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FUNDAMENTALS OF MANUFACTURING TECHNOLOGIES FOR AIRCRAFT ENGINE PARTS MADE OF TiAl BASED ALLOYS

The study presents fundamentals of manufacturing technologies for aircraft engine construction elements, made of light, intermetallic TiAl based alloy, which is characterized by high relative strength and good creep and oxidation resistance. For smelting of alloy, the vacuum metallurgy methods were used, including application of induction furnace equipped with special crucibles made of isostatic-pressed, high-density graphite. To produce good quality construction element for aircraft engine, such as low-pressure turbine blade, there were methods of gravity casting from a very high temperature to the preheated shell moulds applied.

Keywords: TiAl based alloys, induction melting, casting, manufacturing of blades

1. Introduction

Alloys based on structural intermetallic TiAl phase with low density, high relative strength, good creep and oxidation resistance, represent extremely attractive, light, new generation construction material predestined for applying in rotating elements of modern aircraft structures operating at temperatures from 600°C to 850°C [1-4]. Manufacturing methods for TiAl based alloys rely mainly on melting and multiply refining remelting, which is conducted in vacuum or argon protective atmosphere, in furnaces designed for conventional titanium alloys melting. Because of low technological plasticity of TiAl based alloys, the final and semi-products made of them are produced with application of casting technologies supported by machining. Alloys based on intermetallic TiAl phase are characterized by poor castability, significant casting contraction and narrow range of solidification temperatures [5-7]. As a result, they require rapid introduction of the liquid alloy into the casting mould, which results in strong turbulence and appearance of pinholes in the casting. Poor casting properties of TiAl based alloys are also a cause for surface and internal casting defects formation, in a form of: misruns, cracks, shrinkage cavities and porosities, especially by casting of thin-walled products and elements with complicated shapes and diversified cross-sections. In order to minimize the adverse impact of turbulences and poor casting properties of TiAl based alloys, most frequently the casting temperature is raised and/or the heating of casting moulds is applied, which significantly extends the crystallization time. It creates a possibility for gas bubbles transfer to the liquid metal surface and prevents formation of misruns.

The initial microstructure of castings made of TiAl based alloys is a result of peritectic transformation $L+\beta\rightarrow\alpha$, which integral effect is a coarse-grained structure and interdendritic microsegregation of aluminium. Phase α, which appears as a result of peritectic transformation, during further cooling transforms into a lamellar crystals of ordered phases α_2 and γ, with a thickness dependent on the aluminium content and cooling rate during the transformation $\alpha\rightarrow\alpha_2+\gamma$ [3, 8]. An effective primary structure refinement of the intermetallic TiAl based alloys is the application of modifiers such as boron [9] or rare-earth metals [10], as well as special heat treatment methods [11, 12]. In order to minimize the interdendritic microsegregation the homogenization annealing is conducted. To avoid the macro- and microporosities hot isostatic pressing is applied. The analysis of temperature distribution in the working space of aircraft engine [4] reveals that the TiAl based alloys may be used as substitutes for nickel superalloys to manufacture turbine blades operating in the last sections of low-pressure turbine. Development of the fundamentals of technology for producing such blades was the main aim of research described in this paper.

2. Materials and research methodology

In order to produce low-pressure turbine blade with shape and dimensions presented in the Fig. 1 the Ti-47Al-2W-0.5Si alloy (at.%) was applied. Alloy was melted in the vacuum furnace with crucibles made of isostatic-pressed high-density graphite [13] and casted into ceramic sand moulds to the form of ingots with 55 mm diameter, 400 mm length, and the weight of about 4 kg each. The chemical composition of ingots was presented in the TABLE 1. From this ingots, after de-skinning and cutting into pieces, turbine blades were produced, by remelting of alloy and gravity casting into shell moulds placed in the resistance heater, which enabled heating to the maximum temperature

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of 1000°C. After casting the mould was broken up to extract the cast, then the excess metal was removed and the surface was cleaned in the stream of abrasive sand.

