MICROSTRUCTURE AND MECHANICAL PROPERTIES
OF LOW AND HEAVY ALLOYED $\gamma$-TiAl+$\alpha_2$-Ti$_3$Al BASED ALLOYS
SUBJECTED TO DIFFERENT TREATMENTS

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Abstract
Microstructure and mechanical properties of the cast Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy and the Ti-45Al-8Nb-0.2C alloy after hot extrusion followed by heat treatment were studied in the present work. The hot-worked alloy showed significantly higher strength/ductility properties at room temperature as compared with those of the cast alloy, whereas similar strength/ductility properties and long-term strength were obtained for both alloys at elevated temperatures.

Key words: titanium aluminides based on $\gamma$-TiAl+$\alpha_2$-Ti$_3$Al; microstructure; mechanical properties

1. Introduction
Low processing abilities, particularly poor ductility below the brittle-ductile transition, low hot workability and hard machinability appear to be the main obstacles for wide industrial application of cast intermetallic alloys based on $\gamma$(TiAl)+$\alpha_2$(Ti$_3$Al). In an attempt to overcome these deficiencies different approaches based on alloy designing and wrought processing have been explored in the past two decades. The most substantial of them are the following.

1) Obtainment of the duplex microstructure by heat treatment in alloys like Ti-48-2Cr-2Nb, in which the lamellar structure is not stable because of a low content of the $\alpha_2$ phase [1-3]. This approach provides room temperature elongation up to 1.5-2% but results in lower creep resistance at $T > 700^\circ$C and relatively low strength and fracture toughness.

2) Obtainment of the duplex microstructure by hot extrusion in alloys with higher creep resistance based on Ti-45Al-(5-10)Nb [4,5]. The duplex microstructure in these alloys can provide enhanced room temperature ductility (around or more than 1% of plastic strain in the extrusion direction), high strength properties both at room and elevated temperatures and heavy alloying maintains eligible creep resistance.

3) Designing of alloys with the base line composition of Ti-(40-44)Al+Nb, in which refined modulated lamellar microstructure containing ductile phases like the orthorhombic B19 phase can be produced by hot extrusion. As has been recently shown, this microstructure provided room temperature plastic elongations in the extrusion direction up to around 2.5%, high strength properties both at room and elevated temperatures and relatively good creep resistance in spite of the presence of the $\beta$(B2)/B19 phase [6,7].

4) Preparation of thermomechanically treated refined $\gamma$+$\alpha_2$ lamellar structure via using thermomechanical treatment, particularly extrusion at $T \geq T_\alpha$, where $T_\alpha$ is the $\alpha$-transus temperature. This method was found to increase the room temperature ductility (up to 2-4% of plastic strain) and strength properties in relatively low alloyed alloys but seems to be not so effective in heavy alloyed high creep resistant alloys [8-13].

5) Obtainment of refined convoluted structure through the massive transformation of heavy alloyed alloys like Ti-46Al-8Ta. As has been recently revealed, this type of microstructure can give rise to improved room temperature plastic elongations (up to around 1%); however a high level of dendritic segregation in the Ta containing alloy hinders the massive transformation and leads to the formation of inhomogeneous microstructure and significant scatter in the mechanical properties [14]. Additionally, this technique is feasible for thin sections that restrict its practical use.
6) Designing of alloys solidifying solely through the β-phase and alloyed by Nb, Mo, B and other elements. Microstructure refinement in β-solidifying alloys is provided by the alloying effect on the kinetics of the β⇒α transformation and stability of α grains on passing through the (α+β)/α phase field during cooling [15-17]. It seems that improved tensile/strength properties and appropriate creep resistance might be attained in the cast TNM based alloys [18,19].

7) Designing of β(B2)+γ+α2 alloys with lower creep resistance but higher hot workability and good machinability [20,21]. These alloys are appropriate for hot forming, sheet rolling, machining operations but a high content of the β(B2) phase dramatically reduces the creep resistance.

Reviewing these works one can see that the best creep resistant alloys in the lamellar condition (both in the cast and thermomechanically treated lamellar condition) typically demonstrate a room temperature tensile ductility of less than 1% plastic strain [11-14,22], which is of major concern for practical use. Note that thermomechanical treatment providing improved mechanical properties is very laborious in respect of γ-TiAl alloys and achievement of properly balanced mechanical properties in cast alloys is of great practical interest.

The present work was focused on two approaches above designated as 2 and 6: 1) obtainment of the duplex microstructure by hot extrusion in the high creep resistant alloys; 2) obtainment of refined lamellar microstructure in β-solidifying alloys during casting and cooling.

