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Metallurgical processing of titanium aluminides on industrial scale

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ABSTRACT

Plenty of papers with regard to the processing of TiAl alloys via investment casting, forging, rolling, extrusion pressing as well as mechanical machining have been published, whereas the manufacturing of gamma-TiAl based alloys and corresponding semi-finished products has not been entirely described so far. The aim of this paper is to review and evaluate the present technologies of TiAl alloy production on an industrial scale. Metallurgical alloying techniques such as vacuum arc remelting (VAR), plasma arc melting (PAM) and electron beam melting (EBM) are being shortly described and evaluated with regard to their advantages and disadvantages from both technical and economical point of view. Particular focus is set on some specifics in metallurgical processing of TiAl alloys compared to Ti and Ti alloys. Outstanding requests on the accuracy of chemical composition, microstructural homogeneity, acceptable local deviations of alloying elements, small sizes of the products, and, additionally, the very limited wrought processing capability of TiAl alloys require a set of adjusted metallurgical technologies for the manufacturing of semi-finished products. With this regard, the production of small sized semi-finished parts via skull melting technologies and subsequent centrifugal casting in permanent moulds have been successfully developed and industrialized. Both, VAR skull melting (VAR SM) for ingot conversion and induction skull melting (ISM) for the conversion of valuable revert materials result in technically indistinguishable products due to the application of a consistent centrifugal casting technology. Both procedures offer the highest flexibility on product shapes and dimensions for minimizing the specific materials usage, which has a direct positive influence on final component costs. Resulting materials properties of the semi-finished products meet entirely the different (customer related) specification requirements. There are basically no technical limitations with regard to TiAl alloy compositions as it is the case for TiAl alloy manufacturing via other technologies.

1. Introduction

During the last two decades intermetallic titanium aluminides (TiAl alloys) have become a new class of engineering lightweight structural materials. But it took outstanding efforts to bring these materials into real commercial applications.

Between 2000 and 2004 there was a short period of technically very successful use of TiAl alloys for race sport engine components (valves, piston pins) [1]. This terminated abruptly due to changes in the Formula 1 regulations. Ten years later, the first flight on February 8th, 2010, of a Boeing aircraft B 747-8 powered by four GEnx-2B engines started the era of real commercial applications of this lightweight high temperature intermetallic material [2,3]. The novel GEnx aircraft engine family has been designed according to the request for highest fuel efficiency. It is not surprising that weight reduction, particularly in the rotating components, was one of the most important keys to meet the ambitious technical engine specifications. As a matter of fact a TiAl alloy replaced the Ni based superalloys in the last stage(s) of the low pressure turbine (LPT).

The vast majority of newly developed aircraft engines followed this trend setting strategy of General Electric. Pratt & Whitney's geared turbofan aircraft engine family PW1100G and the LEAP aircraft engine family of CFM (Joint Venture Company of GE and SAFRAN) use TiAl as the material of choice in the last stage of the LPT [4,5]. Recently, General Electric announced that the novel GE9x engine powering the renewed B 777 will be equipped with TiAl LPT blades as well [6].

Most surprisingly, the manufacturing technologies for the TiAl components are different for each application. Furthermore, two

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Table 1
Overview about aircraft engines equipped with TiAl LPT blades.

Aircraft Engine	Aircrafts powered	Entering into Service	TiAl alloy composition (at.-%)	Manufacturing technology
GEnx	B 787 B 747-8	2011	Ti-48Al-2Nb-2Cr (TiAl48-2-2)	Investment casting [3]
PW1100GTF	A 320neo	2016	Ti-43.5Al-4Nb-1Mo-0.1B (TNM®)	Isothermal forging [5]
LEAP	A 320neo B 737max C 919	2016	Ti-48Al-2Nb-2Cr	Direct machining of cast semi-finished parts [4,16]
GE9x	B 777max	2020 (estimated)	Ti-48Al-2Nb-2Cr	Additive Manufacturing [7]

different TiAl alloy groups (the GE's TiAl48-2-2, solidifying via the peritectic reaction, and the β-solidifying TNM® alloy) were chosen, approved and certified. Further details are given in Table 1. Note, that compositions are stated in at.-% unless indicated otherwise.

Since 2014 updated regulations allow again the use of TiAl alloys in Formula 1 race sport engines, but production volumes are rather limited. The production technology of in- and outlet valves is based on backward extrusion of the valve stem from small sized cylindrical buttons which are either cast or extrusion pressed and subsequently cut. Several efforts to industrialize TiAl turbocharger wheels failed (except after sales market products) mainly due to the lack of an appropriate investment casting technology. The unknown future of the Diesel engine is a second major drawback for the TiAl turbocharger technology.

