

Finite element analysis of artificial hip joint implant made from stainless steel 316L



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ABSTRACT

Background: AISI 316L stainless steel material is one of the widely used hip joint implant material. Even with excellent properties for the hip joint implant, this material is likely to fail after 12-15 years of implantation because of excessive wear and stresses. The computational analysis using the finite element method can be used to analyze the stress in the hip joint implant. The study aims to evaluate the stresses and safety factors analysis on the hip joint implant using four different types of AISI 316L materials from several manufacturers are highlighted as the objective of this study.

Method: There are four different types of AISI 316L materials used in this study, which are manufactured with different methods. These materials are simulated into Diponegoro University's artificial hip joint design. The ASTM F2996-13 and ISO 7206-4 are considered standard references in the simulation for loading and boundary condition application.

Results: Based on the static structural analysis, the total deformation, equivalent elastic strain, equivalent von-Mises stress, and the safety factor are obtained from Undip hip joint implant design.

Conclusion: The analysis concludes that the four types of stainless steel materials are safe for UNDIP hip joint implants, which have >1 safety factor. The highest safety factor is obtained from the forging material but has a high manufacturing cost that needs to be optimized.

Keywords: Hip joint, Safety Factor, Stress, AISI 316L, ASTM F2996-13.

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INTRODUCTION

One of the most critical joints in the human body is the hip joints, which connect the femur to the pelvis. This joint can deteriorate with time for many problems; the main problem is osteoarthritis.¹⁻³ Other reasons for hip joint impairment are atrophic arthritis and avascular necrosis.⁴ The hip joint replacement called total hip arthroplasties is the major orthopedic surgery with more than 350.000 and 60.000 surgeries performed each year in the United States and the United Kingdom.^{4,5} It is not surprising that many people need this surgery because the hip joint has a function to sustain the upper body weight during many activities that can reach up to 4 times of human body weight, which can decrease its performance due to times.⁶ Because of the high demand for hip joint implants, the Center for Biomechanics, Biomechatronics, and Biosignal Processing (CBIOM3S), Diponegoro University, Indonesia, started to researching this product from numerical and simulational

analysis in 2013 until finally succeeded in making bipolar type hip joint implant in 2020.⁷⁻¹³

The artificial hip joint is consists of two main parts. First is the acetabular component, which replaces the acetabulum in the pelvis. Second is the femoral component, such as the stem and ball head put in place of the femoral head. Many widely used hip joint implant materials can be divided into several pairs: metal to metal, ceramic to ceramic, polymer to ceramic, and metal to polymer.¹⁴ AISI 316L has been widely used as metal implant materials because of its mechanical properties, corrosion resistance, and non-magnetic properties that meet the minimum criteria as implant material.¹⁵ Even with its good properties, researchers stated that the hip implant would degrade its function and fail within 12-15 years.^{16,17}

There is a computational analysis using the finite element method that can be used to compute the stress in the hip joint implant stem.¹⁸⁻²¹ One is referred to



Figure 1. UNDIP femoral stem design.

Load = 2,300 N

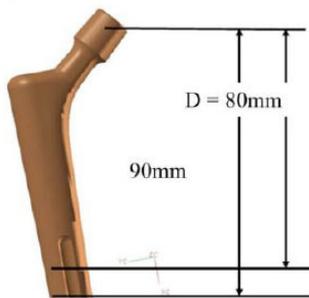


Figure 2. ASTM F2996-13 boundary conditions for 120-250 mm stem length [22].

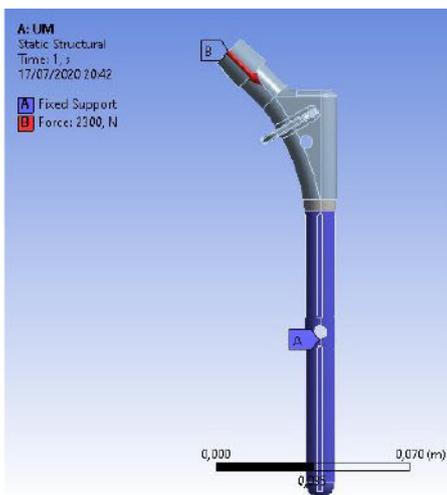


Figure 3. The boundary condition and load applied in the study.

