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A comparative study of manufacturing processes of complex surface parts in Titanium Ti6Al4V

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Abstract

Titanium and its alloys have been increasingly used since the 1950s, because of its excellent characteristics, such as the specific resistance, corrosion resistance, and biocompatibility, among others. The most employed alloys are the alpha-beta Ti6Al4V (representing 50% of the market), normally used in devices that demand optimized designs and complex technological properties. The manufacture of components in titanium requires dedicated equipment and the combination of different technologies, like electrical discharge machining, five-axis machining, investment casting, additive manufacturing and others. This work presents a literature review of casting, machining and additive manufacturing technologies relative to titanium parts manufacturing, indicating the most common problems and the solutions proposed, with special empahsis to Ti6Al4V, due to its wide industrial use. The goal is presenting a comparative experimental study of the surface finishing, geometric accuracy and microhardness, in a Ti6Al4V impeller manufactured by Investment Casting, Machining and Selective Laser Melting.

Keywords: complex surface; Ti6Al4V; machining; investment casting; SLM.

1. Introduction

The titanium and its alloys are characterized by having some excellent physical properties that allow its use in devices with singular applications. For example, due to their specific resistance are employed in landing gears beams and turbines blades in the aerospace industry [1].
Because of its biocompatibility capabilities in the medical field, are used in biomedical implants, dental applications and prostheses [2]. Automotive industry takes advantage of the high-temperature resistance and particular strength, using them in exhaust and inlet valves [3].
These fields demand devices with optimized designs, unique technological properties and complex surfaces [4], produced with specialized technologies, such as investment casting, five-axis machining, chemical milling, electrical discharge machining (EDM) and more recently additive manufacturing (AM) processes [5].
The goal of this paper is to do a review of the technologies available to manufacture titanium parts, with special emphais to the ones produced in Ti6Al4V, and develop an experimental work that compares the surface finish (roughness), geometric accuracy and microhardness of an automotive impeller obtained by investment casting, CNC machining and Selective Laser Melting (SLM).

2. Literature review

2.1. Titanium and titanium alloys

Pure titanium has a thermal conductivity of 14.99 W/(mK), an elastic modulus of 115 GPa, a density of 4.51 g/cm^3, superior resistance to corrosion and high

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chemical reactivity, which distinguish it from other metallic elements. It has 100 different kinds of alloys, but only 20 to 30 are commercialized, and 50% of them are Ti6Al4V [1]. These alloys have different characteristics and are used according to the product properties requirements (Table 1).

Table 1. Properties of Alpha, Alpha + Beta and Beta alloys [6].

Properties	Alpha	Alpha + Beta	Beta
Density	+	+	-
Strength	-	+	+ +
Ductility	/+	+	+ / -
Fracture Toughness	+	/+	+ / -
Creep strength	+	+/ -	-
Corrosion behavior	+ +	+	+ / -
Weldability	+	+/ -	-
Cold formability	-	-	- / +

Ti6Al4V is an alpha-beta alloy, developed in 1950 at the Illinois Institute of Technology [6], and is the most investigated titanium alloy. It has an excellent balance of properties (Table 2), and one should highlight the great resistance to work at high temperatures [7].

Table 2. Properties of Ti6Al4V [8].

Properties	Ti6Al4V
Hardness (HV)	300 ±30
Young's Modulus (GPa)	110 ±10
Yield Strength (MPa)	800 – 1100
Tensile Strength (MPa)	900 – 1200
Elongation (%)	13-16
Transition Alfa-Beta phase (ºC)	995
Thermal conductivity (W/(mK))	7

The properties of Ti6Al4V influence the technological processes used to manufacture the components, due to the high energy required in the process. The main technologies are casting, forging, welding, extrusion, stamping, machining, chemical milling, grinding, powder metallurgy, and additive manufacturing, among others [2], however this works only describes the production of parts using investment casting, machining, and AM.

2.2. Casting

Casting is the main near-net-shape (NNS) technological process for Ti6Al4V. About 90% of titanium parts are produced by casting [7]. It is used to manufacture medium and large series parts, allowing industry to minimize machining costs.

Most Ti6Al4V castings are obtained through investment casting. The biggest difficulties are the high melting point and the high reactivity with the oxygen [9], which reduce the castability. To overcome these problems, the melting is overheated and the mold pre-heated, reducing the temperature gradient between them and raising the fluidity [10].

Casting can preserve the static and dynamic properties of parts, but its fatigue resistance is affected [1]. In general, for casting a complex surface, a safety factor is applied, which allows a security thickness. This increases the production costs due to post-processing (Ti6Al4V can use a casting factor of 1.0). Nastac et al. [7] talks about the possibility of investment castings with sections ranging from 0.9 to 1,3 mm, claiming that is an advantage of this casting process.

Most of the research in investment casting of Ti6Al4V [1,3,7,11] is focused in structure solidification, casting safe factor, shrinkage prediction, porosity defects and processes simulation.

2.3. Machining

Machinability considers criteria such as the tool life, chip formation, surface finishing, material removal rate, cutting forces and power, so one can infer that titanium alloys will not be considered as a material with good machinability [8]. However, machining continues to be the most used process to produce parts with complex geometries and special features [5].

Machining of Ti6Al4V has disadvantages like low thermal conductivity that prevents heat dissipation produced during machining actions. A low elasticity modulus causes elastic recovery at the moment of cutting, and the high chemical reactivity increases the galling with the cutting tool [12].

In machining, spring-back is the reaction of materials to deformation that takes place at the instant of cutting process. It is linked to material elasticity modulus - a lower modulus means more resistance to machining. Ti6Al4V elasticity modulus of 110 GPa, is a low value, when compared with the 210 GPa of steel. To mitigate this problem, a low depth of cut, good grip, and performing operations prior to machining are common solutions [12]. On the other hand, the thermal conductivity (7 W/(mK)) of Ti6Al4V causes that about 80 % of the heat generated in machining is conducted by the cutting tool [13]. This temperature raise generates thermal expansion of the tool,