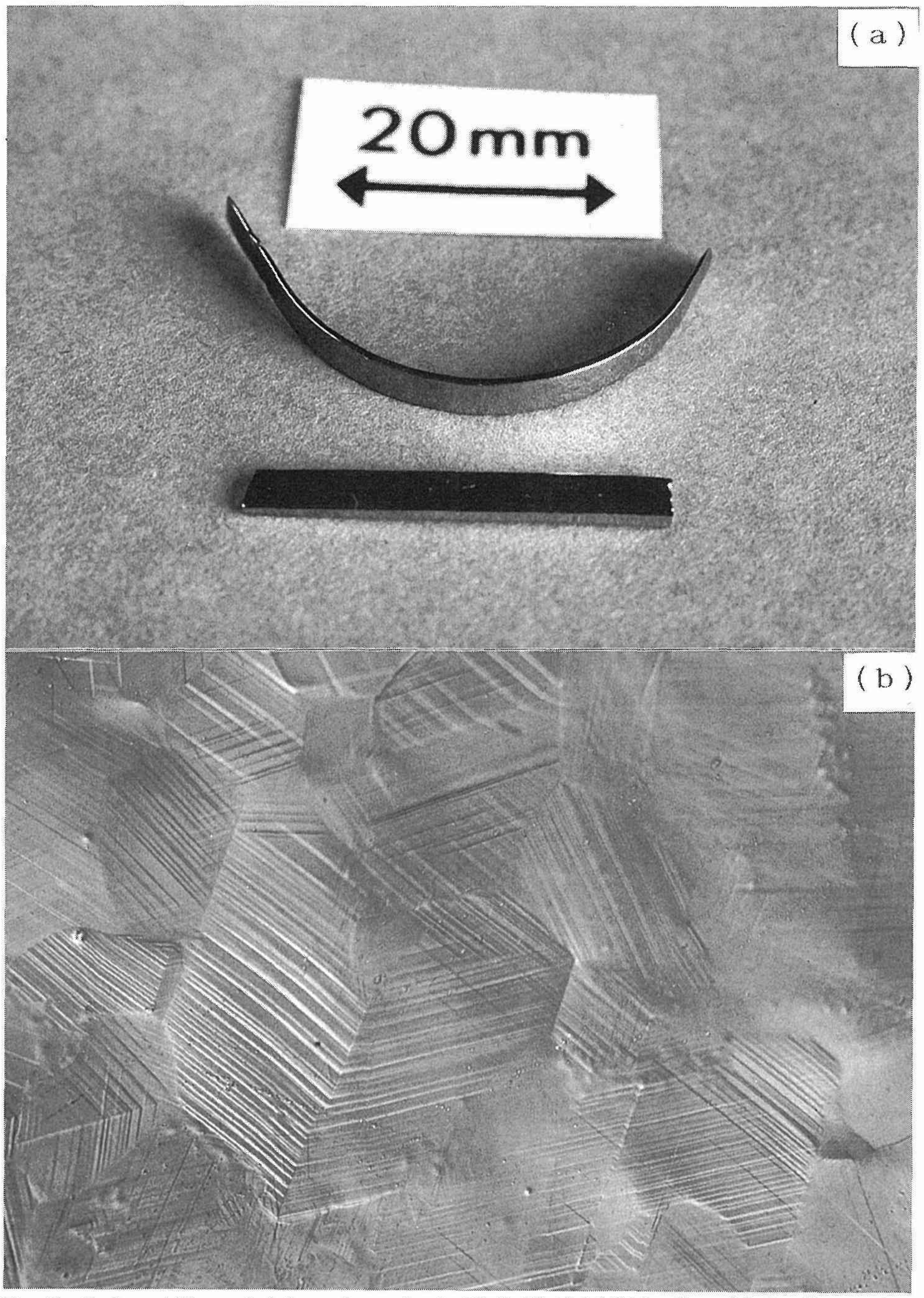


Fig. 10 Deformability and deformation twins in Ti-48.4%Al-1.0%Mn alloy. (a) Bending work at room temperature. (b) Microstructure of polished tension-side surface after the bending.

Generally speaking, the low ductility comes from a small difference between yield strength σ_y and fracture strength σ_f, as illustrated schematically in Fig. 13. Lowering the yield strength and heightening the fracture strength result in augmentation of the plastic deformation range. In the Ti-48.4%Al-1.0%Mn alloys, the occurrence of the twin deformation is considered to have brought the lowering of the yield strength. On the other hand, the fracture strength is considered to have been heightened by an increase of the metallic character as the result of replacing Al atoms by Mn atoms. The local stress concentration has been released partly by the fine dispersion of Ti_3Al and the occurrence of twin deformation. This is

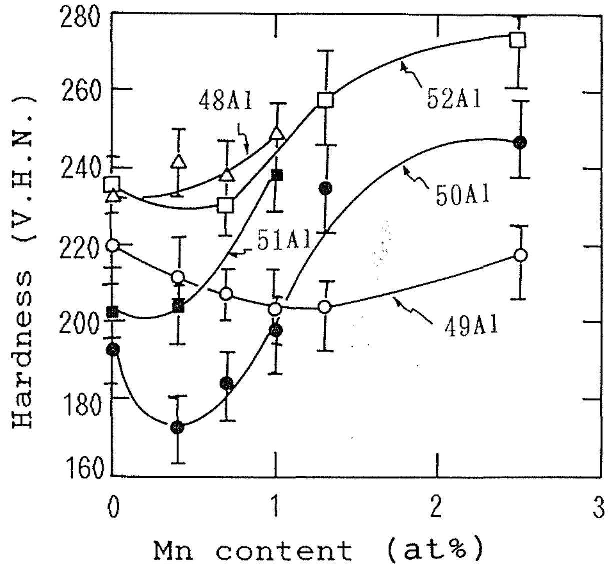


Fig. 11 Micro-Vickers hardness of the γ phase in Mn-added TiAl alloys. The numericals in the figure represent *Al/(Ti+Al)* content of the alloys.

