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Mechanical properties characterization of Ti6Al4V for artificial hip joint materials prepared by investment casting

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Abstract. The Investment Casting (IC) process is a type of casting that can produce the suitable shape and size of components by minimizing porosity and defects. However, research on ICs for the manufacture of artificial hip joints made from Ti6Al4V is still lacking. Therefore, the purpose of this study is to determine the mechanical properties of an artificial hip joint made from Ti6Al4V casted using the investment casting method. The stages of the investment casting process used in this research are wax injection, ejection of wax pattern, tree assembly, slurry coating, final sand mould, dewaxing, preheating, pouring, and final product. The characterization of IC products was carried out by tensile test, hardness test, and impact test. The yield strength, Ultimate Tensile Strength, Elongation (%), Hardness (HRC) and Impact Strength obtained in this study were 636 MPa, 687 MPa, 17%, 29 HRC, and 5.3 J, respectively. The lower oxygen content in Ti Alloy after IC resulted in a decrease in yield strength, ultimate tensile strength, hardness, and impact energy. However, the low oxygen content in Ti Alloy after IC resulted in increased ductility (% elongation).

1. Introduction

The foundry industry is the utmost important segment in the manufacturing sector since it can produce various types of components with various models and thicknesses as well as excellent surface quality [1]. The Investment Casting (IC) process is a type of casting that can produce the right shape and size of components by minimizing porosity and other defects [2]. This casting process is often called lost wax or precision casting. IC is one of the oldest casting techniques. At the time of the Pharaohs, this technique was used by the Egyptian people to make jewellery in the form of gold, silver, and bronze [2]. IC has the ability to produce components with complex shapes and good surfaces with small geometric tolerances and high levels of precision. Complex shapes such as blades, turbines, aircraft components, and various types of modern weapons can be made using IC [3].

During World War II, the United States used IC to manufacture turbines and aircraft engines [4]. In addition to that, IC can also be used in the development of biomedical materials. In the early 19th century, dentists began to use IC to make artificial gums [2]. Some of the advantages of using ICs are maintainable reliability, better tolerances compared to other processes, low cost, environmentally friendly, and can be used to create complex models. The quality of IC products is influenced by 3 factors, namely slurry layer combination, viscosity, dry time of primary coating [5]. The drawbacks of this process are the limited size of components that can be made, expensive raw materials, and the process tends to be longer [2, 6].

Metals, ceramics, and polymers are the three main categories of biomaterials [7]. PLA, PCL, PGA, and PLGA are the most commonly used synthetic polymers as biomaterials in tissue engineering [8]. Hydroxyapatite (HAp) is an example of a ceramic biomaterial in the calcium phosphate (CaP) family that is widely used in tissue engineering because of its chemical similarity to bone mineral components [9, 10]. Metals have long been applied in a wide variety of biomedical applications as biomaterials due to their superior properties, which include strength, wear resistance, and corrosion resistance. Metallic biomaterials, like stainless steels, titanium alloys, and cobalt alloys, are commonly applied as implantable devices for a variety of medical purposes due to their superior mechanical properties [11].

Ti alloys are of great importance these days, especially in their applications for biomaterials. A large number of researchers have been trying Ti alloys in an attempt to combine most of their advantages, such as high specific yield strength, good corrosion resistance, excellent fatigue property, and biocompatibility [12, 13]. Ti6Al4V is one of the most widely used Ti alloys for casting applications. It has an excellent combination of specific strength and toughness, along with excellent corrosion resistance. It is typically used in aerospace applications, corrosion service in chemical plants, pressure vessels, turbine and compressor blades and discs, surgical implants, marine and military applications, etc [14]. In another reference, it is stated that the Ti6Al4V material has the properties of biocompatibility, high bioactivity, the ability to interact and integrate well in all parts of the human body [12, 15, 16]. For this reason, Ti-6Al-4V alloy material is widely used in biomedical activities such as the use of Ti-6Al-4V alloy material in metal-on-plastic hip joint replacement surgeries. In addition to that, Ti-6Al-4V alloy material can also be used in the healing process of osteoarthritis and rheumatoid arthritis. Osteoarthritis and rheumatoid arthritis are diseases that require replacement of the femoral head and acetabular socket, commonly referred to as hip joint replacement [17]. Although there is the potential for cytotoxic effects or neurological disorders due to the presence of vanadium and aluminium in the use of Ti-6Al-4V material [12]. This research was conducted to determine the mechanical properties of the Ti-6Al-4V obtained by the IC method and compared with the mechanical properties of Arcam Ti6Al4V and ISO 5832/3. Comparison of mechanical properties is done to determine the quality of IC products.

