Journal of Materials Processing Technology 244 (2017) 289–303

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Influence of the heat treatment on the microstructure and machinability of titanium aluminides produced by electron beam melting

Vincenzo Tebaldo, Maria Giulia Faga*

Imamoter, National Research Council (CNR), Strada delle Cacce 73, 10135 Torino, Italy

ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 9 January 2017
Accepted 30 January 2017
Available online 1 February 2017

Keywords:
Titanium aluminide
Electron beam melting
Dry turning
Microstructure
Crystalline phases
Wear

ABSTRACT

Additive manufacturing (AM) has been emerging as a promising fabrication technology for polymers and metal products. This technology is able to fabricate complex shape components with high geometrical freedom and allows to reduce the overall waste material, as the powder can be recycled several times, and time from drawing to production can be consistently reduced. In the case of materials for aerospace applications, like TiAl alloys, conventional machining is needed to obtain the required surface finish. The machinability is strongly dependent on the specific alloys and on the production technology used, leading to different microstructures, that can be tuned undergoing the alloys to several treatments after the AM process. The paper focus on the effect of post processing treatment on hardness, structural properties and machinability of Ti48Al2Nb2Cr obtained by electron beam melting process. Untreated and heat treated alloys were considered. Turning tests were carried out under dry conditions by using cemented carbides cutting tools coated with TiCN-Al_2O_3-TiN. The structure, microstructure and hardness of the material were studied and related to machinability, that was evaluated in terms of tool life and surface integrity, focusing on both surface and sub-surface alterations. Tool wear, cutting forces, chip morphology and surface roughness were also analyzed. Adhesion prevailed on abrasion as main wear phenomenon, leading to cutting edge breaking. Results indicated a higher machinability of the alloys that underwent post processing treatment because of the different microstructure and crystalline phases induced. Indeed, α_2 and β phases present in heat treated material enhanced the formation of built up edge, acting as protective layer and then slowing down the degradation phenomena. Also the lower porosity leaded to a lower diffusion phenomenon, positively affecting the tool life.

1. Introduction

Among the studies undertaken in the last few decades, Austin reported that intermetallic titanium aluminides have been identified as possible alloys for a wide usage in aerospace and aeronautical applications, like aircraft engines, where nickel-based alloys are employed (Austin, 1999). Murr et al. studied the mechanical properties of the materials stating that TiAl alloys could replace the heavier nickel alloys (density of about 8 g cm^{-3}) thanks to low density (about 3.7 g cm^{-3}), high specific strength (σ_y/ρ), high specific stiffness (E/ρ), creep, oxidation and corrosion resistance (Murr et al., 2010); Kothari et al. observed that these properties remain unchanged within a temperature ranging from 600 to 900 °C (Kothari et al., 2007). Intensive research has been conducted on production technology and applications of TiAl alloys for about 20 years; Umeda et al. focused the attention on the tailoring of the alloy in order to increase its poor ductility (Umeda et al., 1997).

Kim et al. studied the influence of the microstructure on the mechanical properties of the titanium alloys; these exhibit four different types of microstructure, the so called near γ, duplex, nearly lamellar and fully lamellar (Kim and Dimiduk, 1991), having different mechanical properties. For example, Yamaguchi et al. showed that the duplex structure is preferable for higher ductility, tensile strength and longer fatigue life, but lacks creep resistance; while the fully lamellar structure exhibits higher fracture toughness, good creep properties and high temperature strength retention, but lack room temperature ductility (Yamaguchi et al., 2000). Porter et al. demonstrated that the microstructure is dependent on the manufacturing method: the material can be cooled in different ways and thereby have a different path through the phase fields (Porter et al., 2009).

---

* Corresponding author.
E-mail address: m.faga@imamoter.cnr.it (M.G. Faga).

http://dx.doi.org/10.1016/j.jmatprotec.2017.01.037
0924-0136/

According to Wu, one of the main issues to the manufacture of components made of TiAl alloys are their processing (Wu, 2006). Su et al. highlighted the processing complexity, that still represents one of the main obstacles for a more widespread application of these interesting materials (Su et al., 2005). The TiAl alloys can be fabricated by traditional casting, process analyzed by Hamzah et al. (2005), or extrusion and forging, as reported by Draper et al. (1999); Imayev et al. showed that these processes may cause coarse-grained lamellar structures or chemical inhomogeneity in the microstructure (Imayev et al., 2007). Srivastava et al. found a potential method of overcoming these problems, consisting in using the powder metallurgy approach (Srivastava et al., 2000).

In recent years additive manufacturing has emerged as a promising fabrication technology for metal products. This technology is able to fabricate complex shape components with high geometrical freedom; geometric information is given in the form of 2D layer maps extracted from 3D computer aided design data.

In particular, electron beam melting (EBM) is an additive manufacturing technology that allows to melt a great variety of alloys using an electron beam with high energy density. It allows to reduce the overall waste material, as the powder can be recycled several times without modification of its chemical composition or its physical properties, and time from drawing to production. In fact when component re-design is needed, EBM requires only a CAD modification thus avoiding expensive and time consuming tool reworking. Also, since the part is built up layer-by-layer in a near net shape, only a minimum of machining is necessary.