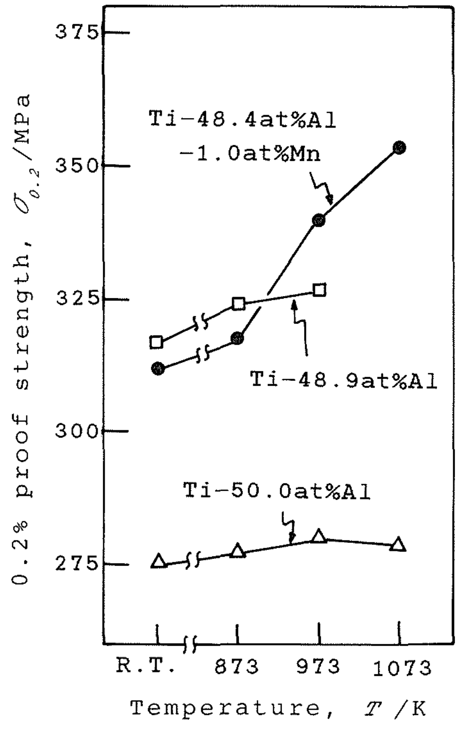


Fig. 12 High temperature properties of polycrystalline TiAl alloys obtained by the compression test.

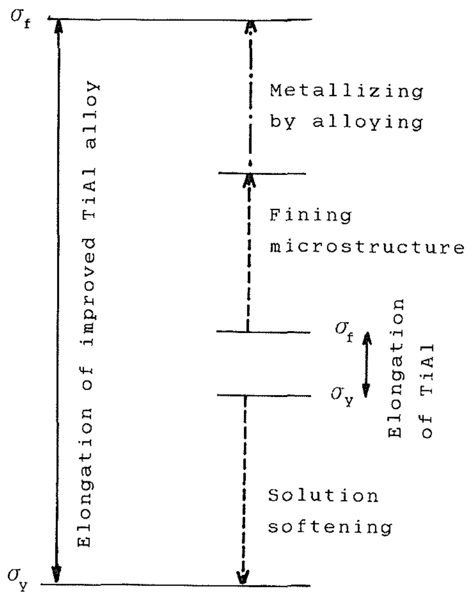


Fig. 13 Basic concept for improving ductility of TiAl by alloying. Room temperature ductility is enlarged by the decrease of yield strength σ_y through solution softening and an increase of fracture strength σ_f through making microstructure fine and TiAl alloys more metallic. Solution softening through activation of twin deformation and the increase of metallic character of TiAl are achieved by replacing Al-atoms of TiAl with Mn-atoms which results in approach of *c/a* in $L1_0$ structure to unity. Fine microstructure is obtained by dispersion of Ti_3Al and formation of small grains.

a picture the authors have about why the above alloy has a good ductility at room temperature.

A dense electron part of the rope configuration connecting the Al atom and the Ti atom is supposed to be formed in the TiAl lattice on formation of the p-d hybrid, which makes the conduction electron density in the remaining part thin. As the cohesive force of atoms in metals is generated between conduction electrons and positive ions, the metallic bonding between the ion and the thin electron part is weak. In the opinion of the author, the thin electron part is responsible for the generation of cleavage and its propagation in TiAl. The above-mentioned "an increase of metallic character" means that the electrons of the thin electron part become dense. Weakening the p-d hybrid results in "an increase of metallic character", decrease of the axial ratio and decrease of the unit volume. It should be emphasized, however, that the decrease of the axial ratio and the unit volume are not sufficient conditions for "an increase of metallic character".

7. Microstructure control by heat treatment and thermomechanical treatment

Remark changes of microstructure and properties by heat treatment cannot be expected in most of the intermetallic compounds. So, a strong interest had not been evoked in the heat treatment or thermomechanical treatment of intermetallic compounds in the past. It is comparatively recent that attention has been paid to the configuration and distribution of the constituent phases in TiAl alloys, and to their control. In this chapter the effects of heat and thermomechanical treatments for binary TiAl alloys of polycrystals are described. The application of these techniques to ternary TiAl alloys and to describe various aspects of results conclusively remains as a coming topic, though remarkable development is being achieved by active researches8),27),28),55–59).

By studying the binary TiAl alloys systematically, we have concluded that their microstructure can be changed remarkably by heat-treatment and thermomechanical treatment. Two important factors are in the background of this strong ability for microstructure control. One is that the equilibrium compositions of the two-phase region of the α and the γ phase in the Ti-Al phase diagram change remarkably with temperature. The other is the similarity of the crystal structures of α and γ phase, as shown in Figs. 3(b) and (d). Although some techniques for microstructure control have been already exploited susccessfully, it has not been regarded even for binary TiAl alloys that all latent possibilities in this technical field have been developed fully until now. It is supposed that there will be some sophisticated techniques remained.

An important work for understanding phenomena encountered on $\alpha \rightarrow \gamma$ phase transformation in binary TiAl alloys has been conducted by Yamaguch *et al.*, who have established the concept of polysynthetically twined crystal and thrown light on its formation mechanism using unidirectionally solidified single crystal60). The basic study on plasticity of binary TiAl alloys has been done by using the polysynthetically twinned crystal by Inui *et al.*61) and Umakoshi *et al.*62). Kikuchi and Yamabe have studied on precipitation mechanism of γ-phase from α-phase for binary TiAl alloys63). Innovative development for thermomechanical treatment of binary TiAl alloys have been accomplished by Nobuki *et al.* as described later in detail.

