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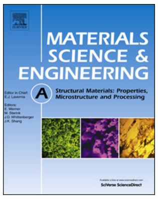

Metal matrix composites based on Ti-6242 synthesized by Spark Plasma Sintering

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ABSTRACT

A composite consisting of Ti-6Al-2Sn-4Zr-2Mo as matrix and Ti-42.3Al-3.8Nb-1Mo-0.1B (at%; known as γ-TiAl-TNM) as reinforcement was developed to increase the working temperature for titanium based alloys. The volume fraction (10 wt%, 15 wt%) and the particle size (< 20 µm, 20–45 µm) of the TiAl-TNM, and the sintering temperature (1100 °C, 1150 °C) were varied. It was shown, that the working temperature of Ti-6Al-2Sn-4Zr-2Mo can be increased to 650 °C by the addition of 10 wt% TiAl-TNM due to an elongation > 2% at room temperature and an increase in yield strength of 100 MPa in the temperature range of room temperature to 650 °C compared to Ti-6Al-2Sn-4Zr-2Mo. Furthermore, the dissolving of TiAl-TNM, which takes place already at 650 °C, does not lead to a decline in yield strength and tensile strength.

1. Introduction

Due to the demand of a reduction of fuel consumption and CO_2 emission, the aircraft and automotive industry tries to replace high-density materials by lighter materials. Especially for parts, that experience a high temperature during operation in aircraft, and automotive parts, nickel base alloys have been partly substituted by TiAl [1–3]. However, TiAl requires a difficult processing, which is costly, and TiAl is not damage tolerant at room temperature due to a low ductility [1,4].

Thus, more ductile titanium alloys are of use. However, their operation temperature is limited to a maximum temperature of 315–400 °C for α/β alloys depending on the alloy composition and to 540 °C for near α alloys [5]. An alternative to shift the maximum operation temperature of these titanium alloys to higher values is the use of composite materials. A TiAl reinforced composite was already introduced in [6] by using Ti-6Al-4V as matrix. The yield strength was increased by 90 MPa at 550 °C through the addition of 10 wt% TiAl. However, Ti-6Al-4V experiences an intensive reduction in strength with increasing temperature. Further, results concerning a TiAl reinforced composite were published by [7], where γ-TiAl was formed in-situ in a titanium matrix next to TiC, whereupon this material is not applicable for operation at high temperature. A titanium based alloy with a higher strength and better temperature resistance (up to ~ 540 °C) is the alloy Ti-6Al-2Sn-4Zr-2Mo (abbreviated as Ti-6242) [8]. It is used in aircraft engines for rear low pressure and front high pressure compressor parts [8]. Therefore, this alloy is suitable as matrix material in composites for high temperature application. Literature about particle reinforced Ti-6242 is hardly found. A large interest in composites based on a Ti-6242 matrix focuses on SiC fibers as reinforcement [9–11]. Critical by the combination of SiC fibers with Ti-6242 is on the one hand the resulting anisotropy of properties and on the other hand the difference in thermal expansion. Due to the different thermal expansion, flaws generate already during production of the composite. A possibility to achieve a strong and heat resistant composite is given by the combination of TiAl as reinforcing particles and Ti-6242 as matrix material. Ti-6242 and TiAl have similar thermal expansion coefficients ($\alpha_{\text{Ti-6242}} = 10.47{\cdot}10^{-6}$ K^{-1} [10]; $\alpha_{\text{TiAl}} = 11{\cdot}10^{-6}\,K^{-1}$ [12]), which lead to only a low thermal mismatch during sintering. It is assumed, that the working temperature can be increased for this composite compared to unreinforced Ti-6242, while keeping a sufficient ductility. Thus, it could replace nickel in further components and prevent the use of TiAl, which is very difficult to machine. However, no results about such a composite material can be found in literature so far.

In this publication, a Ti-42.3Al-3.8Nb-1Mo-0.1B (at%; known as and referred to as γ-TiAl-TNM) reinforced Ti-6242 matrix composite was processed using Spark Plasma Sintering (SPS). SPS is a sinter technology similar to hot pressing, where the powder is heated by a direct electric current, which flows through the powder, the die and the punches [13,14]. Hence, high heating rates and short processing times can be realized. Thereby, diffusion driven processes proceed in a reduced manner. Thus, this technology is excellent for the synthesis of

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Table 1
Particle size of the initial powders and after sieving.

[μm]	d_{10}	d_{50}	d_{90}
Ti-6242	10	26	60
TiAl-TNM	32	63	100
TiAl-TNM < 20 μm	9	18	27
TiAl-TNM 20–45 μm	23	36	44

Table 2
Chemical composition of the matrix alloy Ti-6242.

Alloy elements [wt%]						
Ti	Al	Sn	Zr	Mo	Si	
bal.	6.00	2.04	3.98	2.03	0.077	
Impurities [wt%]						
B	Fe	C	H	N	O	Y
< 0.005	0.030	0.003	0.002	< 0.002	0.19	< 0.005

Table 3
Chemical composition of the reinforcing TiAl-TNM powder.

Alloy elements [at%]					**Impurities [wt%]**			
Ti	Al	Nb	Mo	B	O	C	N	H
bal.	42.34	3.78	0.99	0.08	0.07	0.004	0.003	0.001

TiAl-TNM reinforced Ti-6242. To ensure a sufficient ductility, TiAl powder with a particle diameter < 45 μm was used [HV5].