as ASTM F2996-13 and ISO 7206-4 for the hip joint loading, boundary conditions, and geometry limitation.^{22,23} Using ANSYS Static Structural software, this analysis can be done by the previous study for the different cross-sectional areas of the hip prosthesis.²⁴

MATERIAL AND METHODS

The geometrical analysis in this study uses UNDIP hip joint implant design, which is already obtained from the previous research, as shown in Figure 1.¹³ This design consists of two parts, the head and the stem. The materials used in this study are AISI 316L from different manufacturers. Two materials come from the other hip joint implant products that have already been analyzed in a bachelor student's final project at Diponegoro University. The AISI 316L materials from these two hip joint

Table 1. Properties of AISI 316L variations

Materials	Properties	
	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
(A) Investment Casting/ AIC	579	375
(B) Machining /BM	581	357
(C) Forging/ CF	1065	982
(D) Casting/ DC	536	361

Table 2. The finite element analysis results of different stainless steel 316L in Ansys Static structural

Results	Stainless Steel 316L			
	AIC	BM	CF	DC
Max Deformation (mm)		1.54×10^{-1}		
Max von-Mises Strain (m/m)		1.21×10^{-3}		
Max von-Mises Stress (Pa)		2.34×10^8		
Safety Factor	1.61	1.53	4.20	1.55

products are manufactured by forging and casting, respectively. The other two AISI 316L come from UNDIP hip joint implant materials manufactured by machining and investment casting. The Young Modulus and Poisson's ratio of all materials are 200 GPa and 0.3. The ultimate tensile strength (UTS) and yield strength of the materials can be seen in Table 1.

The analysis method for this study is using finite element analysis with ANSYS Static Structural software. Ansys is computer-aided engineering (CAE) developed by Ansys, Inc. The company has developed many CAE products ANSYS is one of the finite element analysis programs commonly used to analyze rigid body mechanics, fluid analysis, and heat transfer analysis. There are so many benefits of using this ANSYS program to analyze an object structure, a bridge, a bus frame, etc.

Refer to the ISO 7206-4, the stem length of the UNDIP hip joint implant is 165.4 mm. Therefore, from ASTM F2996-13 in Figure 2, the boundary condition for the UNDIP hip joint implant is 90 mm from the center of the head because the length of the UNDIP hip joint prosthesis is between

120 mm and 250 mm. The 2,300 N loading is applied to the head of the stem according to the ASTM F2996-13. The boundary conditions of the UNDIP hip joint implant simulation can be seen in Figure 3.

For the simulation convergence, the stem's optimal mesh size is obtained by varying 5 mm to 1 mm mesh size. It concludes that from 5 mm until 3 mm mesh size, the max Von-Mises stresses are likely to increase significantly. Then, from 3 mm to 1 mm mesh size show that the max von-Mises stresses are stable. Therefore, the 3 mm mesh size is used in this study for stable, accurate, and fast simulation. The total elements and nodes from the 3 mm mesh size are 10,917 and 6,652 respectively. The element size to max von-Mises stresses change graph can be seen in Figure 4.

RESULTS

From the ANSYS Static Structural analysis, the total deformation, equivalent elastic strain, and equivalent von-Mises stress can be seen in Figure 5. Meanwhile, the safety factor obtained from the UNDIP hip joint implant with different AISI 316L materials can be seen in Figure 6. The deformation,

