Deformability assessment of beta-solidifying TiAl-based alloy with Zr, Cr, and Gd content variability

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Abstract. An experimental deformability assessment of 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 isothermal upsetting in accordance with the uniaxial compression scheme in the temperature range 1000–1300°C and strain rates of 0.001–0.1 s⁻¹. It has been revealed that Cr-containing compositions possess significantly higher technological plasticity compared to Zr-containing compositions. Microadditions of Gd in the amount of 0.1 at.% also promote the reduction of stresses upon deformation. It is shown that with the upsetting temperature increase, the stress values decrease in the entire range of deformation rates. It has been established that the most noticeable decrease in stress levels is observed with an increase in the compression temperature from 1100 to 1200 °C – by 2...2.5 times, while with an increase in the compression temperature from 1000 to 1100 °C – only by 1.1…1.3 times, and from 1200 to 1300 °C – by 1.4...1.5 times.

1. Introduction
Heat-resistant intermetallic alloys based on gamma titanium aluminide (TiAl-based alloys) are promising light-weight materials with service temperatures up to 750–800°C for high-temperature applications, e.g. aero-engine components [1].

It is well-known that the optimal combination of mechanical properties of TiAl-based alloys (low-temperature plasticity, strength, fracture toughness, and creep resistance) can be achieved due to a fine-grained lamellar structure with a grain (or intragranular lamellar colonies) size less than 100 μm. The required grain size is to be formed by microalloying with structure modifiers, in particular boron, carbon, and rare-earth elements (REE) [2–4]. But since the size of grains/colonies strongly depends on cooling rates, it is not always possible to provide such a structure in cast products. Another way for grinding coarse-grained ingot structures and casting microporosity elimination is the use of thermomechanical treatment [4,5]. However, the production of defect-free wrought semi-finished products of gamma alloys proves to be a complicated technological task because of natural brittleness and low plasticity thereof. In this work the deformability assessment studies were performed on a new Russian intermetallic β-solidifying TiAl-based alloy [3,6] 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 deformation behavior 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 samples measured 10 mm in diameter (d) and 15 in height (h) were cut from the as-cast ingots without any additional treatment.

The isothermal uniaxial compression tests were performed in laboratory air at temperatures of 1000, 1100, 1200, and 1300 °C, and constant strain rates (ε) of 10⁻³, 10⁻², and 10⁻¹ s⁻¹ on a Walter+Bai LFV-100 servohydraulic testing machine equipped with a radial heating furnace.

Table 1. Actual chemical compositions of the studied TiAl-based alloy samples (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 analysis of isothermal upsetting results has shown similar appearance of the obtained flow curves (in the "stress–strain" coordinates) for all of the tested compositions (figure 1). It has been found that at all investigated temperatures and strain rates, the highest stress level is observed for the compositions with 1.5 at.% Zr (alloys 5 and 6), while the smallest stress level was detected for the compositions with 2.5 at.% Cr (alloys 3 and 4). The compositions containing a lower amount of Cr (1.5 at.%; alloys 1 and 2) occupy an intermediate position. It is important to note that the doping with Gd in the amount of 0.1 at.% exhibits a positive effect on all of the three groups of alloys and, in general, provides a decrease in stress levels.

Figure 1. Stress–strain rheological curves of the six investigated alloy compositions (see table 1) for compression tests of cylindrical samples (d = 10 mm, h = 15 mm) at T = 1100°C and strain rates \( \dot{\varepsilon} = 10^{-3} \text{ s}^{-1} \) (a), \( \dot{\varepsilon} = 10^{-2} \text{ s}^{-1} \) (b), and \( \dot{\varepsilon} = 10^{-1} \text{ s}^{-1} \) (c).
A high level of stresses leads to the formation of a large number of cracks along the surface generatrix of the Zr-containing samples (alloys 5 and 6), while almost no cracks were observed on the Cr-containing samples (alloys 3 and 4) (figure 2).