2. Materials and Methods

The chemical composition of the Ti-6Al-4V material used in this study is shown in Table 1. The material was purchased from Baoji Qicheng Non-Ferrous Metal Co.,LTD. The initial process of this research was carried out by inserting wax into a moulding made of duraluminum (Al-Cu alloy). This process is done by injection moulding so that the wax is denser. The moulding used in this study is shown in Figure 1. The IC product in this study will be subjected to a tensile test so that the moulding design is adjusted to ASTM E8 as shown in Figure 2.

Table 1. Chemical Composition of TI6Al4V

Fe%	C%	N%	O%	H%	Al%	V%
0.12	0.02	0.02	0.08	0.06	6.1	3.9

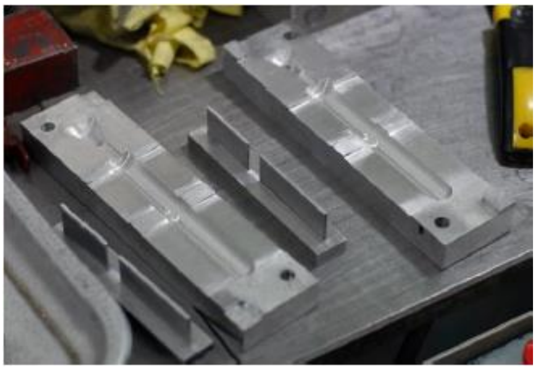

Figure 1. Moulding of Investment Casting

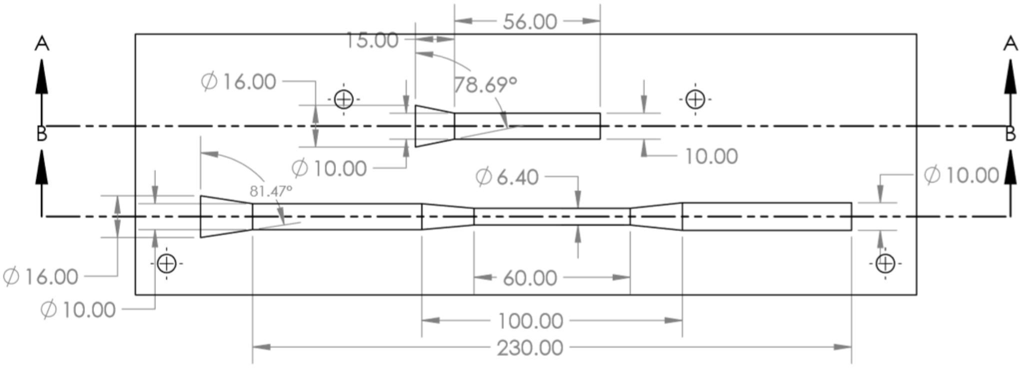

Figure 2. Moulding Design for Ti-6Al-4V Investment Casting

After injection moulding, the next process is the ejection of the wax pattern and the preparation of the wax into a tree or commonly referred to as tree assembly. This process aims to simplify the process of entering the melted Ti-6Al-4V material. Before the wax tree is coated with 7 layers of sand, a slurry coating is applied first. The next process is dewaxing which is carried out to remove wax from the mould using a furnace. Before being used for the casting process, the preheat process was carried out in the mould at a temperature of 1060° C for 30 minutes. The preheat process is carried out to avoid cracks or damage to the mould during the casting process. In addition, a preheat process is carried out to increase the dry strength of the moulding and to remove residual traces of wax and unwanted moisture particles [2]. The melted Ti-6Al-4V material is poured into a mould that has been forged on a rotary machine as shown in Figure 3. The experimental setup in this study is shown in Figure 4. Characterization of IC products was carried out by tensile testing, hardness testing and impact testing. Mechanical properties of IC products were compared with Arcam Ti6Al4V and ISO 5832/3.

Figure 3. Machines used for investment casting process.

