Original Article

Employing the TOPSIS selection method to assess the use of Ti-6Al-4V ELI processed by additive manufacturing in hip implants

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Abstract

The processing of medical components of Ti-6Al-4V ELI typically includes forging and machining. Recently there has been a growing interest in additive manufacturing since this technology allows the production of customized components with high dimensional precision and minimum material loss. However, there are problems associated with additive manufacturing, such as the need to employ finishing methods and mainly the reduction of fatigue performance by internal defects and high surface roughness. This work aimed to evaluate the likelihood of using the Ti-6Al-4V ELI alloy processed by additive manufacturing in hip implants. A material selection method based on the weighting of characteristics was used considering solely aspects of mechanical properties. Hence, in a mechanical performance scenario, some processes involving additive manufacturing were found to be feasible for application in hip implants, for instance Directed Energy Deposition (DED) and Selective Laser Melting (SLM), both followed by machining.

Keywords: Materials selection; Titanium; Implant; Additive manufacturing.

Empregando o método de seleção TOPSIS para avaliar o uso de Ti-6Al-4V ELI processado por manufatura aditiva em implantes de quadril

Resumo

O processamento de componentes médicos de Ti-6Al-4V ELI tipicamente inclui forjamento e usinagem. Recentemente tem havido um crescente interesse na manufatura aditiva, pois essa tecnologia permite a produção de componentes customizados com alta precisão dimensional e perda mínima de material. No entanto, existem problemas associados à manufatura aditiva, tais como a necessidade de empregar métodos de acabamento e principalmente a redução do desempenho à fadiga por defeitos internos e alta rugosidade superficial. Este trabalho teve como objetivo avaliar a probabilidade de utilização da liga Ti-6Al-4V ELI processada por manufatura aditiva em implantes de quadril. Foi utilizado um método de seleção de materiais baseado na ponderação de características considerando apenas aspectos de propriedades mecânicas. Assim, em um cenário de desempenho mecânico, alguns processos envolvendo manufatura aditiva mostraram-se viáveis para aplicação em implantes de quadril, por exemplo, Deposição com Energia Direcionada (DED) e Fusão Seletiva a Laser (FSL), ambos seguidos de usinagem.

Palavras-chave: Seleção de materiais; Titânio; Implante; Manufatura aditiva.

1 Introduction

The weakening of bones or organs due to aging or even trauma and diseases have increased the importance of the biomaterials used in implants. Ceramics, metals, polymers, composites, and natural materials are all potential options for implant materials, depending on the specific application. Ti-6Al-4V with extra low interstitial (ELI) content is one of the most used metallic materials in the manufacture of orthopedic implants. Despite its higher price compared to traditional stainless steel, the Ti-6Al-4V ELI alloy has excellent properties for a medical device, such as high mechanical properties and biocompatibility [1]. Conventional manufacturing of Ti-6Al-4V ELI products relies on primary and finishing processes, such

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as forging, casting and rolling of the raw material followed by machining to impart final shapes and dimensions. These finishing processes typically result in large material waste and increase the manufacturing costs and lead times compared to primary manufacturing processes.

On the other hand, additive manufacturing, an advanced fabrication technology to build up structures from computer-generated models by adding material layer by layer, offers the possibility of manufacturing Ti-6Al-4V ELI products with complex geometries. Compared to traditional manufacturing methods, the most significant advantage of additive manufacturing is the possibility of producing parts directly from raw materials or predetermined shaped parts, without the limitations that the traditional methods have to achieve desired shapes [2]. Especially valuable in the field of orthopedics is such a possibility for easy development of customized prostheses and implants [3]. However, a comparative analysis of the mechanical and surface properties is necessary, particularly because the structural integrity depends on the tensile and fatigue performance of the component produced.

In recent years, research and development in the area of orthopedic implants has focused on the possibility of additive manufacturing of this alloy as a way of exploring the advantages of the technique. The purpose of this work was therefore to apply the concept of material selection as a preliminary way of evaluating the feasibility of using Ti-6Al-4V ELI alloy processed by additive manufacturing for hip implants based on its mechanical properties.