In some cases for the ternary TiAl alloys the β Ti phase is found in the microstructures with the α and γ phases. There are cases where phase ratios among the α, γ, and β differ between an annealed state and a forged state, and where the β phase is not a simple structure of disordered or ordered bcc64),65). Although many difficult problems remain to be solved for explanation of these phenomena, the existence of the β phase is further beneficial to improve the microstructure by means of heat-treatment.

7.1 As-cast structure of TiAl alloys

Coinciding with Fig. 1, the primary is β in binary TiAl alloys containing <50%Al. On cooling the β phase fransforms martensitically into the α phase. In alloys of 52%Al and 54%Al the primary is α and the secondary is γ. In the alloys of 50, 52 and 54%Al the α dendrite characteristic of hcp structure developes clearly34). With decreasing temperature the γ phase precipitates from the α dendrite. The precipitated γ is observed to be continuous with the secondary γ of the matrix11).

It should be emphasized in Fig. 3 that the difference of the crystal structures between the α phase and the γ phase is only stacking sequence of the close-packed plane, except for the arrangement of the atom species. Thus, $(0001)_\alpha$ coincides with $\{111\}_\gamma$ except for a small difference in atomic spacings. This means that the precipitates are formed in plate-like configuration along $(0001)_\alpha$ plane on the precipitation of the γ phase. In fact, it is well known that layered structure or lamellar structure consisting of the α and γ phases is formed by cooling from the α field. Examples of the lamellar structures are shown in Fig. 14. The lamellar structure becomes more regular by annealing as shown in Fig. 14(b).

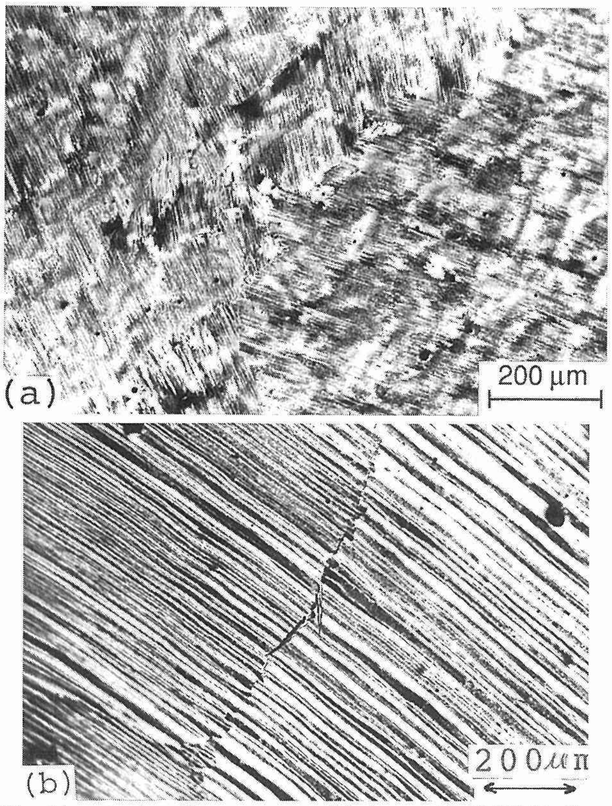


Fig. 14 $\alpha+\gamma$ lamellar structures. (a) As cast Ti-48.2%Al alloy. (b) Ti-44.9%Al alloy annealed at 1640 for 15 min and then at 1450 K for 15 min.

7.2 Structure change with heat treatment

The as-cast structure being not in the equilibrium state can be changed with heat-treatment, as shown in Fig. 15[29),30)]. Here, the cooling rate from the heating temperatures is 3.7 K s^{-1}. In Fig. 15(a) the nucleation of γ grains can be observed in the lamellar structure of the as-cast alloy. With decreasing heating temperature to 1473 K, the γ grain grows and the lamella becomes coarse, as shown in Fig. 15(b). By holding the specimen for long time at 1473 K the lamellar structure changes to the equiaxed grain structure, remaining a small amount of the coarse lamellae near the grain boundaries as shown in Fig. 15(c). By reheating the structure shown in Fig. 15(c), new plates of the α phase are yielded in the γ matrix as in Fig. 15(d). The plates have four orientations, so as to form that the $(0001)_\alpha$ plane of hcp lattice coincides with the $\{111\}_\gamma$ planes of fct lattice. The ductility at room temperature increases with increasing the amount of γ phase in this alloy, and moreover the formation of the α plates by reheating gives a beneficial effect on the ductility.