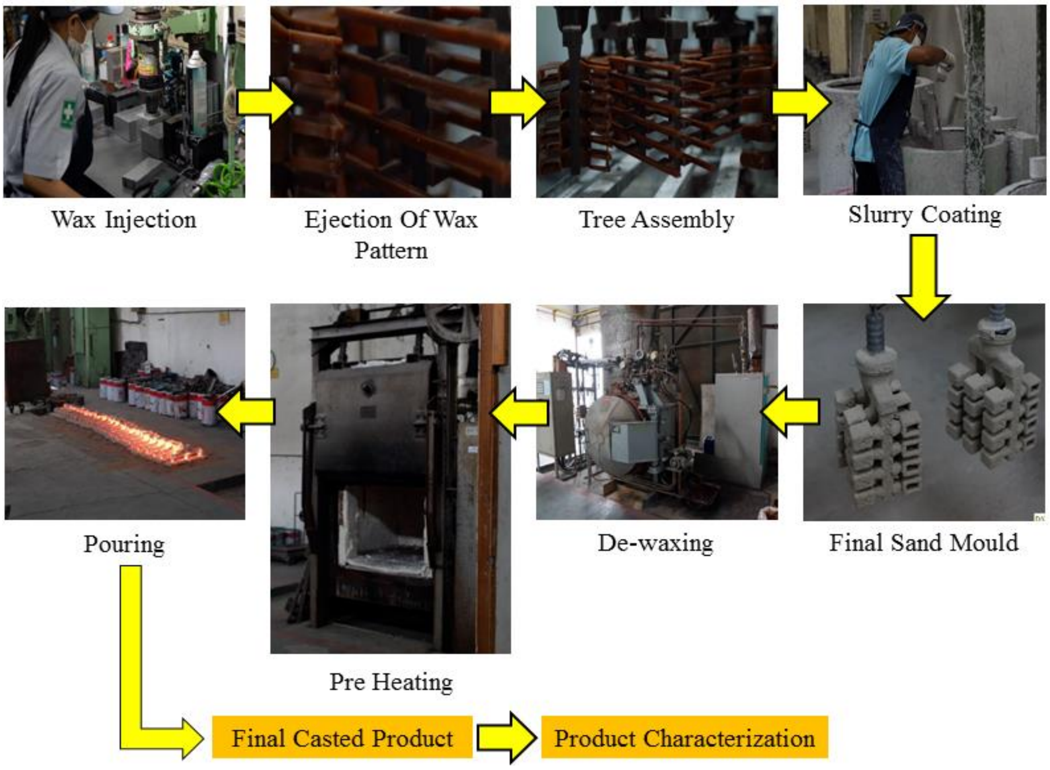

Figure 4. Experiment Setup for Investment Casting

3. Result and Discussion

Table 2 shows the comparison between the chemical composition of the Ti-6Al-4V material used in the investment casting process, Arcam Ti6Al4V and ISO 5832/3. Standard specifications covering chemical composition, structure and mechanical properties of Ti alloys used as artificial hip joints are ISO 5832/3 [18]. The Ti6Al4V material used in the investment casting process has been in accordance with ISO 5832/3 because the % chemical composition is in the specified range.

Table 2. Comparison of The Chemical Composition of Ti-6Al-4V

Chemical composition	Fe%	C%	N%	O%	H%	Al%	V%	Ti
ISO 5832/3 [18]	< 0.3	< 0.08	< 0.05	< 0.2	< 0.015	5.5- 6.75	3.5- 4.5	Balance
Arcam Ti6Al4V [19]	0.1	0.03	0.01	0.15	0.003	6	4	Balance
	0.12	0.02	0.02	0.08	0.06	6.1	3.9	Balance

The tensile test process on IC products used the Shimadzu UH 1,000 kNI machine with 3 repetitions. Table 3 shows a comparison of the mechanical properties of IC products, Arcam Ti6Al4V and ISO 5832/3. The elongation produced in this study was 17%. This result is higher than the % elongation on Arcam Ti6Al4V and ISO 5832/3 materials, which are 14% and 10%. The percentage of the elongation defined the ductility of a material and its capability of undergoing deformation without breaking. The higher the ductility, the higher % elongation (A% or also El%) of the material [20]. The results of this study indicate that the ductility of IC products is greater than that of Arcam Ti6Al4V and ISO 5832/3 materials. The % elongation value of the IC product is higher than the Arcam Ti6Al4V. This happens because the oxygen content in the IC material is smaller than the Arcam Ti6Al4V material with oxygen content of 0.08% and 0.15%. The smaller the oxygen content in Ti Alloy, the higher the ductility (% elongation) value [14, 21]**.**

