GAMMA TITANIUM ALUMINIDE ALLOYS

2014

A collection of research on innovation and commercialization of gamma alloy technology
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PREFACE

This book is a collection of articles describing the current state of research on gamma alloy technology. Many of the articles published here were presented at the Fourth International Symposium on Gamma Titanium Aluminide Alloys (ISGTA 2014) held at the TMS 2014 Annual Meeting & Exhibition, February 16–20, in San Diego, California, USA.

The symposium consisted of eight presentation sessions and one panel discussion session and provided a forum for leading scientists and engineers associated with the gamma-alloy technology to report on recent advances and experiences with introducing the alloys into commercial enterprises, to exchange findings about their limitations and barriers, and to offer insights into the future of gamma alloy technology.

The highlights of the symposium were demonstrations of significant progress made in the industrialization and application expansion of alloy Ti-4822 cast LPT blades. Those in attendance were excited to learn that the first wrought-alloy TNM (beta solidified) LPT blades are nearing implementation. These demonstrations ensured that the foundation of gamma materials–processes technologies have been firmly established along with remarkable advances in required peripheral technologies such as joining, machining, surface protection, and coating. The remaining challenges to produce lower-cost, sound components include casting near-net components, further innovation of processing technologies, and establishing a supply chain capable of mass-production.

Alloy design efforts in wrought-processed material forms were reported and discussed on high Nb-containing alloys, as well as beta-solidified alloys including gamma-modulated alloys, along with related processing such as forging and rolling. Novel processing methods, such as additive manufacturing and spark plasma sintering, and PM route processing were investigated for producing either complex shape and/or low-cost PM products. Unfortunately, these efforts have not shown strategies for achieving higher temperature (>750°C) performing material forms having improved balance in properties. A number of presentations reported familiar results from characterization and phase transformation study of these and other current alloy materials. Some efforts were reported in additional understanding of the influence of microstructures on properties, particularly including applied aspects of PST crystals.

One bright side of alloy design for high temperatures (>750°C) is a new class of gamma alloys called “beta-gamma” alloys that are beta solidified but distinguished from other “beta-solidified” alloys. Beta-gamma alloys are the first alloys that generate gamma-rich, fine-grained fully lamellar structures in both wrought-processed and cast forms with minimized beta volume. These significantly enhance the properties and prospects for improved balance of properties, especially for higher temperatures, potentially raising the gamma alloy-materials to their upper limit of performance.

Organizing Committee

Young-Won Kim
Wilfried Smarsly
Junpin Lin
Dennis Dimiduk
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EDITORS

Young-Won Kim
Young-Won Kim, Fellow of American Society for Materials (FASM) and graduate of Seoul National University, earned his Ph.D. in materials science from the University of Connecticut and worked on strengthening mechanisms and phase diagram construction at Carnegie Mellon University. In 1980, he joined Metcut Research Group (Wright-Patterson Air Force Base) to lead the research and development activities in processing high-strength and high-temperature aluminum alloys. He became well known worldwide and a frequent invited speaker in the areas. In 1989, Dr. Kim began to investigate titanium aluminides, and he joined UES as principal and chief scientist in 1992 to continue his R&D work on gamma titanium aluminide alloys. Since then, he has been involved in all types of projects and experiments and has become recognized worldwide in the areas of alloy design, processing, microstructure control, processing–microstructure–property relationships, environmental resistance, and integration of the data and knowledge toward the applications. After exhaustive R&D and through continuous relations with related industry and OEMs, he began to realize the serious limitations of conventional gamma alloys and their processes. For last several years, he has explored “beta-gamma” titanium aluminide alloys, a robust new class of TiAl-based alloys that exhibit improved balance of properties, especially for higher temperatures, potentially raising the gamma alloy-materials to their upper limit of performance. Other areas of his R&D activity included evaluating or developing Nb-silicides and Mo-silicide based alloys, high-entropy alloys, and dual superalloy disk materials. He is now leading a company, Gamteck, to more effectively contribute to the advances in gamma alloy materials-processes technology through targeted R&D work, consulting on technology details and education. Dr. Kim has published more than 170 articles and six patents; some of his publications on TiAl have been recognized by ISI among the most cited in the area of materials science. He has been actively involved in various technical activities, such as in delivering numerous invited talks and keynote lectures, organizing more than ten major international symposia and workshops, editing eight major proceedings, and serving as a panel member or a sole evaluator for several international and national gamma TiAl alloy programs. He was recognized as the Alumnus of 2003 by the University of Connecticut.
Wilfried Smarsly
Wilfried Smarsly is the Advanced Materials Representative at MTU Aero Engines in München, Germany. Dr. Smarsly earned a degree in Physics, Chemistry and Mathematics from the University of Münster and then completed his Ph.D. in Materials and Manufacturing Process Engineering from RWTH Aachen in 1985. His thesis described forging of Ti 64 powder to improve fatigue strength applied in helicopter engines. He worked as a research scientist at DLR e.V Köln, Institut for Materials Engineering until accepting a position at MTU Aero Engines München in 1987. At MTU, Dr. Smarsly is responsible for the development of advanced materials and raw part processes for aero engine applications. Dr. Smarsly is an expert on intermetallic materials (e.g., titanium aluminides) and has experience with alloys such as nickel superalloys, aluminum alloys, titanium alloys, niobium alloys, and intermetallics such as NiAl, and Mo-Si. He also works with processes such as melting and casting and forging processes and with pyrometallurgical processes, such as metal injection molding and spray forming.

