Research Article

Hot Forging Process Design and Initial Billet Size Optimization for Manufacturing of the Talar Body Prosthesis by Finite Element Modeling

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Received: 10 August 2020; Revised: 5 October 2020; Accepted: 2 November 2020; Published online: 20 January 2021

Abstract
In hot forging industry, the process design and the billet size determination are very crucial steps because those steps directly influence both the product quality and material utilization. The purpose of this paper was to propose a technique used to design the hot forging process for the manufacturing of the talar body prosthesis. The talar body prosthesis is one of the artificial bones, which its geometry is a free form shape. In this study, the Finite Element Modeling (FEM) was used as a tool to verify the proposed design before implementation in a production line. In addition, an initial billet was determined the optimum size in the FEM by varying the mass ratio factor, the diameter, and the length. It was found that the mass ratio factor is a very useful guideline since the optimum size is quite close to the provided size from the guideline. The FEM results showed that the dimensions of the initial billet significantly affect the complete metal filling in the die cavity. Moreover, the optimum size between the diameter and length can reduce the material waste in the hot forging process of the talar body prosthesis. Finally, the experimental results of the hot forging process showed that the proposed process design with the optimum size of the initial billet is achieved in order to manufacture the talar body prosthesis and the material utilization of the new proposed process is improved from the traditional process by 2.6 times.

Keywords: Near net shape manufacturing, Medical prosthesis, CAD/CAM/CAE technologies

1 Introduction

Nowadays, a medical implant has been exponentially improved and widely used to treat patients. A number of artificial bones, such as a dental implant, a skull, a hip joint, and a knee joint, have been developed to replace a missing bone, a diseased bone, and a damaged bone. To produce those artificial bones, many manufacturing processes have been employed [1]–[5]. For example, Werner *et al*. [2] selected a CNC machining process to manufacture the hip joint and a combination of a rapid prototyping and a multi-axis CNC machining processes was employed to produce the femoral component of knee prosthesis [3]. The cranioplasty implant was made by a casting process and a machining process [4]. Furthermore, an additive manufacturing process was used to create the acetabular hip prosthesis cups [5]. Also, it can be seen that almost of the research works have used computer-aided design and manufacturing (CAD/CAM) technologies to deal with the complexity of those geometrical shapes.

The talar body prosthesis, as shown in Figure 1(b), is one of the artificial bones proposed by Harnroongroj *et al*. [6]. It has been developed to treat patients who have a talus with avascular necrosis and a severe crush fracture [6], [7]. In the past, the talar body prosthesis was made of AISI 316L stainless steel, which was the medical grade, by cutting the bulk metal with hand tools and geometrical templates, as shown in Figure 1(a). After that, the surface of the talar body prosthesis was polished by a manual grinding process [6]. Those manual processes are very time-consuming and have excessive material waste. To improve both production rate and material utilization, our research team has selected a combination of a hot forging process, a multi-axis CNC machining process, and an electro-polishing process for the manufacturing of the talar body prosthesis. The first step of the combination process is that the starting material is formed to be a finished forging part by the hot forging process. And then, the multi-axis CNC machining process is used to increase its accuracy and precision of the talar body prosthesis. The final step is that the surface quality of the talar body prosthesis is improved by the electropolishing process.

In this paper, the technique of a hot forging process design and an initial billet size optimization for the manufacturing of the talar body prosthesis was proposed. To design the hot forging process, Vazquez *et al*. [8] provided a very useful flow chart as a general procedure and Tschaetsch [9] also gave a practical guideline. Following those concepts, this study began from that the talar body prosthesis was scanned and created the 3D model and then the finished forging part and the forging dies were designed, respectively. In addition, Finite Element Modeling (FEM) was used as a tool to verify the proposed process design before implementation and to determine the optimal size of the initial billet. The proposed process design with the optimal size of the initial billet was implemented in the hot forging process to produce the talar body prosthesis. Finally, the finished forging parts from the hot forging process were validated to confirm that it will be qualified for the multi-axis CNC machining process.