Table 3. Comparison of Mechanical Properties of Ti-6Al-4V

Mech Properties	IC product	Arcam Ti6Al4V [19]	ISO 5832/3* [18]
Yield strength (MPa)	636	950	780
Ultimate Tensile Strength (MPa)	687	1020	860
Elongation (%)	17	14	10
Hardness (HRC)	29	33	not specified
Impact Strength (J) (Charpy)	5.3	23 [19]	not specified

*Mechanical Properties of Titanium base alloys used for artificial hip joints

Comparison of yield strength and ultimate tensile strength between IC product, Arcam Ti6Al4V and ISO 5832/3 is shown in Figure 5. Yield strength and ultimate tensile strength of IC products are lower than Arcam Ti6Al4V and ISO 5832/3 materials. The results of this study are similar to the results of research conducted by Nastac et al. [14] which compares Ti6Al4V from IC results with wrought Ti6Al4V material. In this study the yield strength and ultimate tensile strength of the IC products were 841 MPa and 931 MPa, whilst the yield strength and ultimate tensile strength of the wrought Ti-6Al-4V material are 896 MPa and 965 MPa [14].

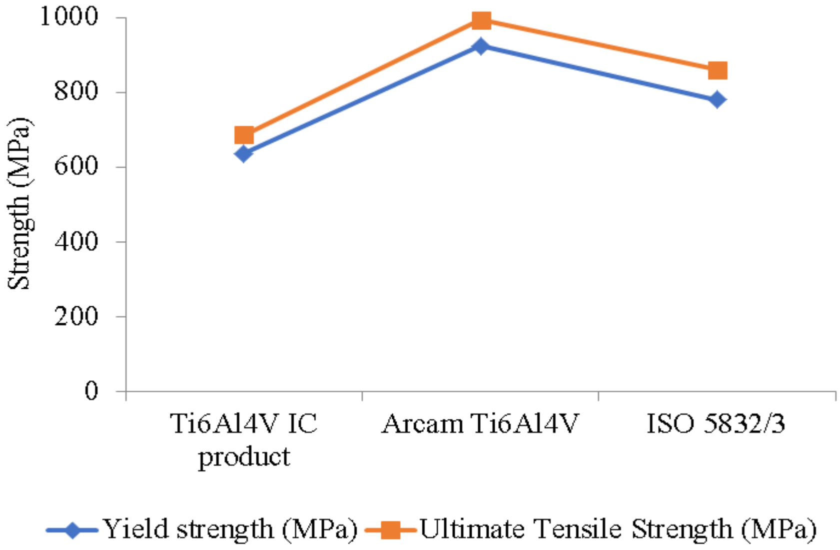

Figure 5. Strength Comparison on Ti6Al4V

The increase in strength and hardness in Ti alloys is due to the high oxygen content of Ti Alloys [14], [21]. In this study, the hardness and impact energy values for the IC products were 29 HRC and 5.3 J. The hardness and impact energy values for the IC products were lower when compared to Arcam Ti6Al4V. This happens because the oxygen content in the IC products is smaller than the Arcam Ti6Al4V material with oxygen content of 0.08% and 0.15%. The smaller the oxygen content, the smaller the value of hardness and impact energy [14, 21, 22]. As the oxygen concentration increases, oxygen atoms form many interstitial elements between the Ti lattice. The interstitial solid solutions cause the lattice strain, so that relaxes the crystalline and causes an increase in the c/a ratio. An increase in the c/a ratio causes hardness and strength to increase due to the limited number of slip planes in the HCP structure [23, 24].

4. Conclusion

The chemical composition of Ti6Al4V used as IC material is in accordance with ISO 5832/3. The IC product has lower yield strength and ultimate tensile strength than Arcam Ti6Al4V and ISO 5832/3. The oxygen content in Ti6Al4V used in IC is lower than the oxygen content in Arcam Ti6Al4V by 0.08% and 0.15%. In addition to causing a decrease in yield strength and ultimate tensile strength, low oxygen content also results in a decrease in hardness and impact energy as well as an increase in ductility. In this study, the Ti6Al4V IC product has lower hardness and impact energy than the Ti6Al4V Arcam. On the other hand, Ti6Al4V IC products have a higher % elongation than Arcam Ti6Al4V and ISO 5832/3 materials.

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