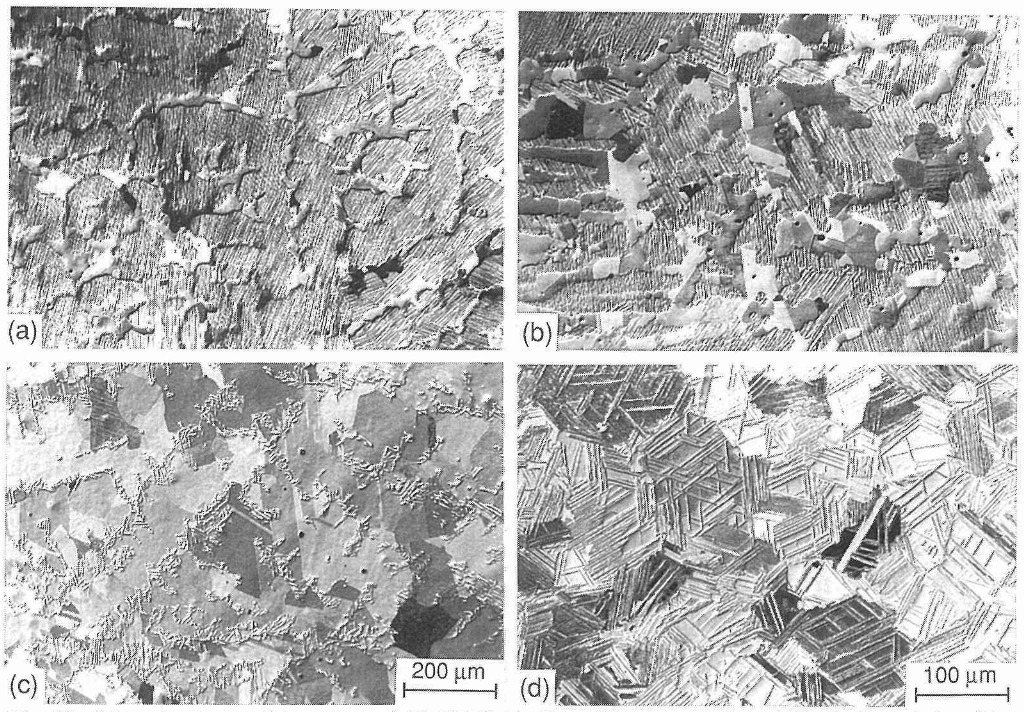


Fig. 15 Microstructures of heat-treated Ti-48.2%Al alloy. (a): Annealed at 1620 K for 0.9 ks. (b): Annealed at 1620 K for 0.9 ks and then at 1470 K for 3.6 ks. (c): Annealed at 1420 K for 86.4 ks. (d): Annealed at 1620 K for 3.6 ks after heating at 1470 K for 86.4 ks.

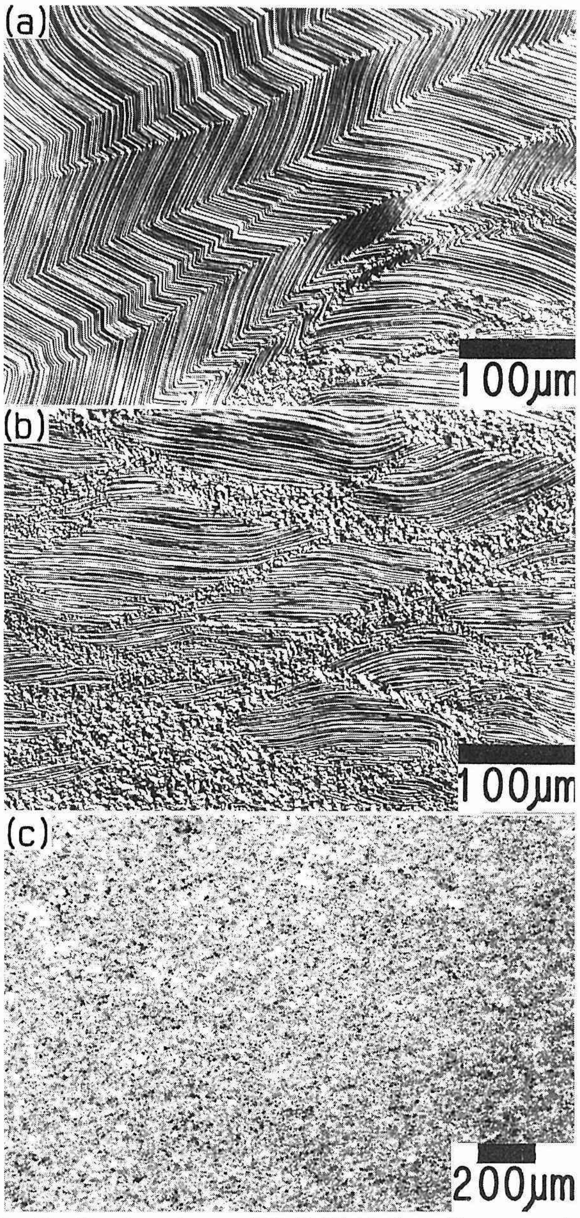


Fig. 16 Structure change of Ti-46.4%Al alloy with compression deformation at a strain rate of 10^{-3} s^{-1} at 1470 K. The compression axis is up-and-down direction in (a) and (b). (a): Intial stage of deformation. (b): Deformation up to 0.9 in true strain. (c): Microstructure after compression deformation from three directions changing by 90° mutually, where the true strain of 1.0 is given for each direction.

7.3 Structure change with thermomechanical treatment

The lamellar structure is stable at high temperatures in the alloys containing Al less than 46%, and the configuration of the lamellae is not changed only by heat-treatment. For such alloys plastic deformation is needed to decompose the lamellar structure.

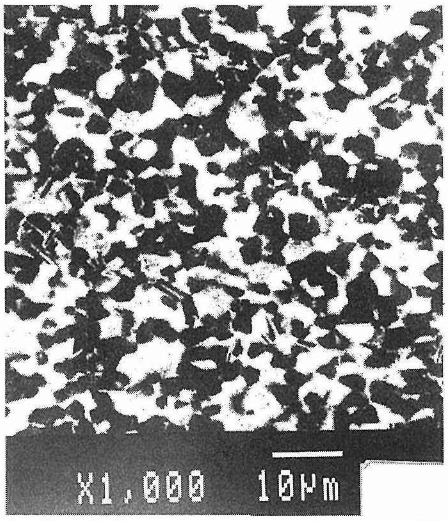


Fig. 17 Backscattered electron image of Fig. 16(c).