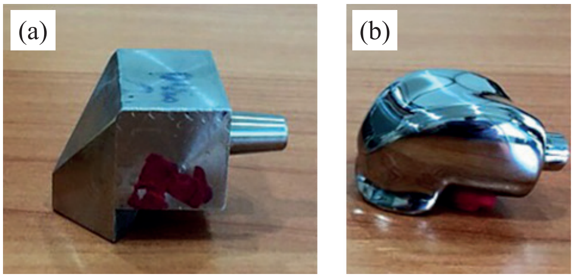

Figure 1: (a) Preform shape of the talar body prosthesis for the manual grinding process, and (b) the talar body prosthesis after the cutting and the manual grinding process.

2 Hot Forging Process Design

To design the hot forging process for the manufacturing of the talar body prosthesis, the procedure was divided into three steps. The first step was to design geometry of a finished forging part. The second step was to design forging dies. Last step was to design the process conditions.

2.1 *Design of the finished forging part*

An optical 3D scanner, ATOS COMPACT SCAN 2M, and commercial CAD software, CATIA, was used as a tool to create the finished forging part. Firstly, the master geometry of the talar body prosthesis was scanned by the optical 3D scanner and constructed a 3D model of the talar body prosthesis by the CAD software. Secondly, the 3D model was used to design

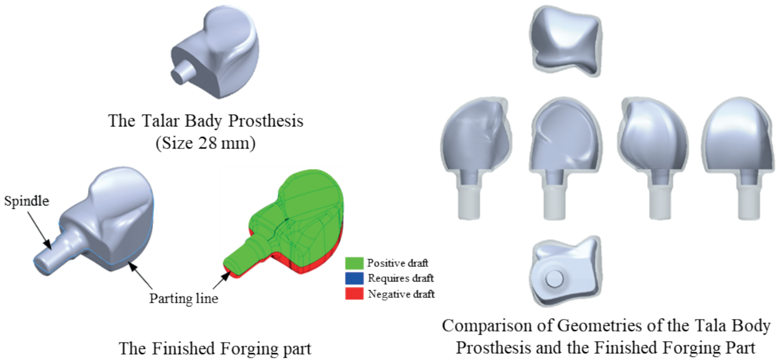

Figure 2: Geometrical shapes of the talar body prosthesis and the finished forging part.

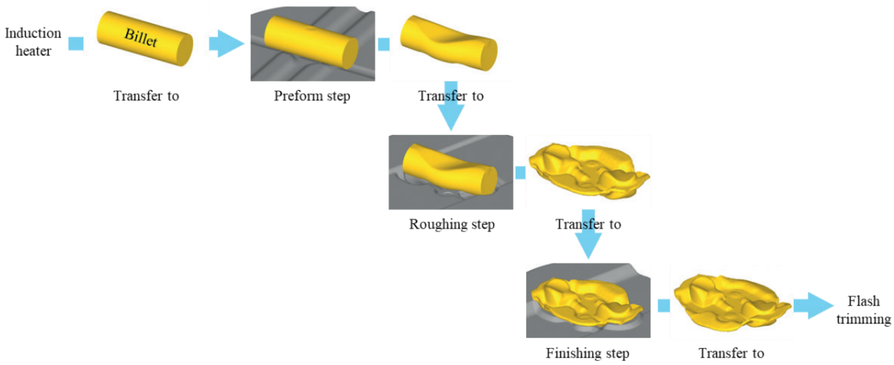

Figure 3: Forming steps in the hot forging process of the talar body prosthesis.

the finished forging part. Thirdly, the finished forging part was offset from the surface of the talar body prosthesis at least 1.0 mm around the body because the finished forging part after the forming process had to be machined. After that, a parting line was placed on the finished forging part following the largest projected area from the top view then the finished forging part was eliminated the undercut by adding the geometry with a draft angle. The minimum draft angle was three degrees. Moreover, the spindle was extended to be longer for clamping during the machining process. Lastly, the finished forging part was checked the draft angle. Figure 2 shows both the 3D models of the talar body prosthesis and the finished forging parts.

