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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, increases the required cutting force, reducing the life of the cutting tool and a poor surface quality and accuracy are obtained [8]. The main cutting parameters involved in this problem are the tool speed rotation and feed.

New refrigeration systems and cooling fluids to reduce the temperatures generated by the machining, and combinations of these methods have been refered to increase the cutting tool life up to five times [14]. Hong et al. [15] evaluated these technologies and classified them in terms of effectiveness, worst to best (dry cutting, cryogenic tool back cooling, emulsion cooling, precooling the workpiece, cryogenic flank cooling, cryogenic rake cooling, and simultaneous rake and flank cooling). Recent research [16,17] suggests an external laser spot heating that decreases the resistance of titanium in the cutting zone, reducing cycle forces, optimizing the cutting speed to 125 m/min.

Only few studies presented the role of the combination of refrigeration systems and laser spot heating. C. R. Dandekar *et al* [18], used a laser spot heating and cryogenic tool cooling to achieve an increase in cutting speed until 150-200 m/min, tripling the service life of the tool.

The most common technique analyzed and studied to solve these and other problems in machining of titanium usually focus on low cutting speeds to extend the life of the cutting tool, bigger cut depths and large cutting fluid flow for reducing temperature.

2.4. Additive Manufacturing

The manufacturing process of metal components is today involved in a new industrial revolution. Additive manufacturing begins to be established like a protagonist of great changes in the production of complex geometric metallic parts. Nowadays is possible to direct manufacture parts of Ti6Al4V with Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) [19,20].

The microstructure, roughness, densification and microhardness of the parts are related with the processing parameters (particle size, laser power, and scanning speed) [19,21,22].

Parts obtained by AM have high roughness and porosity due to the anisotropy of the process. Shot peening post-processing is normally used to homogenize the surface structure and reduces the residual stresses. Thermal treatments are also frequently employed for the same effect [19,23].

Table 3 exhibits a comparative study of the mechanical properties, dimensional accuracy and surface quality of Ti6Al4V obtained by DMLS, EBM, and SLM, where the influence of anisotropy of these processes is observed (for the vertical direction of DMLS process no data is available).

Table 3. Properties of Ti6Al4V obtained by DMLS, EBM and SLM [24], where H is the horizontal direction and V the vertical.

Properties	DMLS	EBM		SLM	
	H	V	H	V	H
Density (%)	98.15	99.23	99.23	98.50	98.50
Yield Strength (MPa)	1109	852	875	1100	858
Tensile Strength (MPa)	1172	940	952	1209	937
Elongation (%)	8	16	13	11	8
Micro-Hardness (HV0.5)	391	342	334	398	393
Roughness (μm)	11.4	19.1	15.9	3.6	3.5
Accuracy (mm)	0.06	0.1	0.1	0.24	0.24

Selective Laser Melting SLM is the evolution of DMLS process, where the partial melting sintering becomes a full fusion. Currently, research in the production of complex geometries with this technology sustains that SLM has a high potential for near-net-shape production [25] and SLM of Ti6Al4V is analyzed in this paper.

3. Experimental

The experimental work does a comparison of the surface finish, geometric accuracy, and microhardness of a Ti6Al4V impeller of 65 mm x 25 mm (diameter x height) and six blades of 1.2 mm of thickness, manufactured by Investment Casting, SLM, and Machining.

3.1. Investment Casting

To cast the impeller, a copper mold was used to produce the impeller wax patterns. This mould was based on a commercial aluminum impeller.

The wax was heated at 67 °C and injected into the mold at 2.5 bars. Six wax models were then welded to the gating system to produce a seven layer ceramic shell. The first two layers were an aqueous solution of colloidal silica mixed with yttria flour and yttria stucco, while the remaining six layers were made with water-based colloidal silica mixed with alumina flour and alumina stucco. The next step was heating the shell in an oven at 900°C for 2h for dewaxing (thermal shock and calcination), followed by a pre-sintering at 1200°C for 1h to improve the mechanical properties of the shell.

Ti6Al4V (ASTM B 348) was cast in the pre-heated shell, at 1000°C, that was covered with a fiberglass blanket to minimize the thermal shock. The alloy was cast at 1700°C and cooled under an inert atmosphere of argon, with a cooling time around 30 minutes. The shell was removed by a vibratory pneumatic hammer, water jetting, and blasting with glass beads. A chemical cleaning with an aqueous solution of nitric (7%) and hydrofluoric acid (15%) was applied to remove any eventual tiny debris still existent in the final parts (Figure 1).

