Temperature–Time–Transformation Diagrams Construction for Beta-Solidifying TiAl-Based Alloy in As-Cast Condition

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Abstract. An experimental investigation of structure evolution kinetics in a new six-component TiAl-based alloy Ti-44.5Al-2V-1Nb-(0.5…1.5)Zr/(1.5…2.5)Cr-(0…0.1Gd) (at.%) with variable Zr, Cr, and Gd content has been accomplished under the conditions of high-temperature exposures in the temperature range 1000–1300°C and durations of 15–240 min. The Temperature–Time–Transformation diagrams have been constructed to summarize data on isothermal phase transformations for both Zr(+Gd)- and Cr(+Gd)-containing compositions with the initial as-cast structure. It is shown that the variation of Zr and Cr contents within the given limits for the studied alloy, as well as the doping with Gd microadditions in the amount of 0.1 at.% do not lead to any noticeable effect on the kinetics of structure behavior in isothermal conditions.

1. Introduction
Gamma titanium aluminide based intermetallic alloys (TiAl-based alloys or gammalloys) are promising structural materials for high-temperature applications wherein light weight is combined with service temperatures of 750–800°C [1–8].

The optimal combination of short-term and long-term mechanical properties can be achieved in TiAl-based alloys due to a fine-grained lamellar structure with the intragranular lamellar colonies size less than 100 µm [9–12]. One of the most common ways for the required type of structure formation is thermomechanical treatment. However, lack of arranged data is observed in literature concerning rational choice of technological parameters for high-temperature processing of the β-solidifying TiAl-based alloys modified with rare-earth elements (REE) [13–16].

The structure formation processes in metallic alloys upon high-temperature exposures which accompany thermomechanical treatment are determined by the mechanism and kinetics of phase transformations under isothermal conditions. The latter can be described by special Temperature–Time–Transformation (TTT) diagrams, plotted in the “temperature (T) – time (t)” coordinates wherein the time scale is often taken to be logarithmic [17].

It is the aim of this work to study the kinetics of isothermal phase transformations in a new Russian intermetallic β-solidifying TiAl-based alloy [18–20] of variable composition Ti-44.5Al-2V-1Nb-xZr/yCr-(0…0.1)Gd (at.%) (x = 0.5–1.5 at.%; y = 1.5–2.5 at.%) with the REE (Gd) microadditions.
2. Materials and methods
Experimental studies of structure evolution kinetics have been carried out on six various alloy compositions (table 1). The initial triple remelted ingots with a diameter of 70 mm and weight of approx. 2.8 kg each were produced by double vacuum-arc remelting followed by vacuum induction melting and final gravity casting in a steel chill mold (VAR + VAR + VIM).

Cylindrical specimens measured 10 mm in diameter (d) and 15 mm in height (h) were cut from the as-cast ingots and subjected to isothermal exposures under air environment at temperatures of 1000, 1100, 1200, and 1300 °C in a Nabertherm LH 60/14 furnace which imitate the temperature–duration conditions of potential thermomechanical treatment. After exposure durations of 15, 30, 60, 120, and 240 min the specimens were quenched in cold water and prepared by grinding/polishing and final etching in a [25 vol.% HF + 75 vol.% HNO₃] reagent for further investigations of phase composition.

X-ray diffraction analysis (XRD) was carried out at room temperature on a Bruker D8 ADVANCE diffractometer in CuKα radiation. The experimental diffraction patterns were processed using DIFFRAC.SUITE and TOPAS software with a licensed copy of JCPDS-PDF-2 Database.

Table 1. Actual chemical compositions of the studied TiAl-based alloy ingots (at.%).

| No.  | Ti  | Al  | V   | Nb  | Cr  | Zr  | Gd  |
|------|-----|-----|-----|-----|-----|-----|-----|
| Alloy 1 | Bal. | 44.3 | 1.91 | 1.02 | 1.53 | -   | -   |
| Alloy 2 | Bal. | 44.4 | 2.01 | 1.00 | 1.45 | -   | 0.11|
| Alloy 3 | Bal. | 44.3 | 1.97 | 0.99 | 2.46 | -   | -   |
| Alloy 4 | Bal. | 44.3 | 1.98 | 1.03 | 2.52 | -   | 0.10|
| Alloy 5 | Bal. | 44.2 | 1.96 | 1.02 | -   | 1.50 | -   |
| Alloy 6 | Bal. | 44.3 | 1.95 | 0.97 | -   | 1.53 | 0.09|

3. Results and discussion
The XRD analysis data for the isothermally exposed and quenched specimens are presented in table 2.