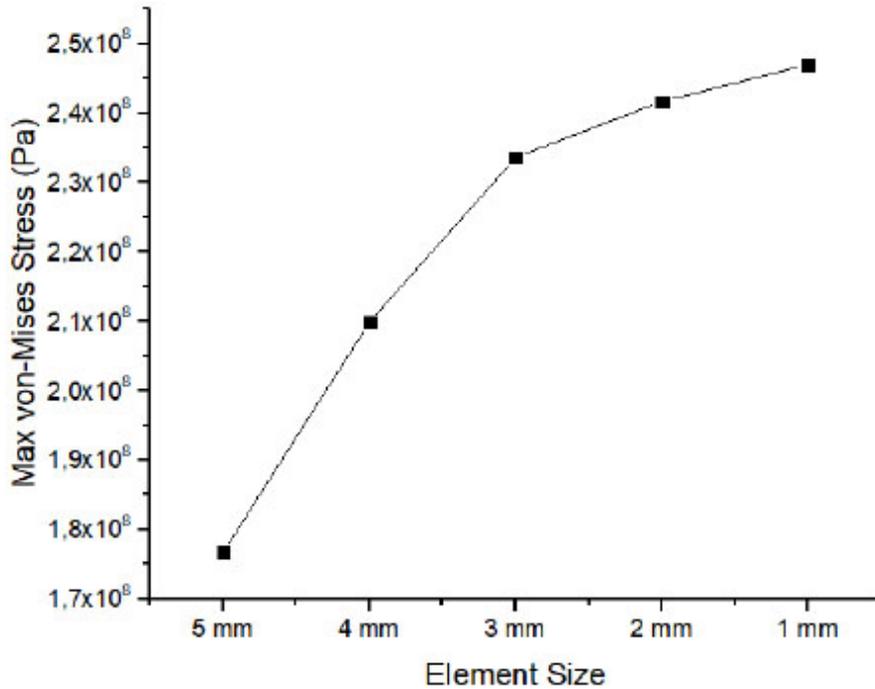


Figure 4. Variation of the von-Mises stress values with a change in mesh size.

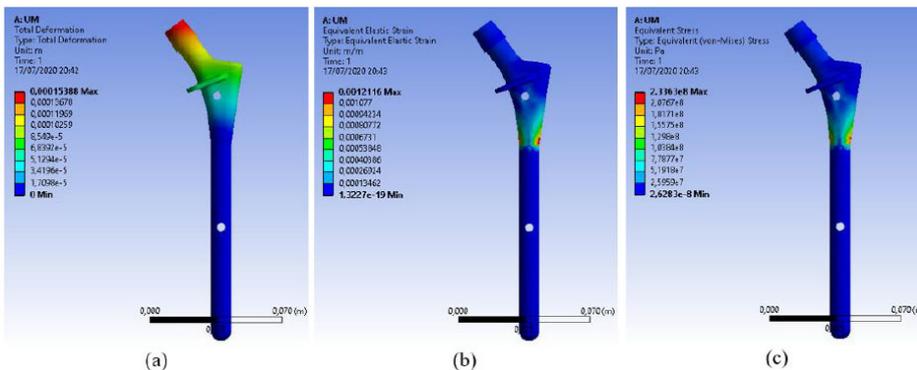


Figure 5. The finite element analysis results: deformation (a), strain (b), and stress of the stem (c).

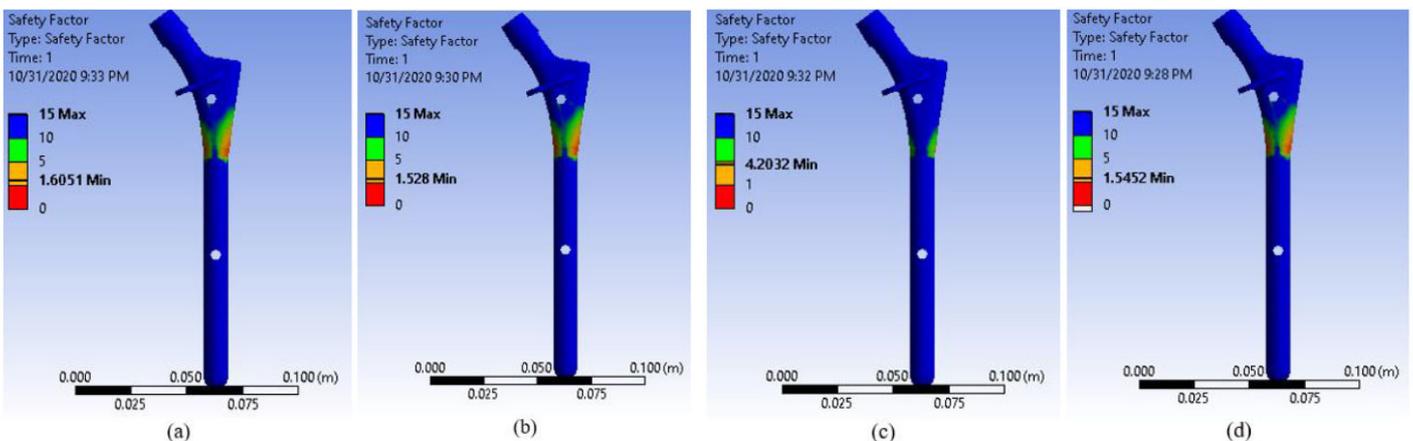


Figure 6. The safety factor results of investment casting (a), machining (b), forging (c), and casting (d) AISI 316L hip joint implant materials.