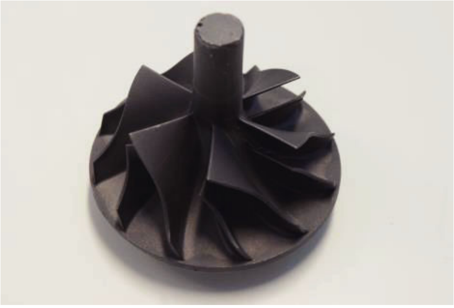

Fig. 1. Casted impeller.

3.2. Selective Laser Melting

Two impellers were manufactured with the SLM process. The first one was made in a 3DSystem Layerwise equipment (company omitted information about the process) (Figure 2.a). A Renishaw AM250 equipment made the second impeller (figure 2.b) with a continuous wave Ytterbium fiber laser YFL (wavelength 1070 nm) with a maximum power of 400 W, laser beam diameter between 34 µm and 70 µm, and the maximum laser speed scanning of 2000 mm/s. The working chamber provides a closed environment with Argon (vacuum pressure 950 Bar) and an oxygen concentration of 100 ppm.

SLM impeller was produced in the following ranges: laser beam 35 µm, laser power 200 W, laser scanning speed 0.4 m/s, powder layer thickness of 60 µm and post processing with High Isostatic Pressing HIP and blasting.

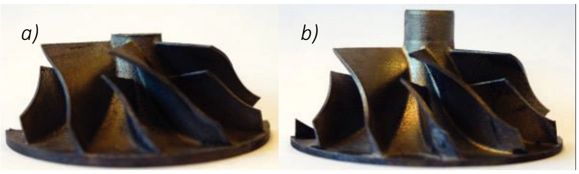

Fig. 2. Impeller produced by SLM a) LayerWise; b) Renishaw.

3.3. Machining

The machined impeller was made with Ti6Al4V (ASTM B 348), in a 5-axis machining center (DMG Mori DMU 60 eVo controlled by Heidenhain iTNC 530). In the roughing slot and finishing blade profile a ball-nose end milling tools of 3 mm was used (Sandvick R216.42-03030-AI03G 1620). This tool has a PVD coating (Physical Vapor Deposit) of titanium aluminum nitride TiAlN. The machine used a high-pressure cooling system at 40 Bar with a mixture of soluble metalworking fluid (Castrol - Hysol XF) and water in proportion 1:5. The cutting parameters that were selected as references are presented in Table 4.

Table 4. Cutting parameters for machining Ti6Al4V.

Operation	Cutting parameters	Value
Roughing Slot	Cutting speed	50 m/min
	Depth	0.15 mm
	Spindle speed	7958 rpm
Finishing Blade Profile	Cutting speed	50 m/min
	Depth	0.05 mm
	Spindle speed	8842 rpm

4. Results and discussion

4.1. Surface finish

The surface roughness was determined in a 3D microscope (Bruker Nplex, with a standard lens of 10 X, with an optical resolution of 0.9 µm). Measurements were carried out on a surface area of 875.25 µm x 1167.00 µm. Table 5 shows the values of the 3D surface mean roughness (Sa) and average roughness profile (Ra).

Table 5. Roughness values.

Process	Sa (µm)	Ra (µm)
Investment Casting	2.819	2.407
SLM	2.976	3.388
Machining	2.593	1.766

Figure 3 shows the topography of impellers, while on SLM parts, Ra values are relatively higher due to the presence of concavities and protrusions. Casted part presents a surface roughness like the SLM but without craters and holes.