On the other side, new powder based technologies for the manufacturing of complex components such as additive manufacturing (AM) and spark plasma sintering (SPS) are getting more and more interesting for the production of very complex γ-TiAl based components [7–9]. There is a rapidly increasing demand for TiAl alloy powders with adjusted properties (particle size distribution, chemical composition with included loss compensations) which has a direct influence on the availability of qualified feed stock materials for gas atomization. Particularly, remelt stocks for the VIGA technology (Vacuum Induction Gas Atomization based on cold crucibles) and cylindrical small diameter rods as EIGA electrodes (Electrode Induction Gas Atomization) are needed.

It is evident that this complex situation with regard to specific demands for TiAl materials and semi-finished products has a direct impact on the materials manufacturing technologies which have to be adjusted to significantly different component production routes. In any case, the availability of suitable industrial materials production technologies was and still is a precondition for succeeding TiAl as a structural material on duty. With this regard, materials manufacturers were faced with the typical “hen and egg problem”: lab scale materials production and processing technologies result in high specific costs preventing any industrial application. But applications are needed to scale up the production technologies in order to improve productivity and reduce manufacturing costs. Knowing that materials will only be considered for use if there is a reliable source available supplying the materials on a very high-quality standard to reasonable costs, GfE started investments to establish industrial scale manufacturing technologies.

Due to the nature of TiAl as an intermetallic compound, the requests on materials composition and materials soundness are outstanding high which is very challenging in terms of keeping production costs under control. Based on experience gained along the learning curve, increase of production volumes and progress in processing technologies, an overall production cost decrease of about 70% has been realized at GfE during the last 10 years. In the same time, production volumes increased by a factor of almost 30 (see Fig. 1).

The first remarkable price reduction was effective in 2012 due to the implementation of the VAR Skull Melting technology with subsequent centrifugal casting to small sized parts. This technology replaced the expensive processing route via extrusion pressing. The second valuable contribution to cost savings was the introduction of the recycling technology for TiAl revert in 2016 [10] which became effective in 2017, see chapter 3.5 in this paper.

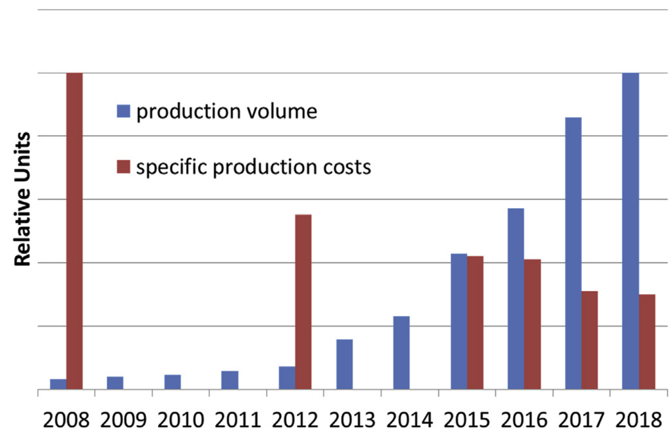

Fig. 1. Development of TiAl production volumes and production costs at GfE during the last 10 years.

2. Metallurgical processing of TiAl

2.1. Materials production

Basically, melting technologies used in the titanium industry such as Vacuum Arc Remelting (VAR), Plasma Arc Melting (PAM) and Electron Beam Cold Hearth Melting (EBCHM) are applicable to TiAl alloys as well (see sketches in Fig. 2).

Since EBCHM processing requires high vacuum conditions, local superheat results in the loss of alloying elements which show a high specific equilibrium evaporation pressure such as Al, Cr or Mn. Presently, there is no strategy available to sufficiently compensate such evaporation losses. Thus, EBCHM processed TiAl alloys do not meet the homogeneity requirements and are, therefore, not in use.

The consumable electrode of the VAR process covers the melt pool and reflects evaporated atoms. Additionally, the pressure of the plasma arc suppresses evaporation as well. In case of TiAl materials with high Mn or Cr contents, evaporation losses can be further suppressed by VAR processing under partial inert gas pressure [11]. Therefore, evaporation losses during PAM processing are fairly small and, if needed, can be compensated by a defined surplus of the affected element in the initial melt stock. Both VAR and PAM result in ingot materials of reasonable homogeneity depending on the number of remelting steps as well as melt rates and the sizes of the homogenization pools. Small local deviations particularly in the Al content are a result of solidification mechanisms which are being influenced by the TiAl alloy composition, specific melting parameters and ingot sizes (diameter).

In the production of TiAl materials both VAR and PAM have been successfully industrialized [8,9].

The preferred TiAl production technology at GfE is VAR because this technology offers the capability to process all types of TiAl alloys, i.e.

- conventional γ-TiAl alloys solidifying via the peritectic reaction