2 Materials and methods

2.1 TOPSIS method and equations

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a classic multi-criteria decision analysis method. The method is based on the classification determined by the distance between each alternative and the ideal solutions, one being positive and the other negative. The first is defined based on values that are considered the best ones, while the second comprises the worst values. The basic principle is to choose an alternative that is as close as possible to the positive ideal solution and as far as possible from the negative ideal solution [4,5].

The method has a wide field of application in the material selection area, since it allows assigning weights to the different characteristics and properties of candidate materials for a given application. For example, the TOPSIS method has been used to select the best metallic material to be used for the design and fabrication of a powered hand truck [6]. Not only engineering materials, but also natural materials have been studied using the TOPSIS method as a tool. It was employed for the selection of an optimal impregnation material for wood [7]. The final classification of materials is usually complemented by software that provides graphics and visual tools for the result [4,5]. The steps of the TOPSIS algorithm can be summarized as follows:

Step 1 – creation of a decision matrix;

Step 2 – creation of a standardized decision matrix;

Step 3 – creation of a weighting for the matrix;

Step 4 – determination of the positive and negative ideal solution;

Step 5 – calculation of the separation distance of each candidate for each solution;

Step 6 – calculation of the approximation coefficient of the candidates of the ideal solution;

Step 7 – classification in descending order of the approximation coefficient.

For step 1, a decision matrix (D) is defined according to Equation 1:

$$D = \begin{bmatrix} d_{11} & d_{1j} & d_{1n} \\ d_{i1} & d_{ij} & d_{in} \\ d_{m1} & d_{mj} & d_{mn} \end{bmatrix} \quad (1)$$

In which the lines refer to the number of candidate materials for the project and the columns are the properties or characteristics of the materials. As such properties have different magnitudes, in order to make an effective comparison among them, the matrix elements need to be normalized, which is done based on Equation 2:

$$n_{ij} = \frac{d_{ij}}{\sum_{i=1}^{m} d_{ij}} \quad (2)$$

Where n_{ij} is a value between 0 and 1. To consider the differences in importance among the properties, a weighted decision matrix is determined from a weight value (w_j) carefully assigned to each of the properties being evaluated. The elements of the weighted decision matrix are calculated by Equation 3:

$$v_{ij} = w_j \times n_{ij} \quad (3)$$

With the weighted decision matrix, the ideal solutions are defined, one being positive (v_j^+) and the other negative (v_j^-). The separation distance between the values of the weighted matrix and the values of the positive and negative solutions are respectively provided by Equations 4 and 5:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \quad (4)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \quad (5)$$

Finally, the approximation coefficient (C_i) of each candidate material is calculated based on Equation 6:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (6)$$

Based on the values of C_i the candidates are classified in descending order, with the best options being those whose global performance is closer to 1. The ordering of these values allows reaching an order of preference for the materials.

2.2 Procedure

The material selection method was used to evaluate the suitability of Ti-6Al-4V ELI alloy for use in hip implants, based on its necessary properties and characteristic. All these data then fed the material selection method for decision making. Once the evaluation of hip implants has been chosen, the project was restricted to the study of the Ti-6Al-4V ELI alloy. The Ti-6Al-4V ELI alloy must meet strict requirements defined in the ASTM F136 standard for use in surgical implants, including precise control of the microstructure's α and β phases and absence of casting defects [8].

Mechanical stresses are a major concern for hip implants, so the study focused on static properties (YS, UTS, and EL) that reflect the material's strength and ductility: yield strength (YS), ultimate tensile strength (UTS) and elongation (EL). The study also focused on the dynamic property (FR) that reflects its resistance to fatigue failure: fatigue resistance (FR). To comply with regulatory standards such as ABNT NBR ISO 7206-4, manufacturers must ensure that their femoral implants meet specific requirements for fatigue resistance. Although Young's modulus is important in inhibiting stress shielding [9], it was not included in the study because it is a material property that does not change with the manufacturing process. To gather relevant technical articles, several databases were searched, including ScienceDirect, Web of Science, and Scielo, which are known for their comprehensive coverage of scientific literature in the field of materials science.