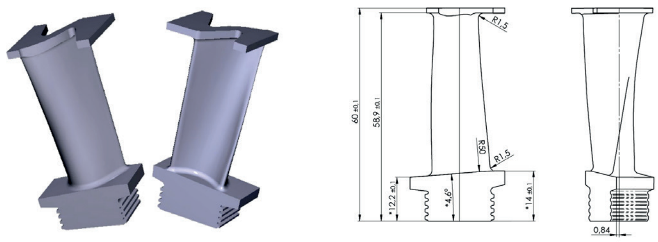

Fig. 1. Shape and selected dimensions of low-pressure turbine blade

TABLE 1
Chemical composition of investigated alloy

Al	W	Si	C	Ti	O	N	H
at.%					ppm		
46.60	2.33	0.43	0.34	Balance	836	120	21

The macrostructure of alloy was observed after each stage of technological processes, using stereoscopic microscope Nikon SMZ 1000, while the microstructure was examined using Nikon Epiphot 200 microscope, with the usage of digital image capture techniques as well as scanning electron microscope Hitachi 3400N. Preparation of material for macro- and microstructure investigations included electrical discharge cutting, wet grinding, polishing and etching in the Kroll reagent.

3. Research results

Operations connected with manufacturing of turbine blade presented in the Fig. 1 from the Ti-47Al-2W-0.5Si alloy were preceded by casting usefulness evaluation, determining crystallization temperature range, castability and casting contraction. The temperature range between liquidus and solidus temperature, of respectively 1520°C and 1470°C, is very narrow and does not exceed 50°C, which necessitates the rapid introduction of the melt into the casting mould. It has been found that the castability of the alloy under test is significantly lower than the castability of typical casting alloys, but it increases with the rise of casting temperature and the mould temperature (TABLE 2). The values of casting contraction are high, within the range 2.20-2.60%, and the increase of casting temperature, as well as mould temperature, results only in insignificant increase of these values (TABLE 2)

TABLE 2
Castability and casting contraction of the investigated alloy

Property	Casting temperature [°C]					
	1650		1700		1750	
	Mould temperature [°C]					
	20	1000	20	1000	20	1000
Castability [mm]	153	206	158	226	198	250
Casting contraction [%]	2.20	2.40	2.20	2.50	2.25	2.60

Manufacturing of low-pressure aircraft engine turbine blade presented in the Fig. 1 from the Ti-47Al-2W-0.5Si alloy by means of gravity casting to ceramic shell moulds required to perform the following operations:

- visualization of the turbine blade model,
- processing of blade visualized model into a resin pattern,
- preparation of silicon mould from the resin pattern,
- preparation of a wax pattern together with running system,
- multiple coatings of ceramic slurry to form ceramic shell mould,
- solidification and hardening of ceramic shell,
- removal of wax,
- heat treatment of ceramic shell,
- alloy melting and casting into mould,
- knockout and cleaning of casting,
- homogenization annealing,
- hot isostatic pressing,
- heat treatment,
- machining,
- surface treatment [14].

To prepare the visualization model, a finished blade and computerized station equipped with 3D scanner were used. The processing of visualized model into a resin pattern made of epoxy resin required application of Rapid Prototyping technology and stereo-lithographic method. By pouring the resin model of the silicone mixture a reusable silicon mould was produced, which was applied to manufacture patterns of turbine blade from red jewellery wax. Wax pattern, after connection with running system made of the same wax (Fig. 2a), was used to prepare ceramic shell moulds (Fig. 2b). First layer of those moulds, directly exposed to the molten alloy, was performed based on a ceramic mixture consisting of a powdered ZrO_2 and so-called Titanbinder. The remaining layers (up to 10) were performed based on Ekosil binder and quartz sand with a grain size from 0.1 to 1.0 mm. Moulds were subsequently emptied of wax in an autoclave and heated for 2 h at 900°C to obtain the desired durability.