In the second case, lower alloying was applied to avoid: i) the formation of very fine ε2 and γ lamellae (with thickness of 50 nm and less), typically observed in heavy alloyed alloys [6,7,23,24] that should be favorable for low temperature ductility; ii) strong dendritic segregation, which is promoted by a high content of niobium and molybdenum; iii) undesirable β(B2)⇒ω phase transformation [23,25] that can also contribute to the ductility. Reasoning from the aforesaid, the present study was aimed at considering the balance between room temperature ductility/strength properties and creep resistance in the Ti-45Al-8.5Nb-0.2C alloy after hot extrusion in the (α+γ) phase field followed by heat treatment and in the cast Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy subjected only to heat treatment.

2. Experimental

The Ti-45Al-8.5Nb-0.2C alloy was produced by VAR technique and delivered in the extruded condition as rods of ∅48×90 mm by GKSS Research Center, Germany. The ingot material was extruded at 1250°C to a ratio of 7:1, then subjected to annealing at 1280°C for 2 h followed by furnace cooling down to 900°C with a rate of ≈1°C s⁻¹ and ageing at 900°C for 3 h followed by furnace cooling. The heat treatment was made to produce equilibrium duplex microstructure free of the metastable β(B2) phase. The Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy was produced by VAR followed by remelting and homogenization in cold crucible. The ingot material with ∅60×200 mm obtained using this technique was then HIP’ed at 1200°C and P=2000 bar (4 h) and aged at T=900°C (3 h). The density measurements performed for both alloys gave 4.24 and 4.03 g/cm³, respectively.

The tensile specimens having gauge section of ∅5×25 mm were prepared from the both alloys. From the extruded material, the tensile specimens were machined parallel to the extrusion axis. The tensile tests were performed at T=20, 600, 700 and 750°C with an initial strain rate of de/dτ=3.3×10⁻⁴ s⁻¹. The specimen surfaces were mechanically polished before testing using grinding papers. Three and two specimens per point were tested at room and elevated temperatures, respectively.

For quick estimating the creep resistance of the materials, long-term strength tests were performed at T=600, 700, 750°C. To do it, the specimens having the gauge section of ∅5×25 mm were subjected to creep testing using relatively a high loading (in the range of P=350-550 MPa) during 100 hours. The specimen surfaces were also mechanically polished before testing. The three-arm load machines having a lever arm ratio of 7:1 was used for these tests. The tests were carried out in air. Total elongation of the specimens was measured after testing.
Scanning electron microscopy (SEM) in the back-scattering electron (BSE) mode was performed in a Leo-1550 (Zeiss SMT) microscope, which was equipped with an energy dispersive X-ray (EDX) analysis system. X-ray diffraction (XRD) measurements were performed using Co-Kα radiation. The software product X’Pert HighScore Plus was used to indicate the alloy phase compositions.

3. Results and Discussion

Microstructure characterization. Figs. 1a,b represent the macro- and microstructure of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy in the HIP’ed and aged condition. One can see that the macrostructure is very homogeneous. The microstructure is lamellar consisting of plates of the γ/α₂ phases with typical boride threads having a length up to 150 µm and locating both along colony boundaries and in the interior of the colonies. Fig. 1c shows histogram of the colony size distribution. The mean colony size is d≈52 µm but relatively coarse colonies with a size up to 200-280 µm were sometimes met.

Figs. 2a,b represent BSE images of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy. The β(B2) phase was not detected that was a result of low alloying by β-stabilizing elements. X-ray diffraction measurement (not presented here) confirmed the presence of the γ-TiAl and α₂-Ti₃Al phase. The EDX analysis showed that the content of Cr and Mo was slightly higher in the α₂ phase than that in the γ phase (Table 1).

![Fig. 1.](image-url)
Fig. 2. BSE images of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy in the cast + HIP’ed and aged condition; b – the regions are marked from which EDX analysis was performed.

<table>
<thead>
<tr>
<th>Area</th>
<th>Al</th>
<th>Ti</th>
<th>Cr</th>
<th>Nb</th>
<th>Mo</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.73</td>
<td>49.70</td>
<td>0.48</td>
<td>2.87</td>
<td>0.22</td>
<td>γ</td>
</tr>
<tr>
<td>2</td>
<td>46.77</td>
<td>49.47</td>
<td>0.45</td>
<td>3.10</td>
<td>0.21</td>
<td>γ</td>
</tr>
<tr>
<td>3</td>
<td>46.94</td>
<td>49.58</td>
<td>0.37</td>
<td>2.97</td>
<td>0.15</td>
<td>γ</td>
</tr>
<tr>
<td>4</td>
<td>38.17</td>
<td>57.80</td>
<td>0.73</td>
<td>3.03</td>
<td>0.27</td>
<td>α₂</td>
</tr>
<tr>
<td>5</td>
<td>39.71</td>
<td>56.49</td>
<td>0.61</td>
<td>2.94</td>
<td>0.25</td>
<td>α₂</td>
</tr>
<tr>
<td>6</td>
<td>37.78</td>
<td>58.34</td>
<td>0.68</td>
<td>2.88</td>
<td>0.32</td>
<td>α₂</td>
</tr>
</tbody>
</table>