3 Results and discussion

3.1 Data treatment

The values of mechanical properties were collected in several articles about the subject [2,10-13]. There is a great concern in the international literature regarding the processing or treatment step that follows the additive manufacturing process, which ends up making it difficult to gather the necessary data to apply the TOPSIS method. Thus, from an initial spreadsheet containing more than a hundred lines of data, each referring to a processing condition and/or a different source, the data were grouped by processing condition.

The processing conditions considered in this work refer to those for which values of all the necessary properties for the TOPSIS method were available. The conditions considered for the sequence of this study refer to those having values for all the necessary properties for the TOPSIS method. Table 1 presents the main static tensile properties (UTS, YS and EL) of the Ti-6Al-4V ELI alloy after its manufacture by different additive manufacturing processes, post-processing techniques and forging. The third column of each property stands for the average of the minimum and maximum values of the corresponding propriety raised from different sources.

The FR was considered apart from the other properties. Table 2 shows it for the processing conditions already presented. Fatigue data are actually very scarce in the literature; thus, some conditions were removed from the study due to the lack of information; some conditions only have a single value for this reason. Moreover, as the data were obtained from different sources, variations were expected in the conditions used to obtain these data, which arise from three main aspects: stress ratio (R), number of cycles to failure (run-out), and value of FR in terms of either maximum stress (σ_{max}) or stress amplitude (σ_a).

Given this scenario concerning the values of FR, some calculations and decision making were necessary to standardize all the data. The first step was to transform the values of resistance in terms of σ_{max} into values in terms of σ_a. To do that, it was necessary to resort to traditional and well-known equations of the fatigue phenomenon, such as (Equations 7 to 9):

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (7)$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (8)$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (9)$$

Applying those equations to the values of R and σ_{max} allowed the calculation of σ_a. Table 3 presents all fatigue resistance data in terms of amplitude.

Only two data in Table 3 do not correspond to a run-out of 10^7 cycles and, therefore, were excluded from the analysis. The next step was to eliminate the effect of the average stress coming from the different values of R (0.1 and –1). There are several criteria in the literature developed with the purpose of evaluating this issue; Goodman's is one of the most used for being the most conservative (appearing even in the ASME code as a design criterion) [14]. Equation 10 summarizes Goodman's criterion:

$$\sigma_a = \sigma_f \left(1 - \frac{\sigma_m}{ST}\right) \quad (10)$$

where σ_a is the stress amplitude at R = 0.1 (case of this work), σ_f (or FR) is the fatigue resistance at R = –1 and

Table 1. Mechanical tensile properties for the different processes and their simple averages [2]

Processing condition	UTS (MPa)			YS (MPa)			EL (%)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
DED/As built/Unmachined	761	923	842	522	906	714	-	6.4	6.4
DED/As built/Machined	984	1185	1085	930	1124	1027	3.0	15.7	9.4
DED/Annealed/Unmachined	700	766	733	620	708	664	-	4.8	4.8
DED/Annealed/Machined	907	967	937	843	889	866	-	11.9	11.9
DED/Aged/Machined	1044	1168	1106	935	1085	1010	3.4	13.3	8.4
DED/Stress reduction/Machined	-	956	956	-	907	907	-	10.8	10.8
DED/Stress reduction/Machined/HIP	-	900	900	-	829	829	-	15.4	15.4
SLM/As built/Unmachined	958	1064	1011	664	920	792	2.5	12.7	7.6
SLM/As built/Machined	1050	1541	1296	973	1326	1150	0.9	12.3	6.6
SLM/Annealed/Machined	896	1116	1006	768	1054	911	1.1	13.6	7.4
SLM/Stress reduction/Unmachined	-	-	-	-	-	-	-	-	-
SLM/Stress reduction/Machined	1032	1140	1086	928	1070	999	2.7	13.1	7.9
SLM/HIP/Unmachined	-	-	-	-	-	-	-	-	-
SLM/HIP/Machined	973	1035	1004	883	942	913	8.1	19.4	13.8
SLM/HIP/Unmachined/Chemical etching	959	967	963	862	868	865	19.4	24.0	21.7
EBM/As built/Unmachined	780	870	825	730	824	777	1.9	4.5	3.2
EBM/As built/Machined	918	1116	1017	836	1051	944	3.7	17.0	10.4
EBM/Annealed/Machined	837	918	878	741	842	792	3.0	9.0	6.0
EMB/Stress reduction/Machined	885	1015	950	778	943	861	3.0	9.0	6.0
EBM/HIP/Machined	817	918	868	723	817	770	3.0	9.0	6.0
Forged	833	1030	932	770	970	870	16.0	23.0	19.5

