Intermetallics 101 (2018) 44–55

Contents lists available at ScienceDirect

Intermetallics

journal homepage: www.elsevier.com/locate/intermet

Isothermal forging of titanium aluminides without beta-phase — Using non-equilibrium phases produced by spark plasma sintering for improved hot working behavior

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ARTICLE INFO

Keywords:
Titanium aluminides
TNB-V5 alloy
Hot workability
Processing maps
Spark plasma sintering
Microstructural evolution

ABSTRACT

This paper investigates the hot forgeability of a TNB-V5 (Ti–45Al–5Nb–0.2B–0.2C, at.%) alloy produced by spark plasma sintering (SPS) from pre-alloyed powder particles using the concept of processing maps. For the first time in this paper, to the best of our knowledge, we report the possibility of the isothermal forging of a TiAl alloy without the necessity to induce the ductile β-phase in the microstructure, by using non-equilibrium phases produced by SPS. At room temperature, the SPSed sample reveals a homogeneous equiaxed microstructure consisting of globular α_2-and γ-grains with the α_2-phase formed mainly at the necks between powder particles as confirmed by EBSD analyses. The necks contain a lower Al content and thus transform into α-phase upon heating to forging temperature. A stable plastic flow is observed for all ranges of the studied strain rates. The presence of a fine equiaxed microstructure at hot working temperature seems to ensure good workability and leads to a relatively wide processing window. The processing map reveals two safe processing windows for the studied alloy. The lower strain rate domain (10^{-3}-10^{-2} s^{-1}) corresponding to a strain rate sensitivity value of ≈0.8 represents superplasticity of the fine and uniform (α + γ) equiaxed microstructure. The higher strain rate domain (10^{-2}-10^{-1} s^{-1}, T > 1215 °C) with a strain rate sensitivity value of ≈0.45 represents dynamic recrystallization of the α-grains at elevated temperatures. The processing map also exhibits a domain of flow instability represented by the deformation conditions of T < 1215 °C and $\dot{\varepsilon} > 10^{-2}$ s^{-1}, which might result from the void formation and/or cracking. Although the TNB-V5 alloy was not designed for forging operations, the SPS process can create a homogeneous equiaxed microstructure consisting of globular α- and γ-grains decorating the interfaces and triple junctions between former powder particles leading to a good hot workability. The current study offers a new process design strategy by opening up the possibility of using local non-equilibrium conditions in the material during the forging process, which could stabilize the ductile phases locally.

1. Introduction

Intermetallic titanium aluminides (TiAl) have been the focus of growing attention for high- temperature applications in aerospace, automotive, and energy industries due to a unique combination of a high specific Young's modulus, high-temperature strength, and an excellent oxidation/corrosion resistance [1,2]. Titanium aluminides have shown great advantages as turbine blades in modern combustion engines [3].

γ-TiAl alloys are considered as a promising alternative to Ni-based superalloys for some components up to temperatures of about 800 °C. The γ-TiAl alloys are processed by various methods, including casting, ingot metallurgy, and powder metallurgy. Near-net shape components such as compressor or turbine blades, turbochargers, and automobile exhaust valves have been successfully cast by investment casting or permanent mold die casting techniques utilizing gravity or centrifugal methods [4,5].

In the ingot metallurgy process, cast ingots undergo hot isostatic pressing followed by hot working (isothermal forging, extrusion, or hot-die forging) [6,7]. Forming of near-net-shape components such as compressor blades and automobile exhaust valves has been successfully demonstrated using isothermal die-forging methods under dynamic recrystallization conditions, and also using high-strain-rate warm/hot die extrusion and forging techniques [8,9].

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https://doi.org/10.1016/j.intermet.2018.07.004
Received 26 May 2018; Received in revised form 9 July 2018; Accepted 10 July 2018

Despite significant progress, low room-temperature ductility and poor workability, specifically hot formability, limit the industrial take-up of forged γ-TiAl parts. Various strategies such as alloying, thermal and thermomechanical treatment including isothermal forging, hot extrusion, and hot rolling were employed to develop alloys with refined microstructure and enhanced ductility [10–14]. Forming of γ-TiAl alloys even at elevated temperature by means of conventional methods is challenging due to the narrow processing window.

Employing a combination of thermomechanical processing and tailoring chemical composition to induce the disordered ductile β-phase (A2) at elevated temperatures is an alloy design strategy to improve the hot deformability of TiAl alloys [15]. Recently, so-called β-solidifying alloys containing a certain amount of more ductile disordered β-phase with bcc lattice have been developed by addition of β stabilizing elements such as Cr, Mn, W, Mo, V, and Nb [16–18]. The ductile β-phase with a bcc lattice facilitates hot forming such as rolling and forging by providing a sufficient number of independent slip systems. As-cast β-solidifying alloys are also attractive for wrought processing routes since the alloys consist of a fine and homogeneous microstructure with weak textures and little micro-segregations. Hot deformability of β-solidifying alloys is remarkably improved compared to conventional γ alloys to the extent that some alloys could be even conventionally forged in cold dies [19]. Moreover, β-solidifying alloys can be forged in closed dies without previous ingot breakdown due to a fine microstructure, which is a remarkable achievement in terms of materials yield and cost compared to wrought processing routes. A significant volume fraction of β-phase should be present in the alloy during ingot breakdown and secondary hot-forming operations. At lower temperatures, the β-phase undergoes an ordering transition to an ordered β_0 phase with B2 structure, which is detrimental for mechanical properties due to its intrinsic brittleness. Therefore, the β-phase should be eliminated from the microstructure or, at least, its amount should be kept very low by suitable heat treatment after the accomplishment of the hot deformation process. At service temperature, thus, the materials should not contain significant amounts of β-phase in order not to decline creep properties [20]. These developments have not yet been exploited industrially, most likely due to the fact that the damage tolerance of γ-TiAl is low, and results found under compressive stress states in lab-scale compression testing cannot be transferred directly to complex forging operations.

