Additive Manufacturing 22 (2018) 118–126

Contents lists available at ScienceDirect

Additive Manufacturing

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

Full Length Article

# Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting for automotive applications

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ARTICLE INFO

*Keywords:*
Selective electron beam melting
Titanium aluminide
Mechanical properties
Heat treatment
Turbocharger wheel

ABSTRACT

Selective electron beam melting (SEBM) is shown to be a viable production route for titanium aluminides components. Fully dense and crack free parts can be produced. In the present paper a titanium aluminide alloy Ti-45Al-4Nb-C was investigated and the complete processing chain was developed, i.e. starting from the determination of the processing window, the evaluation of corresponding material properties for cube like specimens and finally the production of turbocharger wheels. The material properties were optimized by adjusting scanning strategy as well as heat treatment with particular consideration of the application to turbocharger wheels. The issue of dimensional accuracy and the feasibility of joining will be discussed and a proof test is performed.

## 1. Introduction

Selective electron beam melting (SEBM) is a powder bed fusion technology, with an electron beam as heat source. SEBM machines are produced by the company Arcam AB, by default equipped with a 3 kW electron gun [1]. The vacuum chamber, necessary for a good beam quality, runs typically at $10^{-3}$ mbar under controlled helium inlet. The processing of titanium aluminides in SEBM requires a building temperature of about 1000 °C [2–4], which is controlled by the preheating step. During the preheating of the powder a defocused electron beam scatters along the powder and leads to early stages of sintering. In this way sufficient electrical conductivity of the powder bed is ensured to prevent from so called smoke events [5]. The powder bed in its state of initial sintering is subsequently molten locally by using an adapted scanning strategy to tailor the material properties like porosity, chemical composition and grain growth [5]. By lowering the build platform, typically by a distance between 50 µm and 200 µm, a new powder layer can be deposited. All four steps will be repeated until the part is finalized.

The processing of titanium aluminides by selective electron beam melting was evaluated already in several investigations [2,6–8]. Basically, the feasibility of additive manufacturing was shown by the use of simple shaped geometries. After the assessment of the well-known alloy Ti-48Al-2Cr-2Nb recently also further titanium aluminide alloys with varying chemical composition were processed [9,10]. Lately also feasibility studies of complex geometries were published, in order to demonstrate the potential of the manufacturing method for complex parts out of titanium aluminides [9].

This paper will discuss the processing of the titanium aluminide alloy Ti-45Al-4Nb-C. Here the powder was characterized and the processing window was determined in terms of porosity of the samples. Furthermore the microstructure was investigated. Different scanning strategies were analyzed and the influence on the microstructure evaluation was identified. Both tensile and creep properties were tested. In order to optimize the microstructure and the mechanical properties, different heat treatment procedures were carried out. Finally turbocharger wheels were manufactured with adapted process parameters. The parts were evaluated in terms of porosity and microstructure and the earlier optimized heat treatment was applied to the turbocharger wheels. Finally turbocharger wheels were checked for dimensional accuracy and the successful joining of an impeller to a shaft was demonstrated. As such the complete processing route from powder to part is described and investigated in the present paper.

## 2. Materials and methods

As raw material Ti-45Al-4Nb-C bars produced by GfE Gesellschaft für Elektrometallurgie GmbH were used. The raw material was gas

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https://doi.org/10.1016/j.addma.2018.05.008
Received 9 February 2017; Received in revised form 2 November 2017; Accepted 6 May 2018
Available online 07 May 2018
2214-8604/ 

**Table 1**
Preheating parameters for the Titanium aluminide Ti-45Al-4Nb-C processed in selective electron beam melting for a building temperature of 1050 °C to 1100 °C.

| Parameter | Value |
|---|---|
| Beam current [mA] | 35–49 |
| Scanning speed [m/s] | 10 |
| Line order | 10 |
| Line Offset [mm] | 1 |
| Repetition | 40 |

atomized by TLS Technik GmbH & Co. Spezialpulver KG and subsequently sieved to reach a particle size ranging from 45 µm to 150 µm. The parts were built in an Arcam A2X machine which is located at the Neue Materialien Fürth GmbH. A building temperature between 1000 °C and 1050 °C was maintained during the process, whereas the preheating parameters in Table 1 were used.

A layer thickness of 50 µm was set as prior investigations showed a reduced roughness at lower layer thicknesses [11]. Cubic test samples with an edge length of 15 mm were produced to identify melting parameters for full density specimens and to develop heat treatment parameters for adjusting the microstructure. Further, test samples with increased length (15 × 15 × 80 $mm^3$) were produced to cut specimens for tensile and creep tests. Finally turbocharger wheels were manufactured and heat treated to show the feasibility of producing fully dense parts with tailored properties. The used scanning strategy is a snake like hatching, where the melting direction is rotated by 90° after every layer [5]. Eq. (1) describes the heat input per area $E_A$ in J/$mm^2$ in dependence of beam power $P_B$, scanning speed $v_s$ and hatching distance $h_d$.

$$E_A = \frac{P_B}{v_s \bullet h_d} \tag{1}$$

To define a processing window the parameter scanning speed was raised from 1 m/s to 12 m/s at a constant hatching distance of 100 µm and the beam power was varied from 100 W to 1800 W. A second processing window was defined for different hatching distances of 25 µm to 200 µm and a beam power of 600 W. The criterion for fully dense parts in the following is a relative density above 99.5%.