Figure 16 shows changes of microstructure with compression deformation[17),22)]. By a small amount of deformation, twin-like deformation occurs in the lamellae which is parallel to the compression axis as shown in Fig. 16(a). It can be seen that recrystalization starts at the twin-like interface. With increasing the amount of deformation, the lamellae parallel to the compression axis decompose into the equiaxed two-phase structure consisting of the α and the γ grains. In the lamellae perpendicular to the compression axis, however, any decomposition does not occur. Some lamellae being not parallel to the compression axis rotate to the orientation being perpendicular to the compression axis. We cannot expect further decomposition of lamellae by the deformation of this direction in the state of Fig. 16(b), because only the lamellae perpendicular to the compression axis are remained. Therefore, we need to give the compression from the different direction in order to change all the lamellae into the equiaxed grains. The microstructure obtained by such an experiment is shown in Fig. 16(c). Here, the compression deformation with the strain of 1.0 is given in turn from three directions which are changed by 90° mutually. The microstructure shown in Fig. 16(c) is very fine and equiaxed over the whole area. The enlarged image of Fig. 16(c) is shown in Fig. 17, where the white part is the α phase and the dark part

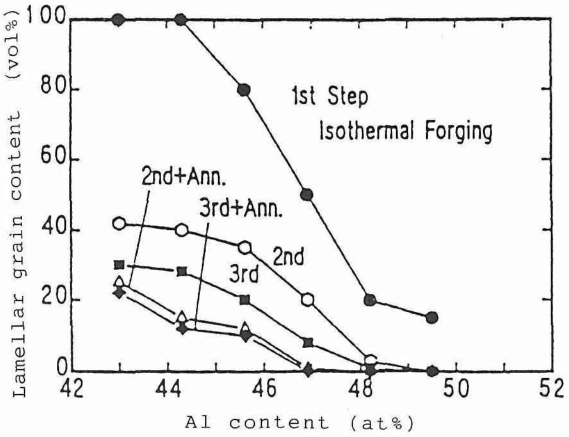


Fig. 18 Change in volume of lamellar structure with thermomechanical treatment in binary TiAl alloys.

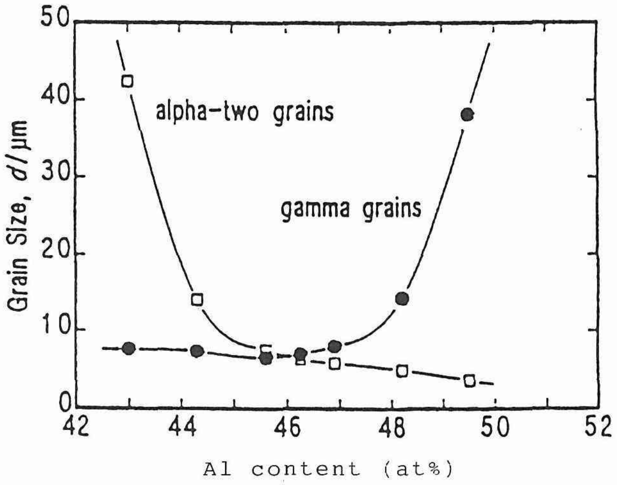


Fig. 19 Relation between grain size and Al content in the alloys for which three step forging and annealing in Fig. 18 are given.

the γ phase.

Microstructure control by a combination of forging and annealing, namely, thermomechanical treatment has been studied. The results are shown in Fig. 18. Here, three step isothermal forging has been carried out by compression with the same method as explained in Fig. 16(c). That is, the forging directions are changed for each step in which strain of 1.0 is given at a strain rate of 10^{-3} s^{-1}. Before the forging the billets are solution treated at 1473 K for 86.4 ks. The first forging step is carried out at 1473 K, and the second and the third step at 1273 K. The annealing is done at 1473 K for 1.8 ks. Fig. 18 shows that the annealing has an effect on the decomposition of the retained lamellar structure which can not be decomposed only by the deformation. The effect of the annealing is remarkable for alloys in which the 2nd step forging is given. In spite of the elaborated thermomechanical process, complete decomposition of the lamellar structure is difficult for alloys containing Al less than 47%.

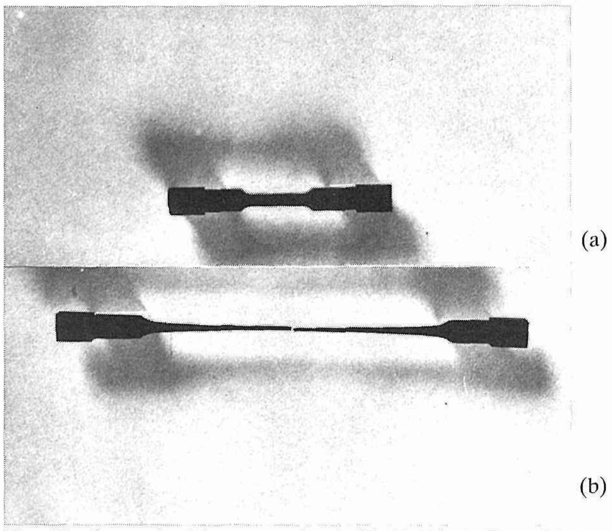


Fig. 20 Superplasticity appearing in Ti-46.4%Al alloy with fine equiaxed grains of $\alpha+\gamma$ two phases. Specimen of gaze size 2×4×10 mm before the tension test (a) and after the test at a rate of 10^{-4} s^{-1} at 1200 K (b).

Figure 19 shows the relation between Al content and the size of the α grains and the γ grains under the condition of same thermomechanical treatment, i.e, the 3rd step forging and annealing. The finest microstructure is obtained for the alloy containing 46%Al. In this alloy the α and the γ grains have an equal size and their distribution is uniform. Such the microstructures tend to remain fine even at high temperatures. Thus, the binary alloy containing Al close to 46% and having the controlled fine microstructures displays superplasticity with the elongation of several hundred percent, as shown in Fig. 20[25].