σ_m is the average or mean stress at R = 0.1. The step-by-step treatment of Equation 10 using Equations 7 to 9 is shown below:

$$\sigma_{m(R=0.1)} = \frac{\sigma_{max(R=0.1)} + 0.1\sigma_{max(R=0.1)}}{2} = 1.1\sigma_{max(R=0.1)}$$

$$\sigma_{a(R=0.1)} = \frac{\sigma_{max(R=0.1)} - 0,1\sigma_{max(R=0.1)}}{2} = 0.9\sigma_{max(R=0.1)}$$

$$\frac{\sigma_{m(R=0.1)}}{1.1} = \frac{\sigma_{a(R=0.1)}}{0.9} \Rightarrow \sigma_{m(R=0.1)} = 1.22\sigma_{a(R=0.1)}$$

$$\sigma_{a(R=0.1)} = \sigma_{f(R=-1)}\left(1 - \frac{1.22\sigma_{a(R=0.1)}}{LRT}\right)$$

The mathematical adjustment in last step provides Equation 11, which allowed the adjustment of all values of FR to R = 0.1, as summarized in Table 4.

$$\sigma_{a(R=0.1)} = \frac{\sigma_{f(R=0.1)} \times UTS}{1.22\sigma_{f(R=0.1)} + UTS} \tag{11}$$

3.2 Application of the TOPSIS method

After preparing the data and calculating the averages for each process, the TOPSIS selection method is likely to be applied. The first step was to insert the data to be worked in the decision matrix, using Equation 1, as shown in Table 5.

Following the decision matrix creation, the second step was to raise the normalized decision matrix with the help

Table 2. FR for the different processing conditions and different values of R and run-out. The gray cells indicate the resistance in terms of σ_a and the others in terms of σ_{max} [2,10-13]

Processing condition	FR (MPa) (R / run-out)	
	Min.	Max.
DED/As built/Machined	500 (-1 / 1x10^6)	600 (0.1 / 1x10^7)
SLM/As built/Machined	475 (-1 / 1x10^7)	550 (0.1 / 1x10^7)
SLM/Stress reduction/Machined	-	500 (0.1 / 1x10^7)
SLM/HIP/Machined	350 (-1 / 1x10^7)	625 (-1 / 2x10^6)
SLM/HIP/Unmachined/Chemical etching	300 (0.1 / 1x10^7)	400 (0.1 / 1x10^7)
EBM/As built/Machined	-	200 (0.1 / 1x10^7)
EBM/Annealed/Machined	200 (0.1 / 1x10^7)	250 (0.1 / 1x10^7)
EBM/HIP/Machined	550 (0.1 / 1x10^7)	600 (0.1 / 1x10^7)
Forged	300 (-1 / 1x10^7)	700 (-1 / 1x10^7)
	300 (0.1 / 1x10^7)	600 (0.1 / 1x10^7)

Table 3. FR for the different processing conditions in terms of amplitude for different values of R and run-out