Table 1

Results of EDX analysis of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy made from the areas marked in Fig. 2b (in at. %)

Figs. 3a,b represent BSE images of the Ti-45Al-8Nb-0.2C alloy after extrusion, annealing and ageing. Near fully fine-grained microstructure with a mean grain size of d≈5 μm, as a result of dynamic recrystallization, was produced in the extruded material. Striped microstructure with stripes parallel to the extrusion axis was observed after extrusion testifying to the texture formation. The lamellae remnants elongated along the extrusion axis were sometimes observed in the extruded condition. After annealing and ageing the duplex type microstructure with a low fraction of lamellae colonies and a grain size in the range of d=2…20 μm was obtained. After the heat treatment, the striped microstructure typical of the extruded condition was not distinguished. The β(B2) phase was not detected in the obtained condition that was in accordance with X-ray diffraction (not presented here). The grains/colonies size averaged d≈10 μm. It should be noted that annealing at higher temperatures (1300…1320°C) led to a rapid growth of the α grain size up to 1-2 mm that gave a very coarse lamellar γ+α₂ structure.

This result seems to be in contrast with refs. [6,7], where two major constituents, lamellar γ+α₂ colonies and pearlite-like structure consisting of the γ, α₂ and β(B2)/B19 phase, were obtained after extrusion and stress-relief annealing at 1030°C in the alloy lying in the composition range of Ti-(40-44)Al-8.5Nb. The presence of lamellar colonies in the extruded condition can be ascribed to the fact that the extrusion temperature was near T₀ due to lower aluminum content, whereas this temperature was significantly lower T₀ for the alloy under study. An appearance of the pearlite-like microstructure can also be ascribed to lower aluminum content, which might promote the phase transformations α(α₂)⇒β(B2)⇒B19 in the regions enriched by niobium [6,7].

Tensile mechanical properties. Figs 4a,b show the tensile mechanical properties of the alloys under study depending on the test temperature. The ductility/strength properties of the extruded alloy at room temperature were found to be appreciably higher than those of the cast alloy that can be ascribed to the fine duplex microstructure. Nevertheless, total plastic elongation...
δ=1% and ultimate tensile strength $\sigma_{\text{UTS}}=614-632$ MPa were reached in the cast + HIP’ed and aged alloy that is a good result in comparison with castable heavy alloyed $\gamma$-TiAl alloys \[13,14, 22-24\]. Note that the room temperature ductility was apparently restricted by the presence of relatively coarse colonies with $d>100-200$ µm. One can speculate that excluding these colonies higher elongations at room temperature might be attained in the alloy.

![Fig. 3. BSE images of the Ti-45Al-8Nb-0.2C alloy: a – after extrusion at $T\approx1250^\circ$C, b – after additional annealing and ageing. Extrusion direction is horizontal.](image)

![Fig. 4. (a) Temperature dependencies of elongation and (b) ultimate tensile strength of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B and Ti-45Al-8Nb-0.2C alloys in the cast and hot-worked conditions respectively.](image)

The elongation of both alloys slightly increased with increasing the test temperature from 20 to 750°C. As was shown for the stoichiometric TiAl alloy \[26,27\], a growth of the ductility can be ascribed to strain delocalization due to: i) absorption of lattice dislocations by grain boundaries, ii) grain boundary sliding, iii) enhancement of generation of lattice and twinning dislocations, iv) enhancement of cross dislocation sliding and climbing. These processes occurred more extensively in the alloy with the duplex microstructure and, therefore, the Ti-45Al-8Nb-0.2C alloy at 750°C showed higher elongations than those of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy. By way of illustration, figs. 5a,b represent typical TEM images of the alloys after straining at 750°C. One can see that higher density of dislocations and twins was reached in the Ti-45Al-8Nb-0.2C alloy in contrast to the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy. Particularly, extensive deformation twinning was observed in the Ti-45Al-8Nb-0.2C alloy whereas only weak twinning occurred in the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy.

Ultimate tensile strength of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy slightly increased with increasing the test temperature reaching maximum at 600°C, then decreased. In the case of the
Ti-45Al-8Nb-0.2C alloy, ultimate tensile strength decreased monotonously with increasing the test temperature. The retention of strength in Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B with increasing the test temperature can be explained by the presence of a high density of coherent and semicoherent γ/α₂ boundaries, in which absorption of lattice dislocations is difficult. In the alloy with the duplex microstructure a decrease of ultimate tensile strength with increasing the test temperature suggests that deformation occurs along interface/grain boundaries, which gradually transform from barriers to dislocation sinks [26]. As a result, the strength properties of the extruded material were significantly higher at room temperature but in the temperature range of 600-750°C were found to be close to one another.