Phase composition of the Zr-containing alloys at room temperature consists of the α₂ and γ phases. Isothermal exposures at a temperature of 1000°C lead to a change in the ratio of the α₂ and γ phases volume fractions with no change in phase constituents (the α₂→α transformation is not observed until the maximum applied exposure duration of 240 min). During isothermal exposures in the temperature range 1100–1300°C the alloys undergo a disordering phase transformation α₂(D0₁₀)→α(A3), i.e. the phase composition changes from (α₂+γ) to (α+γ). At a temperature of 1100°C the α₂→α transformation begins 22 min after the start of exposure (the incubation period) and ends 167 min after the start of exposure; at temperatures of 1200 and 1300 °C the α₂→α transformation is completed within 15 min from the start of exposure, thus the incubation period being less than 15 min. It has been revealed that the full dissolution of the γ phase occurs in 120 min at 1300°C.

Phase composition of the Cr-containing alloys at room temperature is represented by the (α₂+γ+βb₀) phase mixture. During isothermal exposures the phase composition changes from (α₂+γ+βb₀) to (α₂+γ+β), i.e. a disordering phase transformation βb₀(B2)→β(A2) takes place. It completes in 20 min after the start of exposure at a temperature of 1000°C, and in less than 15 min – at 1100–1300°C. Beginning with a temperature of 1100°C and higher, the α₂→α phase disordering process develops accompanied by a gradual full dissolution of the β phase. The α₂→α transformation proceeds with approximately the same kinetics as in the Zr-containing alloys and completes in 170 min after the start of exposure at a temperature of 1100°C, in 20 min – at 1200°C, and in less than 15 min – at 1300°C. It has been revealed that similar to Zr-containing compositions, the full dissolution of the γ phase is completed during 120 min at 1300°C.

The established regularities of the phase transformations kinetics belong both to the compositions with min (1.5 at.%; alloys 1 and 2) and max (2.5 at.%; alloys 3 and 4) nominal content of Cr, i.e. variations in chromium contents within the given alloying limits for the studied TiAl-based alloy (1.5…2.5 at.%) do not affect the kinetics of phase transformations.
It has been shown that microadditions of Gd in the amount of 0.1 at.\% also do not exhibit a noticeable effect on the kinetics of phase transformations in both Zr- and Cr-containing compositions of the studied TiAl-based alloy during isothermal exposures in the temperature range 1000–1300°C for up to four hours (cf. data in table 2).

**Table 2.** Room temperature experimental phase composition of the isothermally exposed specimens.

| No. and initial phase comp. | Exposure duration, min | Phase composition\(^a\)^\(^b\) after exposures at various temperatures, °C |
|-----------------------------|------------------------|--------------------------------------------------------------------------------|
|                             |                        | 1000 | 1100 | 1200 | 1300 |
| Alloy 1, \(\alpha_2+\gamma+\beta\) | 15                     | \(\alpha_2+\gamma+\beta\) | \(\alpha_2+\gamma+\beta\) | \(\alpha_2+\gamma+\beta\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma+\beta\) | \(\alpha_2+\gamma+\beta\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma+\beta\) | \(\alpha_2+\gamma+\beta\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma+\beta\) | \(\alpha_2+\gamma+\beta\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma+\beta\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |
| Alloy 2, \(\alpha_2+\gamma+\beta_0\) | 15                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |
| Alloy 3, \(\alpha_2+\gamma+\beta_0\) | 15                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |
| Alloy 4, \(\alpha_2+\gamma+\beta_0\) | 15                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma+\beta_0\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |
| Alloy 5, \(\alpha_2+\gamma\) | 15                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |
| Alloy 6, \(\alpha_2+\gamma\) | 15                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 30                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 60                     | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 120                    | \(\alpha_2+\gamma\) | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) |
|                             | 240                    | \(\alpha_2+\gamma\) | \(\alpha+\gamma\) | \(\alpha+\gamma\) | \(\alpha\) |

* Phase symbols in parentheses indicate a small amount (volume fraction) of the corresponding phase in the structure;
* Phase symbols in brackets indicate that the corresponding phases cannot be detected separately due to similar crystallographic structure.