Junpin Lin
Junpin Lin is the deputy director and professor of State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing. He has been honored with the “Cheung Kong Scholar” Professorship by the Ministry of Education of China. He received his bachelor’s degree at Harbin Institute of Technology in 1983 and Ph.D. degree in 1989. His major research fields include structural intermetallics (high-temperature TiAl alloys, Fe-Si alloys, etc.), severe deformation and structure controlling for hard-deformed materials, advanced porous materials, and new materials for extra-strong liquid zinc resistance. Dr. Lin is the chief scientist of the Major State Basic Research Development Program of China (973 program) and has already published more than 300 papers, applied 23 patents, and received high-level awards for scientific and technological achievements. He has made more than 30 invited presentations at regional, national, and international levels, including plenary and keynote lectures.

Dennis M. Dimiduk
Dennis M. Dimiduk is a Laboratory Fellow and past technical director of the Structural Materials Division at the Air Force Research Laboratory, Materials and Manufacturing Directorate. Through the early 1980s he performed research on alloy development, phase transformations, and strengthening mechanisms in high-temperature superalloys. Dr. Dimiduk led the intermetallics research area for the Air Force, conducting in-house research and motivating research at other laboratories and universities. Throughout the 1990s, work by Dimiduk and his colleagues on titanium aluminides and refractory intermetallics opened an approach toward raising use temperatures and realizing weight reductions in advanced engines. Their research led to current introductions of titanium aluminides into commercial turbine engines. In 1989, Dr. Dimiduk contributed to and led research seeking to understand...
the influence of chemistry on microstructural evolution and deformation in alloys through computer simulation. The group’s involvement in materials simulations led directly to the community’s current and growing activities in Integrated Computational Materials Science & Engineering (ICMSE) and the Materials Genome Initiative (MGI). That research also led to advancements in the 3D characterization of materials, new techniques for mechanical property characterization at the micrometer scale and, to the discovery of a new regime of size-affected metal deformation behavior. Dr. Dimiduk continues to pursue and explore those advancements today. Dr. Dimiduk received his B.S. degree in Materials Science and Engineering in 1980 from Wright State University. He completed his M.S. and Ph.D. degrees in Metallurgical Engineering and Materials Science at Carnegie Mellon University in 1984 and 1989, respectively. He has authored or co-authored more than 190 technical papers, 13 patents, and 2 book chapters, and has co-edited 4 books. He is a member of the editorial board for Intermetallics and is an adjunct professor at The Ohio State University. In 1993–94 he was a Visiting Scholar at the University of Oxford, UK, conducting collaborative research and lecturing on structural intermetallics. Dr. Dimiduk received the 1991 AFSC Waterman Award for science, the 2004 Charles J. Cleary Award for scientific achievement and, and five "Star Team" awards from the Air Force Office of Scientific Research. He was elected Fellow of ASM International in 1997 and Fellow of the Air Force Research Laboratory in 1998. He was selected for a Carnegie-Mellon University Alumni Achievement Award in 2008. Dr. Dimiduk has been a member of TMS, ASM, and MRS throughout his career. Presently he is the Past Chair of the Structural Materials Division of TMS and served on the TMS Board of Directors.