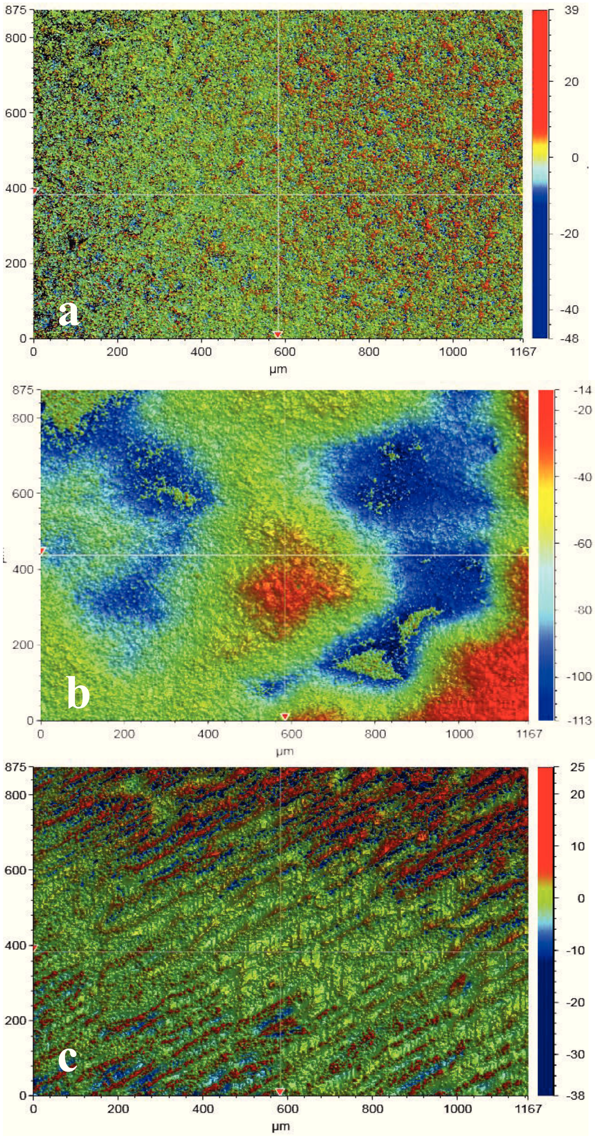

Fig. 3. Surface images, a) investment casting impeller; b) Surface SLM impeller, and c) machined impeller.

4.2. Geometric accuracy

The analyses of geometric accuracy were conducted with software for shape and dimensions inspection (GOM 3D Inspect Professional) which compared the original impeller CAD design and 3D scanned models. It was made with the three-dimensional optical scanner GOM-Atos III Triple Scan with an accuracy of 0.01 mm and a working distance of 500 mm.

This evaluation was performed on the surface of the blades. Investment casting had the less dimensional variation, presenting values between -0.09 mm and +0.08 mm. SLM parts had values between -0.12 mm and +0.13 mm and the machining part presented values of -0.08 to +0.10.

4.3. Microhardness

The samples were mounted on a bakelite support, and polished in a semiautomatic polishing machine at 150 rpm (Struers Planopol-3). The process began with sandpaper numbers 80, 320, 600, 1000 and 1200, and a polishing cloth with diamond abrasives of 3 and 1 µm. Polished samples were chemical etched with Kroll reagent (1 ml of hydrofluoric acid, 3 ml of nitric acid and 500 ml of water) and polished in a cloth with 0.01 microns alumina and a solution of hydrogen peroxide (H_2O_2).

The microhardness was determined in a Shimadzu HMV-2000 micro durometer with a load of 50 gf with and an effective resolution of 250 µm. The indentations were produced in the blades border, due to its thickness. Table 5, presents the average values obtained and the comparison with the commercial supplier information and some scientific papers.

Table 6. Microhardness comparison.

Process	Hardness(HV 0.5)	State of Art
Investment Casting	323	300-400 [8]
LayerWise Vertical	362	427 ± 34 [26]
LayerWise Horizontal	365	
Renishaw Vertical	330	
Renishaw Horizontal	346	
Machining	320	300-400

SLM parts present 17% less hardness that the values presented in the art state, on the other hand, SLM parts has 11.5% higher hardness than parts by investment casting and machining parts, while that machining and investment casting present similar values.

5. Conclusions

The initial review allowed to evaluate the challenges, procedures, and optimal process parameters to machining, investment casting and additive manufacturing of Ti6Al4V titanium alloys and challenges in manufacturing complex surfaces.