8. Deformation at high temperatures

8.1 Hot working

The intermetallic compound TiAl had been regarded as a material for which hot working is very difficult. We can verify this difficulty, if the compound TiAl is deformed at high temperatures with conventional deformation rates used for metals. TiAl is very

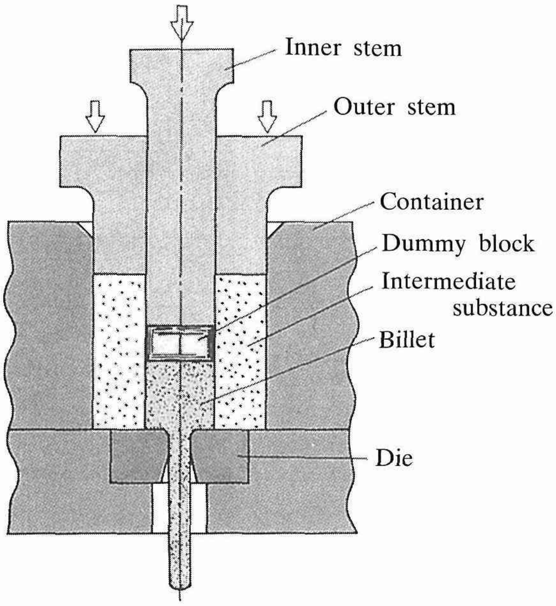


Fig. 21 Schematic figure of "the extrusion method with lateral pressure". This method, developed in NRIM, enables one to extrude hard materials of limited plasticity like TiAl alloys.

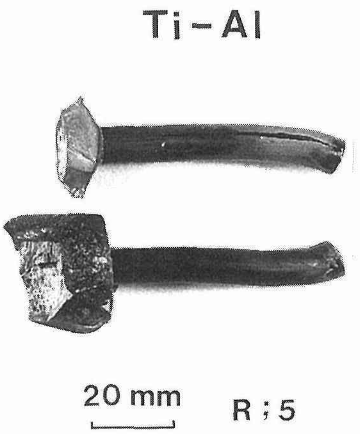


Fig. 22 Examples of extruded stoichiometric TiAl compound with the method shown in Fig. 21. Dies made of Si_3N_4 were used and TiAl billets were heated at about 1600 K.

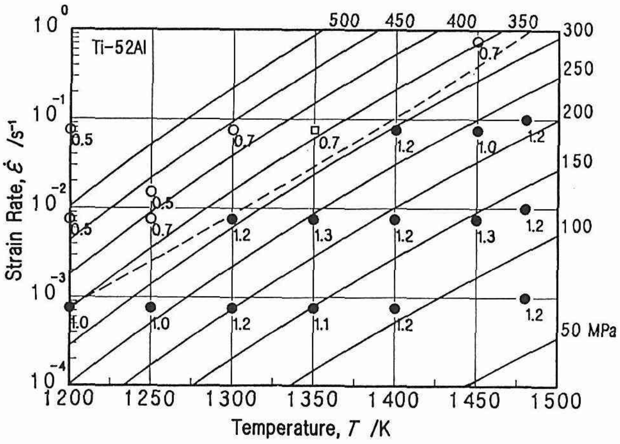


Fig. 23 Flow stress and deformability map for the cast Ti-52.4%Al alloy. Solid lines represent the flow stress indicated by the numerical values (MPa) at the end of each line. The numerical values attached to the symbols denote the true strain given for the specimen. The specimens shown by ○, ● were sound at the given strain and that by □ had cracks. Below the dotted line, the specimens can be deformed soundly greater than 1.0 by true strain.

hard and brittle for working of such the rate. Applying a heavy hoad, TiAl is easily cracked without any deformation. It occurs sometimes on hot working that only working tools are deformed without any shape change in TiAl itself.

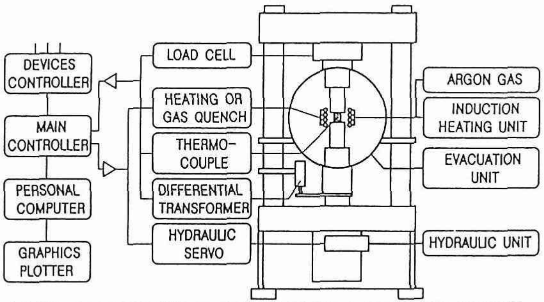
One direction of endeavors to deform brittle materials such as TiAl is to use a specially designed equipment. After many trials for various methods, it has been found that "extrusion with lateral pressure" is quite effective for obtaining hot working products of the compound TiAl. The equipment used for the experiment is illustrated in Fig. 21[66] and the product obtained is shown in Fig. 22[21]. In this equipment the heated intermediate substance such as pyrophyllite is changed to fluid by being pressed with the outer stem and gives lateral pressure to the billet. Then the billet is pushed with the inner stem for extrusion. One of the merits in this equipment is that the billet can be extruded with comparatively slow speed, because the billet is kept warm during extrusion with the intermediate substance. This is the other reason why this method is applicable for extrusion of TiAl in addition to the main factor of lateral pressure. On the other hand, we can not get TiAl rods by means of extrusion under hydrostatic pressure of oil, where the billet is required to be extruded with a high speed in order to prevent cooling of the billet.

Another direction of endeavors is to find out working conditions, i.e, the good combination of temperature and strain rate, under which hot working of TiAl becomes feasible. Isothermal forging technique for TiAl can be shown to be useful by the studies for effects of deformation conditions on deformation properties at high temperatures17),22),23),24),26). An example of the results obtained is shown in Fig. 23. This figure is a working map for compression deformation of the as-cast Ti-52.4%Al alloy, in which the flow stress for deformation and information for the deformation ability are drawn in relation to the deformation conditions. Two features in deformation properties of TiAl become clear from this figure. One is that the flow stress is affected strongly by strain rates, that is, the flow stress is lowered rapidly with decreasing the strain rate. The other is that TiAl has enough deformability when we use low strain rates and high temperatures. The authors are able to point out that the good deformability at the low strain rates connects directly with the low flow stress which does not exceed the fracture stress of TiAl. The high flow stress brings the low deformability by exceeding the fracture stress. The two features in the deformation map indicate that isothermal forging is a valid method to hot work TiAl. This means that TiAl can be deformed without serious difficulty, if we can find working tools being durable at high temperatures for a long time.