Fritz Appel

Fritz Appel has continued to play an active role in TiAl research since his retirement in 2006 as group leader of physical metallurgy. He obtained a Ph.D. in 1973 and his habilitation in 1987 from the Martin-Luther University in Halle. He spent six months in Japan on a JSPS fellowship in 1987, joining the Institute of Materials Research in Geesthacht in 1990. He received the Tammann Award from the German Society for Materials Science in 1999 and the Charles Hatchett Award in 2002 from the Institute of Materials, London. He has authored or co-authored a number of publications and holds six patents in the field. Together with Jonathan Paul and Michael Oehring he wrote the book Gamma Titanium Aluminide Alloys, published by Wiley-VCH (2011).
GAMMA TITANIUM ALUMINIDE ALLOYS 2014

Alloy Design and Development
ALLOY DESIGN CONCEPTS FOR WROUGHT HIGH TEMPERATURE TiAl ALLOYS

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Keywords: High Nb-TiAl alloys, Wrought TiAl alloy, Workability, Mechanical property

Abstract

Wrought TiAl alloys provide more possibility to control the microstructure and give a balanced mechanical properties than cast alloy. Titanium aluminides based on the general composition Ti-45Al-(6-9)Nb (in at.%) exhibit several desired properties for higher temperature applications. Nb addition changes the Ti-Al phase diagram and the segregations of Nb and other elements are easy to form, which induces formation of B2 phase. B2 phase worsens the mechanical properties at both room temperature and elevated temperatures. The new idea is that the β phase is can be used to improve the hot-workability, and the segregations can be lightened during the deformation and finally disappeared, so stable B2 phase is avoided at room temperature. Otherwise, high Nb addition significantly reduces the stalking fault energy (SFE), resulting in abundant twinning and twin intersections, which plays an important role for accommodating heterogeneous deformation and avoiding formation of microcrack at boundaries. The basic compositional characteristics of the high temperature TiAl alloys are high Nb and low Al content, typically 6/9 Nb and 44/46Al. Carefully microalloying using the elements B, W, Y, C may further optimize the properties of the alloys. These wrought alloys have excellent oxidation resistance, balanced mechanical properties and good workability.

Introduction

Gamma TiAl alloys display attractive properties for high temperature applications. They have attracted significant attention in the last 30 years for their attractive properties that have the potential to enable high temperature automobile, aerospace and other industry applications. Due to low density and high strength, TiAl alloys have become front-runners in replacing nickel-based superalloys in gas turbine engines. Replacement of Ni-based superalloy components with TiAl alloys is expected to reduce the structural weight of high performance gas turbine engines by 20-45% [1]. TiAl alloys have been used in General Electric’s GEnx gas turbine engine designed for the Boeing’s 787 Dreamliner [2]. Cast 4822 TiAl alloys are being used in low pressure turbine blades. It is well established that the properties of TiAl alloys are highly dependent on composition and microstructure. An inhomogeneous microstructure resulting from chemical inhomogeneity can lead to a large scatter in mechanical properties. This is undesirable and can result in components being over-designed so that minimum properties can be guaranteed. For the components produced by ingot metallurgy, any chemical segregation during ingot solidification is very difficult to remove, requiring subsequent heat treatment at temperatures within thephase field or even higher. Defects such as cracks, inclusions, or even porosity may be present within ingots. The extent of such defects and elemental macro segregation is magnified as ingot size increases. These inherent problems make the production of large parts, with guaranteed properties and homogeneous microstructures, much more challenging. Wu [3] recently reported that the low ductility is the biggest problem in the application of TiAl based alloys as structural components since 1% is generally accepted as the minimum acceptable level and cast samples in particular seldom reach even this level. The other major problem with TiAl alloys is the difficulty in processing them to form a component. This great issue limits the application in many areas of TiAl alloys.