2. Experimental

The composite powder was prepared by mixing a commercial Ti-6Al-2Sn-4Zr-2Mo powder (LPW Technology Ltd, UK, referred to as Ti-6242) with 10 and 15 wt% TiAl-TNM powder (TiAl-TNM feedstock material produced by GfE Metalle und Materialien and atomized at Helmholtz-Zentrum Geesthacht) respectively. The TiAl-TNM powder was sieved in advance to receive a powder fraction with a particle size < 20 μm and a powder fraction with a particle size in the range of 20–45 μm. For mixing, a shaker mixer Turbular T2 C was used. The particle size of all powder fractions is shown in Table 1 and their chemical composition in Table 2 and Table 3.

The Ti-6242 powder and the powder mixture were sintered under vacuum, using an SPS device HP D 25 (FCT Systeme GmbH). Therefore, the powders were filled in graphite dies with an inner diameter of 80 mm. All powders were heated with 50 K/min to 1100 °C and cooled directly after reaching the maximum temperature. During heating, the powders were uniaxial compressed. The pressure was raised parallel to the temperature up to 48 MPa, which was reached at maximum temperature. To obtain an intensive dissolution of the TiAl-TNM particles, the composite powder with 10 wt% TiAl-TNM (< 20 μm) was additionally sintered at a maximum temperature of 1150 °C without dwell time.

To investigate the stability of the TiAl-TNM particles, one specimen of the composite variation with 10 wt% TiAl-TNM particles (< 20 μm), sintered at 1100 °C was annealed for eight hours at 650 °C.

The microstructure of the sintered samples was investigated by light optical microscopy and scanning electron microscopy (SEM) in combination with EDX. Furthermore, specimen for tensile tests and creep tests were manufactured. The tensile test specimen had a diameter of 5 mm and a gauge length of 25 mm. Quasi-static tensile tests were carried out at a strain rate of 10^{-4} s^{-1} at various temperatures (room temperature to 650 °C) using a testing machine AGG100 (Shimadzu). To determine the fatigue strength at room temperature, rotating bending fatigue tests were conducted using the composite with 10 wt% TiAl-TNM and the unreinforced Ti-6242 (test frequency 60 Hz). The specimen were hourglass shaped with a length of 42 mm and a minimum diameter of 3.8 mm. Furthermore, the surface of the samples was electrolytically polished. Hardness was measured using Vickers indentation with a loading of 49.03 N.

3. Results and discussion

After sintering, the composites and the matrix were dense as indicated by SEM micrographs (Fig. 1). The unreinforced Ti-6242 and the matrix of the composite exhibit a lamellar microstructure consisting of α and β phase. Due to the pin effect of the TiAl-TNM particles, the lamellar colonies are smaller in the composites compared to the unreinforced Ti-6242.

If the composite was sintered at a maximum temperature of 1100 °C, the TiAl-TNM particles are clearly visible (marked by white arrows in Fig. 1). The TiAl-TNM particles were tolerably homogeneous distributed and the interfaces between reinforcement and matrix are free from defects. In [6], the former TiAl-TNM particles consisted of three regions, a grey edge, a dark grey core and a light grey interspace. Only the core exhibited the chemical composition of the former TiAl-TNM particles with a constant Ti content and a constant Al content [6]. The other two regions were diffusion zones [6]. In the present study, TiAl-TNM particles consisting of these three regions are found only in the composite with TiAl-TNM particles, which had a diameter of 20–45 μm. However, the Ti and the Al content are roughly constant within this core as indicated by EDX measurements (Fig. 2). Furthermore, the niobium content slightly increases within the TiAl-TNM area and the zirconium content decreases, though niobium was not present in the initial matrix powder and the initial TiAl-TNM powder did not contain zirconium. Hence, these elements diffused during sintering. According to [15], the initial TiAl-TNM particles consisted of α_2, β and γ phase. However, it is not possible to distinct assign the phases due to its very fine microstructure. Furthermore, the phase composition might not be the same due to diffusion. If the initial TiAl-TNM particles were < 20 μm, this core within the TiAl-TNM particles does not exist. Due to short diffusion paths from the middle of the particle to the edge within these smaller particles, the initial chemical composition is not existent in these particles. The particles were slightly dissolved after annealing at 650 °C for eight hours. Hence, if the composite would be applied at 650 °C, the TiAl-TNM particles would dissolve during application.

An increase in temperature of only 50 K leads to a complete dissolution of the TiAl-TNM particles (Fig. 1c). In [6], for TiAl-TNM reinforced Ti-6Al-4V with TiAl-TNM particles up to 100 μm, it was stated, that niobium and molybdenum remain at the regions of the former TiAl-TNM particles. However, EDX mappings of powder compacts sintered from powder mixture with smaller TiAl-TNM particles (< 20 μm) at 1150 °C indicated a homogeneous distribution of all present elements. Hence, the material sintered at 1150 °C is technically speaking no composite anymore, but a new alloy.

As shown in Fig. 3, the composites exhibit with 356–370 HV5 a higher hardness compared to the unreinforced Ti-6242 (mean hardness 336 HV5). Furthermore, there is no gradient of hardness along the cross-sectional area of the sintered samples. Besides, the hardness was not influenced by the size and the state of dissolution of the TiAl-TNM. However, the hardness values scatter strongly, especially for the unreinforced Ti-6242. This is caused by the much coarser microstructure of the unreinforced Ti-6242. Due to the coarse microstructure, the hardness indentation possibly indents only one former β-grain in the Ti-6242. Therefore, the hardness depends on the orientation of the particular laminated disc packs. On the contrary, the scattering of hardness