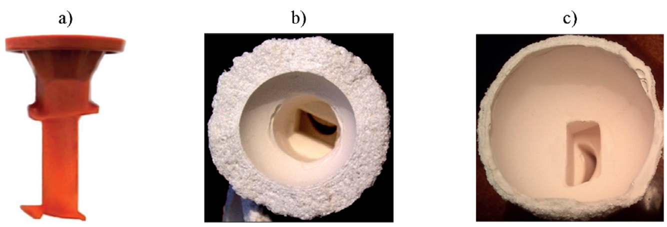

Fig. 2. Wax model set of blade (a) and ceramic shell moulds (b, c)

The casting process of low-pressure turbine blades from Ti-47Al-2W-0.5Si alloy, with using presented in the Fig. 2b ceramic shell mould, despite the very high casting temperature (1750-1775°C) and mould temperature (1000°C) rarely brought the expected effect in a form of high-quality turbine blade (Fig. 3).

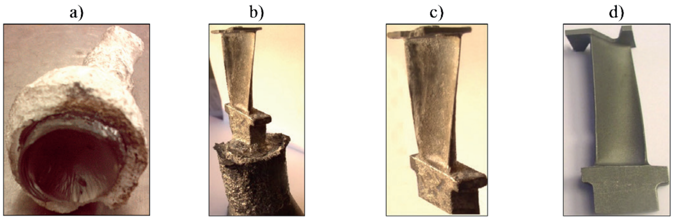

Fig. 3. Low-pressure turbine blade made of Ti-47Al-2W-0.5Si alloy after: casting (a), knocking out of ceramic mould (b), cutting off the riser (c) and surface cleaning (d)

In most cases, a large hindered casting contraction of Ti-47Al-2W-0.5Si alloy caused cracks near the Z-shaped shroud (Fig. 4a). There was also confirmed the occurrence of surface defects in form of burns caused by intense reactions on molten alloy/mould material interface, multiplied by required, extremely high casting and mould temperature (Fig. 4b). Lowering of the casting or/and mould temperature, which decreases the possibility of burns occurrence, caused in turn the presence of misruns (Fig. 4c) what resulted from lower castability of the alloy (Table 2).

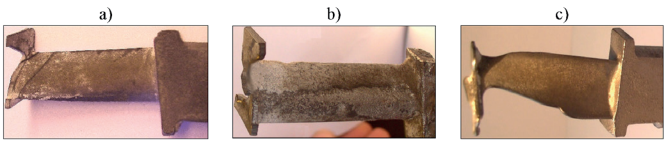

Fig. 4. Defects accompanied of Ti-47Al-2W-0.5Si alloy casting into the shell moulds: cracks (a), surface defects (b) and misruns (c)

Achievement possibilities of casted blades without any misruns and cracks were seen in the application of very high casting and mould temperature, by simultaneous reduction of ceramic mould wall thickness (application of 2-3 layers instead of hitherto 10) and thickness enhancement of thin-walled cross-sections of casting, especially blade body and its Z-shaped shroud. It required correcting suitable dimensions of wax pattern of the blade and replacing of finish grinding process by milling.

Performed tests revealed that application of very high casting temperature (1750-1775°C) and mould temperature (1000°C), as well as replacement of thick-walled moulds (Fig. 2b) by thin-walled moulds (Fig. 2c), together with thickening of some casting walls enabled, with satisfactory reproducibility, receiving of low-pressure turbine blade castings with occurring on their surface burns and oxides, however without cracks and misruns (Fig. 5a).

Fig. 5. Low-pressure turbine blade made of Ti-47Al-2W-0.5Si alloy after casting, knockout of the ceramic mould, cutting off the riser (a) and surface cleaning (b)

After knockout of mould and cutting off the riser, casting surface was subjected to cleaning in the stream of sand abrasive material. Sandblasting enabled only removal of visible in the Fig. 6a „burnt" moulding sand and oxide layer from the casting surface. In contrast, to remove the reaching deep high-hardness diffusion layer (Fig. 6b), so-called „alfa case", chemical etching in a water solution of hydrofluoric and nitric acid was applied. After etching the blade surface was clean and slightly porous (Fig. 5b).