Processing condition	FR (MPa) (R / run-out)	
	Min.	Max.
DED/As built/Machined	500 (-1 / 1x10^6)	270 (0.1 / 1x10^7)
SLM/As built/Machined	475 (-1 / 1x10^7)	248 (0.1 / 1x10^7)
SLM/Stress reduction/Machined	-	225 (0.1 / 1x10^7)
SLM/HIP/Machined	350 (-1 / 1x10^7)	625 (-1 / 2x10^6)
SLM/HIP/Unmachined/Chemical etching	135 (0.1 / 1x10^7)	180 (0.1 / 1x10^7)
EBM/As built/Machined	-	90 (0.1 / 1x10^7)
EBM/Annealed/Machined	90 (0.1 / 1x10^7)	113 (0.1 / 1x10^7)
EBM/HIP/Machined	248 (0.1 / 1x10^7)	270 (0.1 / 1x10^7)
Forged	425 (-1 / 1x10^7)	700 (-1 / 1x10^7)
	135 (0.1 / 1x10^7)	270 (0.1 / 1x10^7)

of Equation 2 in order to normalize the values in Table 5. Table 6 was therefore built up.

In the third stage, it was necessary to define different weights for the properties to be analyzed in the normalized decision matrix, which makes it possible to obtain different analysis scenarios. A specific mechanical performance scenario was then considered and discussed.

3.3 Mechanical performance scenario

The process selection was made prioritizing the best mechanical properties for application in implants. For weighting, greater weights were attributed to FR due to the constant cyclic effort which the hip implants go through, and to YS, which is the point at which the material starts to deform permanently (something mechanically undesirable). The choice of weights was based on the importance attributed to each property in relation to the efforts to which the implant is subjected. After that, Table 6 was considered back in order to be turned into a weighted decision matrix with the help of Equation 3, which is presented in Table 7.

After raising the weighted decision matrix, the ideal positive and the ideal negative values were identified. For the positive one, the highest value for each mechanical property was taken, the opposite being valid for the negative one. Having the values of v_j^+ and v_j^-, the separation distance between the values of the weighted matrix and the ideal solutions was calculated by Equations 4 and 5. From these

Table 4. FR for the different processing conditions in terms of amplitude for R = 0.1 and run-out of 10^7 cycles

Processing condition	FR (MPa)		
	Min.	**Max.**	**Avg.**
DED/As built/Machined	-	270	270
SLM/As built/Machined	248	328	288
SLM/Stress reduction/Machined	-	225	225
SLM/HIP/Machined	-	245	245
SLM/HIP/Unmachined/Chemical etching	135	180	158
EBM/As built/Machined	-	90	90
EBM/Annealed/Machined	90	113	101
EBM/HIP/Machined	248	270	259
Forged	135	365	250

Table 5. Decision matrix

Processing condition	UTS (MPa)	YS (MPa)	EL (%)	FR (MPa)
DED/As built/Machined	1085	1027	9.4	270
SLM/As built/Machined	1296	1150	6.6	288
SLM/Stress reduction/Machined	1086	999	7.9	225
SLM/HIP/Machined	1004	913	13.8	245
SLM/HIP/Unmachined/Chemical etching	963	865	21.7	158
EBM/As built/Machined	1017	944	10.4	90
EBM/Annealed/Machined	878	792	6	101
EBM/HIP/Machined	868	770	6	259
Forged	932	870	19.5	250

Table 6. Normalized decision matrix

Processing condition	UTS (MPa)	YS (MPa)	EL (%)	FR (MPa)
DED/As built/Machined	0.1189	0.1233	0.0928	0.1432
SLM/As built/Machined	0.1420	0.1381	0.0652	0.1527
SLM/Stress reduction/Machined	0.1190	0.1199	0.0780	0.1193
SLM/HIP/Machined	0.1100	0.1096	0.1362	0.1299
SLM/HIP/Unmachined/Chemical etching	0.1055	0.1038	0.2142	0.0838
EBM/As built/Machined	0.1114	0.1133	0.1027	0.0477
EBM/Annealed/Machined	0.0962	0.0951	0.0592	0.0536
EBM/HIP/Machined	0.0951	0.0924	0.0592	0.1373
Forged	0.1021	0.1044	0.1925	0.1326