The first report on the isothermal forging of TiAl in Japan has been submitted by Mitao *et al.*67), which is stimulated by the work in NRIM. As the working tools Mitao *et al.* have adopted Nimowal which can be used below 1320 K. Here, Nimowal developed by Hitachi Metals, Ltd is a Ni-base cast-alloy containing 12%W, 10%Mo, 6%Al and 0.01%Y in mass ratios.

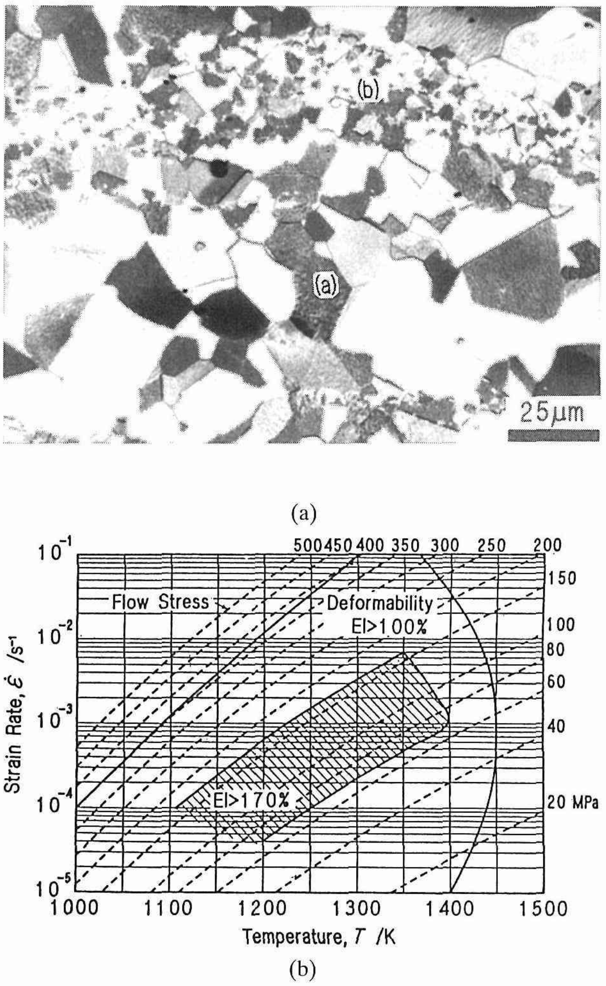
8.2 Superplasticity

To investigate working maps over a wide range of temperature an apparatus shown in Fig. 24 has been developed in NRIM20),21). In this apparatus Sialon is adopted as the working tools. The effects of alloy compositions and microstructures in TiAl alloys on the working maps have been studied extensively using this apparatus17),24). In this study the importance of microstructure to deformation properties at high temperatures has come out, and a phenomenon of superplasticity has been found first. Figure 25 is taken from the first report to show the condition of superplasticity in TiAl alloys26). The microstructure of the used TiAl alloy is shown in Fig. 25(a), and the



Drive system	Electro-hydraulic servo
Max. load	620 kN
Max. speed	200 mm·s^{-1}
Max. heating	1800 K (Induction heating)
Quench system	Argon gas jet of max. 40 K·s^{-1}
Atmosphere	Vacuum (0.001 Pa) or Argon gas
Control system	Program control by personal computer

Fig. 24 Schematic illustration of hot deformation apparatus.



(a)

(b)

Fig. 25 Occurrence of superplastic deformation in Ti-49.5%Al alloy. (a): An optical micrograph of the alloy which was obtained by isothermal forging at 1170 K. (b): Hot workability map on tensile deformation of the alloy having the microstructure of (a).

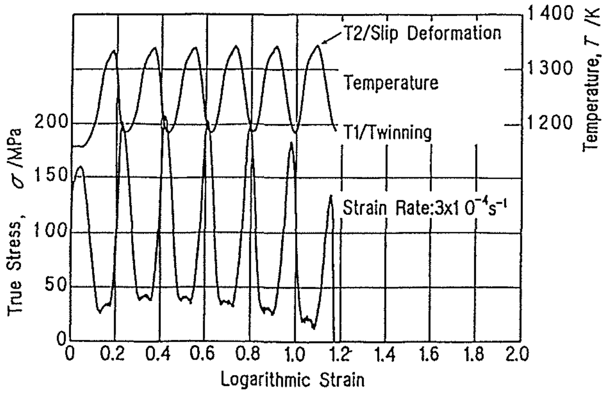


Fig. 26 True stress-strain curve obtained by repeated change of deformation temperature between T_1 and T_2. The material of Fig. 25(a) and a strain rate of 3×10^{-4} s^{-1} were used.

workability map obtained is shown in Fig. 25(b). In those days the elongation attained as much as 200% was a surprise. The superplasticity is attributed to the fineness of microstructure, especially in the part (b) in Fig. 25(a). The part (a) in the figure consists of the γ grains and the part (b) consists of a mixture of the α and γ grains. As mentioned in the previous section, however, at present we can get the tensile elongation of several hundreds percent for the binary TiAl alloys which have the controlled microstructures.

If the temperature is changed during tensile deformation, we can see a new kind of superplasticity. This is shown in Fig. 26. This superplasticity occurs even in alloys whose microstructures are not controlled. This is the so-called dynamic superplasticity, which comes from the change of the deformation mechanism between a low temperature and a high temperature. It is assumed that twinning deformation occurs at the low temperature and slip deformation occurs at the high temperature[22]. The merit of this method is that superplastic hot working can be applied even for as-cast TiAl alloys.