Hot working, such as extrusion, forging and rolling, either singly or combined, are often used to refine the cast microstructures and improve the mechanical properties of ingot material. There is the thermo-mechanical processing to adjust specific microstructures by means of forging and/or ensuing heat treatments. So, the wrought TiAl alloys provide more possibility to control the microstructure and give a balanced mechanical properties than cast alloy. High temperature TiAl alloys (high Nb-TiAl alloys) developed by Chen et al. [4-6] were suggested to be the first example for the development of high performance TiAl alloy for high temperature application by Young-Won Kim [7]. Titanium aluminides based on the general composition Ti-45Al-(6-9)Nb exhibit several desired properties for higher temperature applications. Nb addition changes the Ti-Al phase diagram and the segregations of Nb and other elements are easy to form, which induces formation of B2 phase. B2 phase worsens the mechanical properties at both room temperature and elevated temperatures. The new idea is that the β phase is can be used to improve the hot-workability, and the micro segregations can be lightened during the deformation and finally disappeared, so stable B2 phase is avoided at room temperature. Otherwise, high Nb addition significantly reduces the stalking fault energy, resulting in abundant twinning and twin intersections, which plays an important role for accommodating heterogeneous deformation and avoiding formation of micro-crack at boundaries. The intention of the present paper are:

1. to identify the effect of Nb addition in the phase transformation of TiAl alloy;
2. to figure out the strengthening mechanism in high temperature TiAl alloy;
3. to discuss the deformation behaviors and workability;
4. to evaluate the oxidation resistance and mechanical properties.

Effect of Nb addition in the phase transformation of TiAl alloy

The high Nb addition greatly changes the phase diagram of binary TiAl alloy. The quasi-phase diagrams of Ti-Al with 8Nb and 10Nb addition are shown in Fig. 1 [8], for comparison the binary Ti-Al phase diagram is presented as dotted lines [9]. It can be seen that 8-10 Nb addition has pronounced effect on the phase relationship of TiAl alloys. The effects are summarized as follows [9].

1. The melting point increases by about 60-100 °C, for example, from ~1500 °C of Ti-45Al alloy to 1610 °C of Ti-45Al-10Nb alloy.
2. The β transus (β/α+β boundary) decreases by 50-80 °C, and the β phase region is extended to higher Al concentration.

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(3) The α transus decreases by about 30 °C. The α/α+β transus decreases by 50-100 °C. The α phase region becomes narrowed and moves to higher Al concentration.

(4) The low temperature phase region (α+γ) is replaced by the α+γ+B2 ternary phase region if Nb content exceeds 10%.

Nb element is strong stabilizer of β phase, so the area of β phase enlarges remarkably; the β phase solidification occurs at Al content of about 44-46%, avoiding the peritectic transformation, which results in the grain refining and reduces the micro-segregation of Al and Nb. Another important result is that the B2 phase is equilibrium phase if Nb content reaches 10%, and this means that micro-segregation of Nb can depress the occurrence of B2 phase. It can be concluded that high Nb addition can enhance the workability of TiAl alloys at high temperature because of existence of β phase; Nb content cannot exceed the 10%, avoiding stable B2 phase at room temperature, which worsen the mechanical properties at both ambient and high temperatures.

**Strengthening Mechanism in high temperature TiAl alloy**

Our many works reveals that the high strength of high Nb-TiAl alloy comes from the solid-solution hardening effect of Nb additions [10-13]. In order to examine whether the high strengths come merely from the strengthening of lamellar interfaces, the strengths of binary (-0 Nb) and ternary alloy (-10 Nb) were plotted as a function of the lamellar spacing for the alloys containing 44-49% Al (Fig. 2) [10]. As can be seen, the hardening effect of lamellar spacing at 900 °C follows the Hall-Petch relation. The hardening coefficients k0 shown in the Fig. 2 for the alloys with Nb and without Nb additions are 0.14 and 0.12 MPa m1/2, respectively. These results suggested that the strengthening effect of lamellar interfaces is eventually the same in both binary TiAl and ternary TiAl-10Nb alloys. The value of k0, observed in Fig. 2 is close to the k0 reported by Liu et al [14] (k0 = 0.15 MPa m1/2 at 800 °C).