Table 7. Weighted decision matrix for the mechanical performance scenario

w_j	0.2	0.3	0.1	0.4
Processing condition	**UTS (MPa)**	**YS (MPa)**	**EL (%)**	**FR (MPa)**
DED/As built/Machined	0.0238	0.0370	0.0093	0.0573
SLM/As built/Machined	0.0284	0.0414	0.0065	0.0611
SLM/Stress reduction/Machined	0.0238	0.0360	0.0078	0.0477
SLM/HIP/Machined	0.0220	0.0329	0.0136	0.0520
SLM/HIP/Unmachined/Chemical etching	0.0211	0.0312	0.0214	0.0335
EBM/As built/Machined	0.0223	0.0340	0.0103	0.0191
EBM/Annealed/Machined	0.0192	0.0285	0.0059	0.0214
EBM/HIP/Machined	0.0190	0.0277	0.0059	0.0549
Forged	0.0204	0.0313	0.0192	0.0530
v_j^+	0.0284	0.0414	0.0214	0.0611
v_j^-	0.0190	0.0277	0.0059	0.0191

Table 8. Di+, Di– and Ci values in descending order for the mechanical performance scenario

Processing condition	D_i^+	D_i^-	C_i
SLM/As built/Machined	0.014906	0.045156	0.751819
DED/As built/Machined	0.014248	0.039711	0.735950
Forged	0.015328	0.036662	0.705170
SLM/HIP/Machined	0.016055	0.034284	0.681059
EBM/HIP/Machined	0.023521	0.035843	0.603781
SLM/Stress reduction/Machined	0.020368	0.030235	0.597492
SLM/HIP/Unmachined/Chemical etching	0.030311	0.021546	0.415489
EBM/As built/Machined	0.044501	0.008294	0.157100
EBM/Annealed/Machined	0.045423	0.002474	0.051644

values, the approximation coefficient C_i was determined from Equation 6. The coefficient allowed classifying the materials in a descending way; the highest values were those of the process with the best overall mechanical properties. The classification is shown in Table 8.

From Table 8, aiming at the best mechanical performance scenario, two different additive manufacturing processes are better classified than the forged alloy, DED and SLM, both of which are only subjected to further machining.

These processes are much superior to all others in terms of YS and UTS and moderately superior in terms of FR. Interestingly, other post-treatments, such as HIP or annealing, were not helpful for the alloy to overcome the other conditions in a more holistic analysis.

4 Conclusions

The work analyzed the use of Ti-6Al-4V ELI alloy processed by different additive manufacturing techniques as an alternative for the material typically processed by forging and machining, focusing on hip implants. The material selection method took into account mechanical tensile and fatigue properties. In the stage of gathering the information in the international literature, a great limitation was noticed in the availability of fatigue studies, which is intriguing due to the importance of this property for any structural application. Although the industry works with high safety factors to avoid fatigue failures, the study of this property is very incipient.

Yet concerning the fatigue property, there is not a great standardization regarding the fatigue tests, even with standards to be followed. The literature brought results obtained with different values of R and run-out, making data treatment complex. It is important to mention that the use of Ti-6Al-4V ELI alloy in implants requires a low content of interstitials, and the fatigue behavior is very sensitive to these elements. The values found for the alloy by additive manufacturing do not consider this level of specificity, but they are still satisfactory parameters for comparison. Despite all the difficulties mentioned, the scenario build-up for the material selection method greatly impacted fatigue.

Finally, in a mechanical performance scenario, the feasibility of replacing the forged alloy with one processed by DED or SLM was observed, with subsequent machining. The appropriate scenario is a function of the target audience of the component to be manufactured, not forgetting the advantages brought by the literature on additive manufacturing processes.

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