For the investigation of the microstructure the cubic test samples as well as the turbocharger wheels where cut parallel to the building direction. The cross sections were ground, polished and etched using 8% $H_2O_2$ in a 25% KOH solution at 60 °C. The microstructure was investigated by optical microscope and scanning electron microscope. For the chemical investigation a spark spectrometer (Spectro Spectromaxx) was used. The content of oxygen was measured by EMGA-620W (Horiba).

For the determination of the phase transition a dynamic differential scanning calorimetry Netzsch STA 409 CD was used. The heat treatment was performed at temperatures between 1100 °C and 1320 °C followed by air or oven cooling, see Table 2. The tests were conducted in air atmosphere to enable the different cooling rates. The mechanical test samples were machined afterwards with a minimum removal of 2 mm depth of the surface to prevent increased oxygen content in the samples.

**Table 2**
Heat treatment procedure for the SEBM processed Ti-45Al-4Nb-C in air atmosphere. A constant holding time of 10 min. was applied.

| Temperature [°C] | Cooling condition |
|---|---|
| 1100 | Air |
| 1250 | Air |
| 1290 | Air |
| 1290 | Oven |
| 1320 | Air |
| 1320 | Oven |

The tensile tests were conducted at room temperature in air. A constant cross head speed of 1 mm/min was used. The gauge length of the specimens was 30 mm and the gauge diameter 6 mm. Creep tests were performed under compressive loading by use of cylindrical specimens with a diameter of 5 mm and a length of 7 mm under air. The test temperature was set to 900 °C and the stresses between 50 MPa and 250 MPa were applied. The specimens were investigated in terms of their microstructural stability by optical microscopy. Furthermore the turbocharger wheels were examined by optical microscopy regarding porosity and microstructure in both, as built and heat treated condition. The fringe projection system COMET 5 4M (field-of-view: 100) with INSPECTplus inspection software version 4.03.07 (Carl Zeiss Optotechnik GmbH) was used to analyze the dimensional accuracy of SEBM manufactured turbocharger wheels. The surface roughness of turbocharger wheels was estimated from primary profiles measured by Mitutoyo SJ 400 sensing device (Mitutoyo Deutschland GmbH) with tip radius of 2 µm.

## 3. Results and discussion

### 3.1. Processing window

For the determination of the processing window the porosity was evaluated. The porosity originates from two different phenomena, trapped gas and insufficient melting. The resulting defects are termed gas porosity and bonding faults, see Fig. 1.

Gas porosity in SEBM samples is caused by entrapped gas in the powder particles during the gas atomization process and cannot be completely avoided. Bonding faults occur due to low heat input and consequently a lack of fusion between two layers. By increasing the energy input respectively the area energy bonding faults disappear and the relative density reaches values greater than 99.5%. Such material will be termed fully dense in the following. For different scanning strategies the area energy $E_A$ necessary for fully dense parts varies. This was already discovered for other materials like Ti-6Al-4V, In718 and Ti-48Al-2Cr-2Nb [2,12,13]. Especially scanning speed $v_s$ and hatching distance $h_d$ have a great influence on the required energy input. Fig. 2a) shows the appearance of porosity in dependence of area energy and scanning speed. The minimum area energy, as indicated by the dashed line, represents the minimum required energy input necessary for producing fully dense parts. The minimum area energy drops to lower values with increasing scanning speed, because of a reduction of heat loss [12]. Fig. 2b) shows the processing window in dependence of area energy and hatching distance whereas the beam power is kept constant. The dashed line indicates the transition from porous to fully dense parts. The increase of the hatching distance leads to less required energy input to produce fully dense parts as a lower energy loss occurs [14].

### 3.2. Microstructure

Ti-45Al-4Nb-C produced by selective electron beam melting shows a duplex microstructure, see Fig. 3.

The XRD measurement confirms the occurrence of a duplex microstructure, as y peaks and $\alpha_2$ peaks are visible. The grain size is rather small with a diameter of 5.0 µm and the lamella distance is in the range of 78 nm. The microstructure is caused by a combination of solidification conditions and the subsequent heat treatment during the process. The two effects can be separated by comparing the last layer deposited, which has seen no further annealing, with the bulk of the deposited structure, where some annealing has occurred with every newly deposited layer. After solidification, i.e. in the last layer a fully lamellar microstructure with fine lamellae and grain sizes in the range of 50 µm