Part III Concluding Remarks

9. Tomorrow of TiAl alloys

Vast endeavors are being made to study various problems related to TiAl alloys in the academic field as well as in the technological field in Japan. As TiAl alloys are the new material not yet to have been cultivated fully, we still have a wide margin of learning and contrivances. This makes TiAl alloys an interesting and useful object of study and, in fact, new research topics have appeared in waves. Those facts encourage us for further development of the TiAl alloys. From the author's point of view, in all cases where a new material of practical use comes into existence, a new research field must be always developed. In other words, there must be a science system of its own in the area of steel, in the area of Al alloys, and in the area of TiAl alloys. The new science system, which is a requisite for developing the new material with special features, is being created in TiAl alloys. The idea of the author for the next steps of development in the TiAl alloys are the following.

A definite theory which describes precisely the true nature of TiAl alloys is expected to be built up from among the following fundamental researches. In the first place, there is a study on nature of atomic bonding in TiAl and effects of third elements on the bonding. These basic factors reflect directly the axial ratio *(c/a)*, and occupation sites of third elements in TiAl, and deformation behavior of TiAl. Prediction for occupation sites of third elements in TiAl has also been tried by semiempirical methods or various kinds of alloy theories, and these predictions are compared with experimental results for the site occupation which are obtained by x-ray diffraction analysis or by field ion microscopy. The occupation site is important information, because it is related strongly to the crystal structure and the deformation behabior of TiAl, and constitution of ternary phase diagrams of Ti-Al-X systems.

An improvement of ductility at ambient temperature is expected to be provided from further studies on alloying effects, microstructure control, and environmental effects. On the other hand, studies on plasticity of Ti_3Al and TiAl, and study on interface of Ti_3Al/TiAl have possibilities yielding a new idea for ductility improvement. It is becoming clear that studies on crack initiation and propagation are important, because cracks tend to propagate in a different way from those in typical metallic alloys.

The selling point of TiAl alloys is that they are light and heat-resisting. Designers of apparatus, however, are looking for better abilities of performance for TiAl alloys. There are many problems to be solved for enlargement of practical use. For use at above 1270 K, the oxidation resistance and high temperature strength, especially creep strength, should be improved. For heightening the reliability, the impact properties at ambient and high temperatures and the effects of environment on mechanical properties including fatigue should be elucidated. For improvement of high temperature strength, formation of microstructure with fine lamellae and dispersion of ceramics in TiAl alloys are known to be effective. For this purpose some studies are in progress.

Various processing techniques for TiAl alloys are being developed now. The best quality is provided by wrought TiAl alloys. Products of near net shape are obtained by powder metallurgy, and products of complicate shape by casting. These are conventional methods for shaping. Combustion synthesis is a unique technique for synthesis of compounds. Diffusion synthesis after shaping is an interesting technique because shaping can be done in a stage of a mixture of metallic raw materials. The qualities of the products differ by the processes, which is closely related with the kind of alloying adequate for processing and the degree of microstructure control.

TiAl alloys are a fronting material whose practical use will be realized within tomorrow. One merit by use of TiAl alloys is to heighten thermal efficiency of various heat engines. This comes from being able to raise the operating temperature and to lighten the moving parts. The other merit is to decrease weight of engines and bodies. This effect is larger for transport machines with higher speed, especially in airplanes and space vehicles. Thus, use of TiAl alloys promotes abilities of human beings. It should be noted once more that TiAl alloys are a new material belonging to metals, which means that the production in large scale without any complex processing is possible.

10. Role of NRIM in present and near future

The drawbacks of TiAl alloys have been surmounted, the new methods to improve the properties have been found, and the various processing techniques have been developed. That is, TiAl alloys have changed from a mere brittle substance to a structure material of high performance impending in practical use. Such the rapid growth is beyond our imagination at the starting of the research in NRIM. After the research boom, vast energy has been poured for R & D of TiAl alloys by many research facilities. In such the situation, the research of TiAl alloys in NRIM is conducted mainly by the third research group. This group is put in charge of three projects.

In the national project "High performance materials for severe environments" organized by MITT, NRIM has been playing an impotant role of "Clarifying the relation between microstructure and properties of TiAl alloys". The research contents in NRIM are closely connected with R & D program of the other organizations included in the project, that is, alloy design for TiAl alloys with high strength at high temperatures, and developing hot rolling technique to sheets and secondary forming technique of sheets into structure components.

In the national project "Evaluation and analysis based on modeling for forecasting physical and chemical properties" organized by STA, NRIM has been evaluating fundamental characteristics of TiAl alloys as an industrial material, and has been examining mechanisms of fracture. In this study the obtained mechanical properties are being analyzed from a fundamental viewpoint.

Another project is the designated research which is set up by NRIM from its own policy. In this project seeds for developing new aspects in TiAl alloys are being studied. These seeds are engendered from the abundant experience for TiAl alloys, inherent challenging spirit of NRIM, and unique constitution of the group members.

Reasonability for the research course and the research organization of NRIM is proved by the facts that plenty of latent possibilities for TiAl alloys has been found successively in NRIM and that the science world has regarded NRIM as an excellent center for the research of TiAl alloys. The author believe that the third group will fulfill a key role for further development of TiAl alloys, with which Japan contributes toward progress in science and technology of the world.

Acknowledgements

This study was carried out when the author was in the third research group. The author is very much indebted to the members of the group and other colleagues. The main collaborators are Drs. M. Nakamura, N. Aritomi, H, Kurabe, M. Nobuki, K. Hashimoto, K. Yamaguchi, H. Onodera and M. Takeyama, and Messrs. T. Mitsui, K. Kasahara, H. Doi, N. Sakuma, H. Suga and O. Nakano. This report is collected laying stress on the works executed by Drs. M. Nobuki and K. Hashimato.

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NRIM Special Report
(Research Report)
No. 93–01

Date of issue: 31 March, 1993

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Printed by Tokyo Press Co., Ltd.

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