As a consequence, the conventional processing route for producing TiAl alloy components consists of casting, hot isostatic pressing to remove cast porosities, isothermal forging, and machining. The cast ingot microstructure is coarse and inhomogeneous and normally contains lamellar colonies [4]. As-cast material is often subjected to hot isostatic pressing to remove the porosity. Due to the high material cost and expensive finishing operations of TiAl alloys, near-net-shape forging operations are desirable. However, the poor workability of TiAl alloys at elevated temperatures requires the workpiece to be shaped by isothermal forging, which still calls for further optimization of the process chain.

Third-generation γ-titanium aluminides (TNB alloys) containing 5 to 10 at.% Nb[1] as an example of the class of β-solidifying TiAl alloys show a high potential for industrial applications since the required enhancement of ductility and oxidation resistance above 700 °C could be achieved in these alloys [21,22]. Furthermore, an addition of 5–10% of niobium considerably increases the creep resistance [23].

Interstitial elements of C, O, and N markedly decrease the room temperature ductility while either improving or deteriorating the strength [24]. In particular, the effect of C is beneficial due to both solid solution hardening and formation of C-containing precipitates [25]. Scheu and co-workers reported a substantial improvement in the room temperature tensile yield strength of Ti–45Al–5Nb sheets with near-γ microstructure from 800 MPa for the C-free sheet to 1070 MPa for the 0.5% C-containing sheet while retaining a similar microstructure [26]. To ensure a grain refining effect during solidification, boron is added that forms stable borides and retards undesirable grain coarsening at elevated temperature by pinning of grain boundaries [27].

C-containing TiAl alloys such as TNB-V5 are suitable for powder metallurgical processing such as metal injection molding (MIM) [28] which involves the extrusion of powder-binder mixtures and subsequent sintering. MIM aims at producing components directly from powder material but suffers from remaining porosities [28–31]. An alternative sintering method is the field-assisted sintering technology/spark plasma sintering (FAST/SPS), which is a sintering and synthesis technique that allows a rapid solid-state consolidation of powders by synchronous application of a direct electric current and a uniaxial pressure. For conductive powders, the electrical current flows through the material and heat is generated due to the Joule effect [32]. The heating occurs between the particle contact regions, where the electrical resistance is the greatest. As a result, the SPS technique provides considerably localized and thus very efficient heating for metallic powders. SPS leads to the full densification of the samples with a finer microstructure at a shorter sintering time in comparison with conventional techniques. FAST/SPS has been proved very successful in sintering various titanium aluminides such as G4, 48-2-2, TNB, and TNM alloys with refined microstructures yielding improved creep resistance and ductility [33–35]. A disadvantage of SPS is that the pressure distribution in the parts depends on the part shape and defect-free parts with a complex shape are hard to produce by SPS.

Recently, Weston et al. [36] developed a new cost-effective hybrid processing route called FAST-forge as a replacement for the conventional multi-step process for consolidating titanium powder into near-net shaped forged components. This process eliminates the ingot casting step and most of the thermomechanical treatment of the ingot to achieve the desired microstructure and shape. The results show that the FAST-forge technology is promising for manufacturing of forged Ti-6Al-4V [36] and Ti-5553 [37] components with microstructures and flow behaviors similar to those of conventional billet materials while shortening the processing chain.

In an effort to stabilize phases of good workability in the TNB-V5 alloy (Ti–45Al–5Nb–0.2B–0.2C) locally, at the necks between former powder particles, this work draws upon the SPS process for producing specimens from pre-alloyed powders. Unlike the work presented by Weston et al. [36], this paper focuses on using SPS to create preforms for forging using the possibility to stabilize phases locally in the microstructure, which are present during the forging process but would eventually disappear if the workpiece was kept at forging temperature for a longer time. For the first time, the hot forgeability of the TNB-V5 alloy is controlled by the phases generated in the SPS process.

The hot workability is investigated using processing maps in the current paper. The concept of processing maps (see details in section 2.5) has been successfully employed to optimize the hot working parameters of different alloys including Ti alloys [38–40], Mg alloys [41,42], and austenitic stainless steel [43,44] during isothermal compression. The majority of research results verified the applicability of processing maps for defining optimum hot deformation conditions.

2. Materials and methods

2.1. Characterization of initial powder

Gas-atomised powder made from a TNB-V5 alloy (Ti–45Al–5Nb–0.2B–0.2C, at.%) at Helmholtz-Zentrum Geesthacht, Germany with an average particle size of about 45 μm was employed in the current study. The distribution of powder particle size was not determined for the used powder batch; however, what is available is that the fraction of powder particles used is smaller than 45 μm. Prior to

[1] Throughout the text all compositions are expressed in at.% unless otherwise stated.