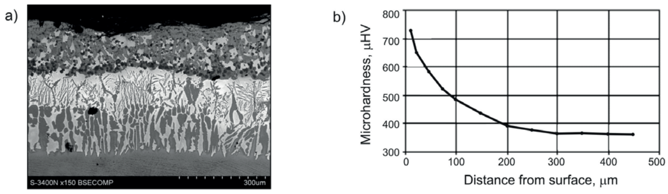

Fig. 6. Cross-section of casted blade (a) and the distribution of microhardness on the cross-section (b)

Macrostructure analysis on cross-sections taken from various locations of blade subjected to homogenization annealing for 1 h at 1400°C revealed that the macrostructure is heterogeneous, when the grain size is considered (Fig. 7). The finest grain characterizes the blade body, the coarsest grain is present in the shank and in the shroud, where the blade cross-section is largest. The occurrence of porosities was also confirmed, especially in the shroud (Fig. 7e). Those porosities resulted from adverse influence of high casting and mould temperatures.

Blade castings were subjected to hot isostatic pressing in order to remove the porosities. Blades remained for 4 h at the temperature of 1260°C and stress of 170 MPa in the press chamber with highest purity argon. It was found that after using this method the porosities in the blades macrostructure almost no appear (Fig. 8). The macrostructure is also fine-grained when compared with this achieved before the process (Figs. 7,8), however differences in the grain size are still visible under the blade (Figs. 8a,b). Similar differences appears also in the microstructure. In the shank, where blade cross-section is largest, occurs a typical duplex microstructure (Fig. 8c), while in other zones of the blade there is a pseudo-lamellar microstructure with poorly formed grain (Fig. 8d).

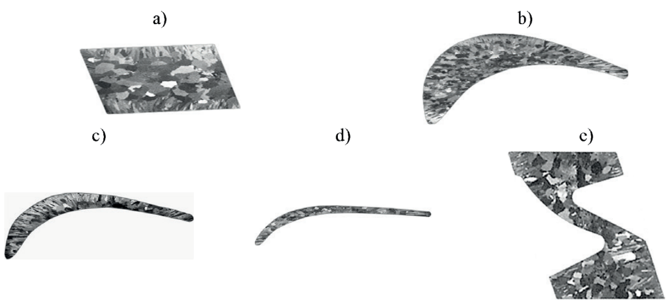

Fig. 7. Macrostructure on the cross-section of: shank (a), at the base (b), at mid-height (c), at the top (d) and in the shroud (e) of blade after casting and homogenization annealing

To minimize of the difference of macro- and microstructure between the zones of casted blade after homogenization annealing (Fig. 7) and less after hot isostatic pressing (Fig. 8) a multi-stage heat treatment was proposed. It consisted of cyclic heat treatment, long-term under – annealing and short-term full annealing. The effectiveness of this authorial treatment has been frequently confirmed for TiAl based alloys [15,16]. Fig. 9a and b present macrostructures on the transverse section of blade after heat treatment process.

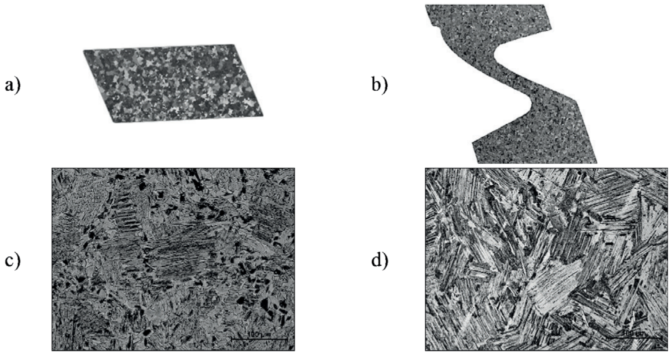

Fig. 8. Macro- (a, b) and microstructure (c, d) on the transverse section of shank (a, c) and shroud (b, d) of blade after casting, homogenization annealing and hot isostatic pressing