Regarding the results obtained about the surface quality, geometric accuracy, and microhardness of the impellers, one can summarize:

1. SLM part presents an average of 3D surface roughness (Sa) that is not higher than the casted part, but present an unequal surfaces that give an irregular appearance. The main studies of SLM parts in Ti6Al4V, are made on regular surfaces; which raises new challenges.
2. SLM part has differents hardness due to anisotropy, this variation can be considered a problem for post processing by machining because affects tools wear.
3. In the manufacture of free-form surfaces, SLM should be carefully considered because of the higher roughness and hardness of the parts.
4. The machining of free-form surfaces in Ti6Al4V obtained by additive manufacturing processes, it is presented as a future field of research, due to the variability of surface characteristics that present these process, where cutting parameters selection, tool geometries, cutting forces, among other can be studied to improve the surface quality of the parts.

There are little research about this area, and so further work is still demanded.

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References

[1] F.H. Froes, Titanium: Physical Metallurgy, Processing, and Applications, ASM International, Berlin, 2015.
[2] C. Cui, B. Hu, L. Zhao, S. Liu, Mater. Des. 32 (2011) 1684.
[3] F. Appel, J.D.H. Paul, M. Oehring, Gamma Titanium Aluminide Alloys: Science and Technology, 1st ed., Wiley, Singapure, 2011.
[4] H. Duan, Y. Han, W. Lu, L. Wang, J. Mao, D. Zhang, Mater. Des. 99 (2016) 219.
[5] J.P. Davim, Machining of Complex Sculptured Surfaces, Springer, London, 2012.
[6] C. Leyens, M. Peters, Titanium and Titanium Alloys: Fundamentals and Applications, Wiley, Weinhein, 2003.
[7] L. Nastac, M.N. Gungor, I. Ucok, K.L. Klug, W.T. Tack, Int. J. Cast Met. Res. 19 (2006) 73.
[8] F.C. Campbell, Manufacturing Technology for Aerospace Structural Materials, Elsevier, Oxford, 2006.
[9] G. Lütjering, J.C. Williams, Titanium, Springer, Berlin 2007.
[10] R.C.S. Rodrigues, E.P.. Almeida, A.C.L. Faria, A.P. Macedo, M.G.C. Mattos, R.F. Ribeiro, J. Prosthodont. Res. 56 (2012) 58.
[11] F. Nogueira, L.M.G. Fais, R.G. Fonseca, G.L. Adabo, J. Prosthet. Dent. 104 (2010) 265.
[12] J.P. Davim, Machining of Titanium Alloys, Springer, London, 2014.
[13] ASM-International, ASM Handbook, Machining - Volume 16, ASM International, Ohio, 2004.
[14] I. Deiab, S.W. Raza, S. Pervaiz, Procedia CIRP 17 (2014) 766.
[15] S.Y. Hong, Y. Ding, Int. J. Mach. Tool. Manu. 41 (2001) 1417.
[16] H. Ding, N. Shen, Y.C. Shin, J. Mater. Process. Technol. 212 (2012) 601.
[17] M.J. Bermingham, W.M. Sim, D. Kent, S. Gardiner, M. S. Dargusch, Wear 322–323 (2015) 151.
[18] C.R. Dandekar, Y.C. Shin, J. Barnes, Int. J. Mach. Tool. Manu. 50 (2010) 174.
[19] W.E. Frazier, J. Mater. Eng. Perform. 23 (2014) 1917.
[20] T. Wohlers, T. Caffrey, "Wohlers Report 2015, 3D Printing and Additive Manufacturing State of the Industry Annual Worlwide Progress Report", Forth Collins, 2015.
[21] M.M. Rasheedat, S. Mukul, P. Sisa, in: S. Loredana and J. P. Davim (Ed.), Surface Engineering Techniques and Applications: Research Advancements, IGI Global, Hershey, PA, USA, 2014, pp. 222.
[22] B. Vayre, F. Vignat, F. Villeneuve, Mech. Ind. 13 (2012) 89.
[23] F.H. Froes, S.J. Mashl, J.C. Hebeisen, V. S. Moxson, V. A. Duz, JOM 56 (2004) 46.
[24] F. Gomes, "Comparação de Processos de Fabrico Aditivo que utilizam metais", Master Master Degree, Engenharia Mecânica, Faculdade de Engenheria da Universidade do Porto, 2014.
[25] B. Song, S. Dong, B. Zhang, H. Liao, C. Coddet, Mater. Des. 35 (2012) 120.
[26] H.K. Rafi, N.V. Karthik, H. Gong, T. Starr, B. Stucker, J. Mater. Eng. Perform. 22 (2013) 3872.