It is important to note that the strengths of FL ternary alloys are much higher than that of FL binary alloys with a similar lamellar spacing. Considering the similar colony size of both kinds of alloys, the high strength of FL ternary alloys is resulted from the solid solution strengthening of Nb addition. The friction stress σ0 in the Hall-Petch equation at 900 °C is 267 MPa for ternary TiAl-10Nb alloys, nearly 100 MPa higher than that of binary TiAl alloys (178 MPa).

Fig. 1 Quasi-phase diagrams showing the effect of 8Nb and 10 Nb additions on the phase relationship of near γ-TiAl alloys (solid lines) [8]. The binary Ti-Al diagram is drawn in dotted lines for reference.

Fig. 2 Hall-Petch relations for both FL binary alloys and 10 Nb containing ternary alloy

It is interesting that the lower SFE leads to the twinning intersections even in the cast high Nb-TiAl alloys, as shown in Fig. 3 (index as the arrows). During the deformation at high temperature, a lot of intersections of twins and platelets, resulting formation of new twins and dislocations, as shown in Fig. 4, that significantly reduces stress concentration, avoiding formation of microcrack at boundaries. So the high Nb addition remarkably increases the strength at room temperature, maintaining enough ductility.
Deformation behavior and workability

It is very hard to produce industrially required large and complex parts from TiAl alloys by hot-forging, due to limited equipment capability, cracking, etc. For the application of wrought TiAl alloys, the reduction of high temperature flow stress and improvement of deformability is essential. In the case of TiAl alloys, the most effective way to accomplish this is the introduction of B2 phase during the deformation [13]. Fig.5 shows the microstructures of cast ingot with a weight of 1000kg of high Nb-TiAl alloy by plasma arc melting. It can be seen that this is refine NF microstructure with B2 phase and the high magnification image shows dark ω phase in the light B2 phase.

In general, the route for rolling sheet for TiAl alloys is that multi-step canned forging is first, in order to refine the coarse cast microstructures, then hot rolling. Fig.6 shows the sheet with the size of 310x80x4.68 mm³ by hot rolling directly from cast ingot, and deformation is ~70%. This reveals that the cast ingot of high Nb-TiAl alloy has an excellent workability, which results from the fine microstructure and some volume of B2 phase.
Oxidation resistance and mechanical properties

The actual service of TiAl alloy has been hindered by their poor oxidation resistance above about 750 °C. A great deal of research work has been undertaken to improve the oxidation behavior of these alloys by adding ternary and quaternary elements. In view of third element addition, niobium and several other elements have been reported to be effective in the oxidation resistance of TiAl [17-21]. High Nb addition greatly improves the oxidation resistance of TiAl alloys. Alloys with higher Nb contents (up to 10 %) show much smaller mass gain in the isothermal oxidation at 900 °C [21]. Nb is firstly supposed to function as a dopant element with a higher valence than titanium, which is expected to decrease the oxygen vacancy concentration owing to the electroneutrality in the oxide, and thus to suppress rutile growth [22]. The addition of Nb also has other effect on the oxidation behaviors, such as increasing the activity of Al, lowering the solubility of oxygen in the alloy and promoting the formation of TiN at the oxide scale/substrate interface, which impede the diffusion of titanium and oxygen ions [23-25]. Our recent work reveals that an appropriate amount of Y addition (depend on Nb) is effective in improving the oxidation resistance, especially high temperature long term oxidation resistance (1000hrs and 1000 cycles) by refining the oxide particles, promoting formation of a protective continuous Al2O3 scale and improving the adherence of the oxide scale and matrix the inter-layer adhesion [26-27].