![Figure 2. Appearance of cylindrical samples (d = 10 mm, h = 15 mm) upset at T = 1100°C and strain rate $\dot{\varepsilon} = 10^{-2}$ s$^{-1}$: (a) alloy 1; (b) alloy 2; (c) alloy 3; (d) alloy 4; (e) alloy 5; (f) alloy 6.](image)

The maximum number of deep diagonal cracks is observed at a maximum strain rate of $10^{-1}$ s$^{-1}$, which corresponds to the highest stress values. A decrease in the upsetting rate to $10^{-3}$ s$^{-1}$ leads to a significant reduction or complete absence of cracks on the samples surface. The intermediate strain rate of $10^{-2}$ s$^{-1}$ ensures the production of practically defect-free upset items from Cr-containing alloys 3 and 4, and alloy 2 with 1.5 at.% Cr + 0.1 at.% Gd (see figure 2). It should be noted that alloy 4 containing 2.5 at.% Cr + 0.1 at.% Gd shows the best technological plasticity and almost complete lack of surface cracks on the samples compressed even at a strain rate of $10^{-1}$ s$^{-1}$.

Thus, the strain rates of $10^{-2}...10^{-3}$ s$^{-1}$ are preferable for deformation processing of the investigated TiAl-based alloy with variable compositions, since almost defect-free workpieces (samples) can be obtained. However, taking into account the duration of the upsetting process (for the tested samples measured d = 10 mm and h = 15 mm the upsetting time is about 50 s at $\dot{\varepsilon} = 10^{-2}$ s$^{-1}$ and about 500 s at $\dot{\varepsilon} = 10^{-3}$ s$^{-1}$), the most rational strain rate will be $\dot{\varepsilon} = 10^{-2}$ s$^{-1}$ from the point of view of the subsequent scaling up to industrial conditions.

It has been established that with an increase in the upsetting temperature of the samples, the stress values decrease for each strain rate applied. At the same time, it has been found that the most noticeable decrease in stress levels is observed with an increase in the compression temperature from 1100 to 1200 °C – by 2...2.5 times, while with an increase in the compression temperature from 1000 to 1100 °C – only by 1.1...1.3 times, and from 1200 to 1300 °C – by 1.4...1.5 times. It can be assumed that an intense stress level decrease in the temperature range 1100–1200°C takes place due to the high rate of the $\alpha_2$(D0$_{19}$)$\rightarrow\alpha$(A3) phase disordering process at 1200°C and above. At a temperature of 1300°C
accelerated oxidation of the samples begins. In addition, at such high temperatures the deformation process becomes more energy intensive which leads to an increase of the processing costs. Thus, for carrying out deformation treatment of the studied TiAl-based alloy, it is rational to choose 1200°C as the initial upsetting temperature.

The limiting degree of isothermal deformation of the TiAl-based alloy samples during upsetting before the first cracks appearance is estimated. Cracks at a deformation degree of 65% were not detected for the compositions containing 1.5–2.5 at.% Cr and 0.1 at.% Gd after upsetting at a temperature of 1200°C and strain rates of 10⁻² and 10⁻³ s⁻¹. In Zr-containing compositions the first cracks upon upsetting at T = 1200°C and \( \dot{\varepsilon} = 10^{-2} \text{s}^{-1} \) appear when the degree of deformation reaches 50%.

4. Conclusions
It has been revealed that Cr-containing compositions possess significantly higher technological plasticity under the studied conditions of deformation compared to Zr-containing compositions. It is shown that the microaddition of Gd in the amount of 0.1 at.% results in a positive effect on the manufacturability of all of the studied TiAl-based alloy compositions, reducing the levels of yield (\( \sigma_{0.2} \)) and flow stresses.

It is notable that with an increase in the upsetting temperature, the stress values decrease in the entire range of strain rates. The most noticeable decrease in stress levels is observed with an increase in the compression temperature from 1100 to 1200 °C – by 2...2.5 times, while with an increase in the compression temperature from 1000 to 1100 °C – only by 1.1...1.3 times, and from 1200 to 1300 °C – by 1.4...1.5 times.

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