Fig. 5. TEM images of the sample working parts near the fracture zones of the (a) Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B and (b) Ti-45Al-8Nb-0.2C alloys after straining at T=750°C.

The heat treatment of the Ti-45Al-8Nb-0.2C alloy was performed so that to exclude the β(B2)-phase and the β(B2)⇒B19 phase transformation. These phases were really not detected. Nevertheless, room temperature elongations obtained in the present work and in the Ti-(40-44)Al-8.5Nb alloy [22] were found to be close to one another. This suggests that the room temperature ductility in the Ti-45Al-8Nb-0.2C alloy was determined by the fine duplex microstructure (together with a favorable texture resulted from the extrusion). Lower strength properties obtained for Ti-45Al-8Nb-0.2C in contrast to those obtained in ref. [6] are associated with the lower fraction of lamellar colonies and the absence of the modulated perlitic-like lamellar microstructure, which had an impact on the strength properties. Note that appreciably higher room temperature ductility and slightly lower strength properties of the Ti-45Al-8Nb-0.2C alloy in contrast to those obtained in [5] can be ascribed to higher lamellar constituent and microstructure inhomogeneities obtained after extrusion in the last case that in turn was probably a result of some variations in the alloy composition.

Long-term strength tests at elevated temperatures. Table 2 represents the results of long-term strength tests at elevated temperatures of the alloys under study. As follows from the tests performed, the Ti-45Al-8Nb-0.2C alloy had slightly higher creep resistance at 600-700°C and near the same creep resistance at 750°C. On the whole, the lamellar condition with d≈50 µm of the low alloyed alloy and the duplex microstructure with d≈10 µm of the heavy alloyed gave similar long-term strength at 600-750°C. The result shows that heavy alloyed alloys like Ti-45Al-8Nb-0.2C with refined duplex type microstructure can have long-term strength at T=600-750°C similar to that of low alloyed alloys like Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B with the lamellar microstructure. On the whole, both combinations of the mechanical properties seem to be of interest. Taking into account that the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy was not subjected to any hot working, it seems that this alloy is more preferable for manufacturing of complex shaped parts, the production of which is very laborious by wrought processing followed by machining. In this case, the probable processing route of complex shaped parts manufacturing might include
near in-size casting followed by machining [1,2] or in-size casting using centrifuging process [3,4].

Note that the creep resistance of the cast Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy can be improved via heavier alloying by niobium. However, as mentioned, this can lead to a decrease of the low-temperature ductility. It should be also noted that the density of the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy is appreciably lower than that of heavy alloyed alloys. For instance, the density difference of the alloys under study was ≈5%. The comparison of the mechanical properties of the cast Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy with those of heavier alloyed castable γ(TiAl)+α₂(Ti₃Al) alloys shows that the reached properties are quite competitive taking into account the lower density of the alloy under study [13,14,22-24].

Table 2

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Test temperature, °C</th>
<th>σ₁₀₀h, MPa</th>
<th>Elongation after 100-h loading, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 / N2</td>
<td>600</td>
<td>500 / 550</td>
<td>0.6 / 0.4</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>450</td>
<td>7.25 / 2.2</td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>350</td>
<td>7.0 / 6.8</td>
</tr>
</tbody>
</table>

4. Conclusions

The mechanical properties of two alloys, the Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy in the cast plus HIP’ed and aged condition and the Ti-45Al-8Nb-0.2C alloy with the duplex microstructure obtained through hot extrusion followed by heat treatment, were studied and compared between one another. The room temperature ductility and strength of the Ti-45Al-8Nb-0.2C alloy (in the extrusion direction) were found to be higher than those of the cast Ti-43.7Al-3.2(Nb,Cr,Mo)-0.2B alloy. However, the tensile strength, ductility and long-term strength at elevated temperatures (600…750°C) were close to one another. From practical point of view, the hot-worked heavy alloyed alloy can be applied for parts, in which robust low-temperature ductility is strictly required, whereas the cast low alloyed alloy can be used for parts, in which the low-temperature ductility like 2-3% of plastic strain is not severe requirement. It seems that better balanced mechanical properties can be reached through further alloy designing based on an idea of the β-solidification. The results obtained for the Ti-45Al-8Nb-0.2C alloy suggest that the key to additional improvement of the low-temperature ductility in the cast γ-TiAl+α₂-Ti₃Al alloys can lie in a further microstructure refinement with a higher alloying level, which would support acceptable creep resistance.

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