The high Nb-TiAl alloys have good workability, so high-quality pancake can be produced by multi-step canned forging of the ingot. Microstructure in the major part of the pancake is homogenous with a DP microstructure containing equiaxed y-fine α'/γ lamellae with a grain size of about 20-30 μm, while in the near surface zone is a fine-grained DP and retained lamellar colony. The metastable β phase is eliminated, and the long boride ribbons are broken off. Both microstructures of the alloy had excellent strength at room and high temperatures. Fig. 7 shows the typical engineering tensile stress-strain curve for wrought high Nb-TiAl alloys at room temperature. The yield stress and ultimate stress are 782 MPa and 912 MPa, respectively. The most important is that the elongation is 2.3%.

The as-forged material was stronger and much more ductile than the as-cast material, exhibiting a brittle-ductile transition with an elongation 2.3% at room temperature increasing to 59.1% at 815 °C [28]. The YS and UTS of the as-forged material are 537 and 648MPa at 815 °C, respectively.

For the high temperature application, the creep behaviors are very vital. The creep properties for the wrought high Nb-TiAl alloys are better than that of the conventional TiAl alloys with both DP and FL microstructures. The creep temperatures of high temperature TiAl alloy are 60-100 °C higher than that of conventional TiAl alloys [29]. The higher creep strength can be attributed to higher friction stress, lower recrystallization rate, higher microstructure stability and lower SFE and diffusion-assisted transport processes [29].
Challenge for wrought high Nb-TiAl alloy is how to get the homogenous fine Fl microstructure by ensuing heat treatment, in order to further enhance the high temperature capability.

![Graph](image)

Fig. 7 The engineering tensile stress-strain curve for wrought high Nb-TiAl alloys at room temperature

**Conclusion**

1. High Nb addition changes the TiAl phase relationships and the segregations of Nb and other elements are easy to form, which induces formation of B2 phase;
2. The new idea is that the P phase is can be used to improve the hot-workability, and the segregations can be lightened during the deformation and finally disappeared, so stable B2 phase is avoided at room temperature.
3. High Nb addition significantly reduces the stalking fault energy, resulting in abundant twinning and twin intersections, which plays an important role for accommodating heterogeneous deformation and avoiding formation of micro-crack at boundaries.
4. The basic compositional characteristics of the high temperature TiAl alloys are high Nb and low Al content, typically 6/9 Nb and 44-46 A1.
5. These wrought alloys have excellent oxidation resistance, balanced mechanical properties and good workability.

**Acknowledgement**

The authors thank the National Basic Research Program of China (973 Program) for financial support under contract No. 2011CB605501 and The National Natural Science Foundation of China for financial support under contract Nos. 51271016 and State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, under contract No. 2012Z-06.

**References**

PHYSICAL METALLURGY AND PERFORMANCE OF THE TNB AND γ-Md Alloys

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Abstract

The paper describes the alloy systems TNB and γ-Md, which are based on the general composition Ti-(42-45)Al-(5-10)Nb (at. %). Optimized alloys exhibit exceptional constitution, microstructure and properties. A collection of mechanical data will be provided, involving strength, ductility, toughness, creep, and fatigue. With regard to technical applications several aspects of processing will be discussed.

Introduction

Due to their outstanding thermo-physical properties titanium aluminate alloys are being considered as lightweight structural materials for high-temperature technologies. However, in spite of long-standing research and development over almost three decades, practical applications are still rare [1]. A critical factor in the decision of whether the new materials will be used is certainly the benefit that can be achieved over the materials currently in use. In this respect TiAl alloys are often inferior to nickel-base superalloys or conventional titanium alloys even if the mechanical properties are compared on a density compensated basis. Major concerns are in particular, bad balance of strength and ductility [2], insufficient creep resistance [3] and low fatigue strength [4]. In an attempt to overcome these deficiencies, two alloy systems, TNB and γ-Md, have been developed at the Helmholtz-Zentrum Geesthacht (formerly GKSS). The physical metallurgy and the mechanical properties of these alloys will be assessed in the present contribution.