Based on the obtained experimental results, the TTT diagrams have been constructed for the two variable compositions (at.%): Ti-44.5Al-2V-1Nb-1.5Zr-(0…0.1)Gd (figure 1a) and Ti-44.5Al-2V-1Nb-(1.5…2.5)Cr-(0…0.1)Gd (figure 1b) with the initial as-cast structure. The diagrams make it possible to evaluate the kinetics of phase transformations in the alloys upon isothermal exposures at various temperatures of the \([\alpha+\gamma]\) and \([\alpha_2+\gamma+\beta]\) phase fields.
The equilibrium temperatures of critical points \( T_\gamma, T_E \) depicted by horizontal dashed lines on the TTT diagrams were calculated in our previous studies [20] as follows.

For 1.5 at.% Zr: \( T_\gamma[(\alpha)/(\alpha+\gamma)] = 1259°C; T_E[\alpha\leftrightarrow\alpha_2+\gamma] = 1024(\text{lower}) \ldots 1059(\text{upper}) °C. \)

For 2.5 at.% Cr: \( T_\gamma[(\alpha)/(\alpha+\gamma)] = 1233°С; T_E[\alpha\leftrightarrow\alpha_2+\gamma+\beta] = 1034(\text{lower}) \ldots 1063(\text{upper}) °С. \)

**Figure 1.** Summarized TTT diagrams for (a) Zr(+Gd)- and (b) Cr(+Gd)-containing compositions. Designation: \( T_{\gamma}(\alpha)/(\alpha+\gamma); T_{E(\text{low})}/T_{E(\text{up})} – \text{lower/upper eutectoid temperatures} \).

### 4. Conclusions

It has been revealed that in the Zr-containing alloys which possess the room temperature phase composition of \((\alpha_2+\gamma)\), a disordering phase transformation \( \alpha_2(D0_{19})\rightarrow\alpha(A3) \) takes place upon isothermal exposures at 1100–1300°C and completes in 167 min after the start of exposure at 1100°C, and in less than 15 min at 1200 and 1300 °C; a change in the ratio of the \( \alpha_2 \) and \( \gamma \) phases volume fractions is detected during the exposure at 1000°C and accompanied with no change in qualitative phase composition. The \( \gamma \) phase dissolution is completed within 120 min at 1300°C.

It has been revealed that in the Cr-containing alloys which possess the room temperature phase composition of \((\alpha_2+\gamma+\beta_0)\), a disordering phase transformation \( \beta_0(B2)\rightarrow\beta(A2) \) ends in less than 20 min at 1100–1300°C. The complete disordering of the \( \alpha_2 \) phase is observed after isothermal exposures at 1100, 1200, and 1300 °C for 170, 20, and less than 15 min, respectively. The \( \gamma \) phase completely dissolves during 120 min at 1300°C.

It is shown that the variation of Zr and Cr contents within the given alloying limits, as well as the doping with Gd microadditions in the amount of 0.1 at.% do not exhibit a noticeable effect on the kinetics of phase transformations in both Zr- and Cr-containing compositions of the studied TiAl-based alloy during isothermal exposures in the temperature range 1000–1300°C.

### 5. References

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Acknowledgement
This research project was supported by the Russian Science Foundation (grant No. 18-79-10249).

The work was performed as a part of the implementation of the complex scientific direction 7.1 “Intermetallic Alloys Based on Titanium” (“Strategic Directions for the Development of Materials and Technologies of Their Processing for the Period until 2030”) [21].