The comparison to macrostructures of blades after homogenization annealing and hot isostatic pressing (Fig. 8) indicates that proposed multi-stage heat treatment is an effective way not only to refine blades' grain, but also to minimize its difference between thin-walled and thick-walled cross-sections. This observation also applies to the alloy microstructure, which after multi-stage heat treatment is characterized by lamellar construction and limited grain size – optimal and expected due to the potential use – without showing significant differences between significantly different cross-sections (Figs. 9c,d).

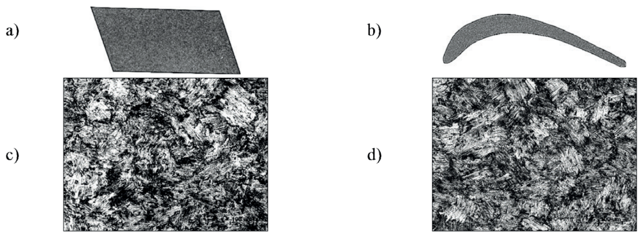

Fig. 9. Macro- (a, b) and microstructure (c, d) on the transverse section of shank (a, c) and at mid-height of blade body (b, d) after casting, homogenization annealing, hot isostatic pressing and multi-stage heat treatment

Castings of blades after cleaning the surface (sandblasting and etching), homogenization annealing, hot isostatic pressing and multi-stage heat treatment were subjected to finishing machining consisting of rough and finishing milling. The result of these activities were finished low-pressure aircraft turbine blades, made of Ti-47Al-2W-0.5Si alloy (Fig. 10).

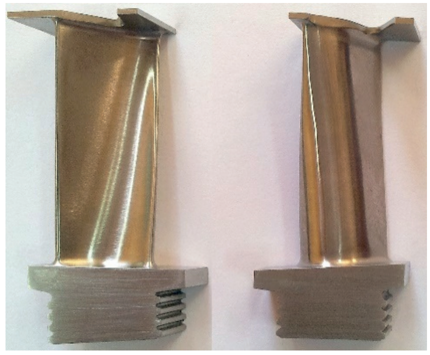

Fig. 10. Finished low-pressure turbine blades made of Ti-47Al-2W-0.5Si alloy

4. Summary

Ti-47Al-2W-0.5Si alloy, which belongs to the group of alloys based on intermetallic TiAl phase, is characterized by narrow temperature range, in which its crystallization may take place, poor castability and large casting contraction. These properties do not predispose this alloy for the production of thin-walled low-pressure turbine blades with complex shapes and variable cross-sections due to the possibility of cracking and formation of misruns.

Performed research showed that for the manufacturing of thin-walled low-pressure turbine blades with complex shapes and variable cross-sections from the Ti-47Al-2W-0.5Si alloy, without disqualifying surface and internal defects, as well as with suitably formed microstructure, there may be applied technology of gravity casting to preheated shell moulds in combination with the homogenization annealing, hot isostatic pressing, special multi-stage heat treatment and machining.

In order to prevent cracking of thin-walled low-pressure turbine blade castings the usually used thickness of mould wall was minimized and the thickness of thin-walled cross-sections of casted blades was enhanced.

In order to prevent misruns, the casting process was performed from the casting temperature of 1750°C into ceramic shell moulds preheated to the temperature of 1000°C. Very high casting and mould temperature resulted in occurrence of porosity in the blades castings as a result of shrinkage, coarse-grained structure, as well as in inhomogeneity of the macro- and microstructure.

Application of hot isostatic pressing procedures proved to be sufficient to eliminate porosity and significant grain refining of the blades. Further grains refining as well as minimization of grain size variations and microstructure between its thin-walled and thick-walled cross-sections was achieved after application of multi-stage heat treatment.

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