strain, and stress of all materials are the same because of the same design, Young Modulus, and Poisson's ratio of AISI 316L used in this study. The recapitulation of the ANSYS Static Structural results from all materials is shown in Table 2.

DISCUSSION

From the max von-Mises stress and the yield strength properties, the safety factor is calculated directly in the ANSYS Static Structural. It concludes that all materials' safety factor values are more than 1 (>1). It concludes that all of the materials can be used for manufacturing the UNDIP hip joint implant. For the comparison, the highest safety factor is obtained from forging material, followed by investment casting, casting, and machining AISI 316L in the study using ASTM F2996-13 reference. The safety factor chart of the materials in this study is shown in Figure 7. From the safety factor result, the forged material is considered to have too high safety factor, which is unfavorable for manufacturing cost because the forging process is relatively expensive than the casting method.

From the previous study, AISI 316L material is known to be unable to withstand the ASTM F2996-13 loading because of the lower yield and tensile strength compared to materials in this study.²⁵ Furthermore, the other research, according to hip joint implant loading when jumping, AISI 316L also cannot be used because the safety factor is less than 1 (0.98), which is predicted to fail.²⁶ But in this case, direct

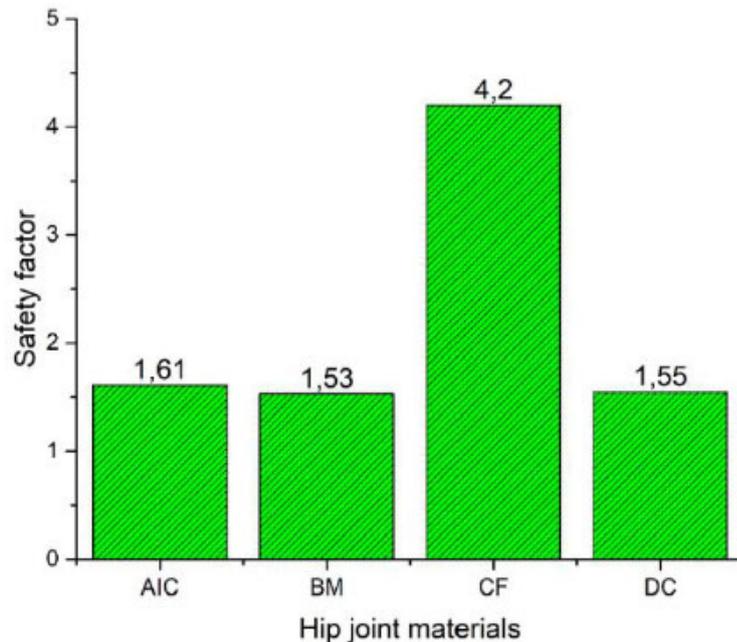


Figure 7. Safety factor results of the materials from the ANSYS static structural analysis.

loading according to ASTM F2996-13, confirms that stainless steel 316L material can be used as hip joint implant material besides CoCr and Ti6Al4V material with different designs.²⁴

CONCLUSION

All of the AISI 316L material variations in ANSYS Static Structural using ASTM F2996-13 as the reference are considered safe for UNDIP hip joint implant manufacturing. They have more than 1 (>1) safety factor value: 1.61, 1.53, 4.20, and 1.55 for investment casting, machining, forging, and casting. For manufacturing cost consideration, the forging material has too high safety factor, which is not favorable for the manufacturing cost and needs to be optimized for future research.

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DISCLOSURE

The author reports no conflicts of interest in this work.

AUTHOR CONTRIBUTION

All author had contributed equally on manuscript preparation and agreed to final version of the manuscript for publication.

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