Constitution and Microstructure

Gamma TiAl alloys with high additions of Nb have been the subject of research for a long time [5-8]. Nb is soluble in the α2 and γ phases up to at least 8 at. % and thus, such alloys are of particular interest with respect to solid-solution effects. The constitution of the Ti-Al-Nb system has been intensively studied [9-12], due not only to the engineering importance of high Nb containing alloys but also because of their complexity. Recently, a thermodynamic re-evaluation has been carried out which represents the current knowledge about the system, although some unresolved discrepancies remain [12]. This work confirmed the high solubility of Nb in the α2 and γ phases and also the fact that the phase boundaries between these phases run roughly on lines of constant Nb concentration in composition ranges relevant for γ alloys, i.e. the constitution of ternary alloys bears some similarity to binary Ti-Al alloys for these compositions. A direct comparison of the quasi-binary system for 8 at. % Nb and the binary alloy system in the range 35-55 at. % Al showed that the α-transus temperature is slightly decreased, the peritectic and eutectoid temperature significantly raised by ~ 50-60 K, and the Ti solubility in the γ phase increased by around 1.5 at. % for the quasi-binary system [10]. The latter observation results in higher volume fractions of γ phase compared to binary alloys for Al concentrations in the two-phase region. Thus, for a given volume fraction of γ phase, the Al content in ternary alloys is lower; this is associated with a lower α-transus temperature. Further, by adding 8 at. % Nb to binary alloys, the eutectoid composition is shifted from ~ 40 to 42 at. % Al [10, 12, 13]. This means that a considerable fraction of γ lamellae in Nb containing alloys is only formed if the material is cooled below the eutectoid temperature, whereas in binary alloys the fraction of γ phase only slightly changes when the eutectoid temperature is crossed. Besides these differences additional phases occur in the ternary system, for example in alloys with Nb concentrations above 8 at. %, the B2 phase forms around the eutectoid temperature. Appel et al. [14] found a new phase in Ti-42Al-8.5Nb that had an orthorhombic B19 structure, and which was not predicted by the known phase diagrams. This phase, that is not easy to detect due to its extremely fine dispersion, occurs in a wide range of TNB alloy compositions and generates a new type of microstructure. Additionally, at low temperatures the ω-phase with B2 structure also arises for Nb concentrations higher than 3 at. % [12, 15]. Here it has to be mentioned that phase transformations below 700 °C are generally sluggish in Nb-bearing alloys and thus, the phase constitution may often not be in thermodynamic equilibrium and depends on the prior processing route. In the present study the so-called TNB [16, 18] and γ-Md [17] alloys will be discussed, whose compositions are given in Table I.

Table I: Designation and composition of TNB and γ-Md alloys.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Composition (at. %)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNB</td>
<td>Ti-45Al-(5-10)Nb-(0-0.2)(B, C)</td>
<td>16</td>
</tr>
<tr>
<td>TNB-V2</td>
<td>Ti-45Al-8Nb-0.2C</td>
<td>16</td>
</tr>
<tr>
<td>TNB-V5</td>
<td>Ti-45Al-5Nb-0.2B-0.2C</td>
<td>16</td>
</tr>
<tr>
<td>TNB-V15</td>
<td>Ti-45Al-5Nb-2Mo</td>
<td>18</td>
</tr>
<tr>
<td>γ-Md</td>
<td>Ti-42Al-8.5Nb</td>
<td>17</td>
</tr>
</tbody>
</table>

TNB-Alloys

The alloys have Al concentrations in the range 44-46 at. % and contain further alloying elements (see Table I), which implement additional phases such as carbides and/or borides in order to improve properties such as creep resistance or result in microstructural refinement. In a specific alloy variant the β phase is stabilized by elements like Mo [18]. Since the addition of very high amounts of β stabilizing elements can completely change the constitution of such alloys, and are thus beyond the scope of this article, they will only be described briefly.

Due to the similarities in constitution of high Nb containing alloys and their binary counterparts, after certain processing schemes similar microstructures often evolve. For lower Al concentrations,