This technique is developed by Arcam AB in Sweden. Heinl et al. described the process; each layer is obtained through the following four steps: spreading of the powder, preheating and sintering step using a strongly defocused beam (it gives mechanical stability and electrical conductivity to the powder layer), melting step using a focused beam and lowering of the build platform by one layer thickness (Heinl et al., 2007).

The whole process takes place at elevated temperatures (up to 1100 °C) and under a low partial pressure of He ($2{\cdot}10^{-3}$ mbar), so it is suited for materials with a high affinity to oxygen such as titanium alloys.

Cormier et al. (2007) and Murr et al. (2010) were among the first to obtain titanium aluminides prototypes by additive manufacturing using electron beam melting (EBM).

Sometimes the quality or the type of microstructure achieved with this technology is not the one desired. In this case, as reported by Yamaguchi et al., the alloy can be subjected to different kinds of treatments to change the microstructure (Yamaguchi and Inui, 1993). Hot Isostatic Pressing (HIP) and common heat treatment are some examples. Several researches have been carried out to analyse the first one; Jeon et al. used it to reduce the porosity within the components (Jeon et al., 1999), while Ramanujan et al. resort to HIP to produce a homogeneous microstructure and remove the anisotropy within the material (Ramanujan, 2000). Depending on the alloy, material and manufacturing process, the resulting microstructure after HIP may be different. Habel et al. have shown that the ductility of the material increases enhancing HIP temperature (Habel and McTiernan, 2004), usually over 1200 °C.

Novoselova et al. described how the heat treatment leads to change of the intermetallic phases formation and by varying the conditions the desirable intermetallic phases can be formed (Novoselova et al., 2007), with control over grain growth and lamellar spacing.

Mercer et al. found that fracture toughness and ductility of TiAl were inversely proportional; in fact ductility increases and fracture toughness decreases by decreasing grain size (Mercer and Soboyejo, 1996). Kim demonstrated that fracture toughness is also inversely proportional to the lamellar spacing (Kim, 1995).

Similarly, Liu et al. showed that the tensile strength is not dependent on the grain size but it has been shown to be dependent on the lamellar spacing (Liu et al., 1996). As this decreases, the tensile strength increases. Umeda et al. (1997) have shown that reduction of the lamellar spacing decreases the ductility as well as the yield stress increases. Also the chemical composition and the appropriate selection of alloying elements influence the microstructures and the mechanical properties of the TiAl alloys, as reported by Hu (2001).

The Ti48Al2Nb2Cr alloy, certified by General Electric (GE) and tested for use in commercial turbofan engines (Austin and Kelly, 1993), offers increased toughness and ductility at lower temperatures compared to other TiAl alloys. Chromium is added to increase the ductility and machinability of the material, while niobium improve the majority of the materials properties, except the creep resistance, and makes the TiAl suitable for usage at higher temperatures.

As earlier mentioned, the TiAl alloy at the end of the additive manufacturing process requires a minimum of machining in order to obtain a proper surface finish. The machinability is strongly dependent on the specific alloys and on the production technology used. For example, Ti48Al2Nb2Cr has advantageous mechanical properties over a wide temperature range but it is brittle, which leads to problems during semi-finishing or finishing machining.

Titanium aluminides are classified as “difficult-to-cut” alloys, since, as demonstrated by Aspinwall et al., during machining operations produce excessive tool wear, heat (because of the low thermal conductivity) and cutting forces, difficulties in chip formation and poor surface quality (Aspinwall et al., 2005).

Mantle et al. showed that the low thermal conductivity often reduces the tool life and causes thermally induced geometrical deviations on the machined surface (Mantle and Aspinwall, 2001). An excessively worn tool can also lead to consistent residual stress and microcracks. The extreme thermal loading can be limited either by lowering the cutting speed and the feed rate or by using cutting fluids for cooling and lubrication purposes. Dudzinski, for example, showed that the cooling effect increases the tool life as it reduces thermally induced wear phenomena (diffusion and adhesion), while the lubricating effect of cutting fluids reduces mechanical wear (abrasion) on the rake face of the cutting edge (Dudzinski, 2004).

However, as demonstrated in the study carried out by Byrne et al., application of conventional cutting fluids creates several environmental problems such as water pollution, soil contamination during disposal and health problems to operators (Byrne and Scholta, 1993). The International Agency for Research on Cancer reported that mineral oil conventionally used in metal workings is carcinogenic and exposure to it could result in skin cancer. Greaves et al. (1997) showed that chronic bronchitis, asthma, chest symptoms and airway irritation were linked to aerosol exposures of traditional cutting fluids.

Manufacturers have used various green machining strategies to respond to increasing pressures for sustainability, like non-traditional lubrication techniques or improved tool materials, coatings or tool geometries. Diniz et al. reported that dry machining requires less power and produces smoother surface than wet turning under particular cutting conditions (Diniz and Micaroni, 2002).

A few publications, focused on conventional machining, can be found in the scientific literature and the results are strongly dependant on the specific alloys and on their employed production technology, strongly affecting the alloy microstructure and mechanical properties. As example, Priarone et al. (2012) investigated the machinability in milling of a titanium aluminide fabricated via electron beam melting and then thermally treated.