2.2 *Design of the forging dies*

The finished forging part was employed to design the forging dies. In the beginning, the cavity of the forging dies at a finishing step was constructed similarly as the geometry of the finished forging part. In order to reduce the production time and the material waste, the forging dies were designed to have two cavities, which consist of the left and the right sides of the talar body prosthesis. Both were formed in one forging cycle. Due to the complexity of the geometry, the three-forging operation step, which comprises of preform, roughing, and finishing steps, was designed to form the finished forging part, as shown in Figure 3. The forging dies at the roughing step were designed backward from the geometry of the finishing step to achieve the complete metal filling in the die cavity. Finally, the forging dies at the preform step were designed to distribute the mass of the initial billet and to eliminate the oxide scale. For the forging dies at the preform and the roughing steps, the design skills and the experience were required because there are no absolute solutions.

2.3 *Design of the forging process*

To design the process conditions, ASM metals handbook vol. 14 forming and forging [10] was used as a guideline. The forming temperature of a billet took up around 1,050°C, being a typical forging temperature for AISI 316L stainless steel. The billet was heated by the induction heater. Besides, the temperature of the forging dies was preheated at around 150°C. Furthermore, the water-based-graphite lubricant was used to lubricate the surface between the forging dies and the workpiece at both the roughing and the finishing steps and also used as a coolant for each forging cycle. Finally, the hot forging process of the talar body prosthesis was conducted with the 1,500 ton mechanical press machine. The characteristic of the press machine was 280 mm of the stroke height and 70 strokes per minute of the ram speed.

3 Finite Element Modeling (FEM)

To verify the design of the hot forging process and determine the optimal size of the initial billet, commercial CAE software, DEFORM-3D, was used as a tool before implementation.

3.1 *Pre-processing*

The Finite Element Modeling (FEM) was established for six steps, which consist of three steps of heat transfer with the environment and three steps of the forming, as shown in Figure 3. On the first hand, the workpiece in the FEM was defined as the viscoplastic material model. The material of the workpiece is AISI 316L stainless steel and Figure 4 shows the material property of AISI 316L stainless steel, which is a function of strains, strain rates, and temperatures from the software database. The tetrahedral solid element was applied to model the workpiece with 100,000 elements. On the other hand, the forging dies in the FEM were defined as the rigid body with thermal properties for heat transfer. In addition, the assumption of the FEM was defined as a non-isothermal problem. The conduction heat transfer coefficients between the contacts of the forging die and the workpiece and the convection heat transfer coefficients between the workpiece and the environment were shown in Table 1. The other is that a shear friction model was defined for the interface between the forging die and the workpiece. The friction coefficients were also presented in Table 1. All of the coefficients referred from previous publications [11], [12] because the hot forging process

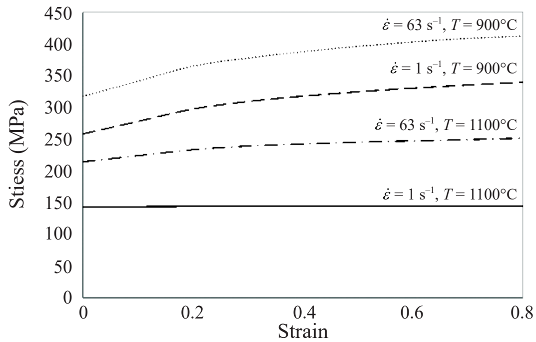

Figure 4: Material property of AISI 316L stainless steel at different temperatures and strain rates.

of the talar body prosthesis was conducted in the same factory and the environment as those reports.

Table 1: Coefficients for setup the FEM

Coefficients	Value	(Unit)
1. Interface friction coefficient m (Shear friction) - At preform step - At roughing and finishing steps	 0.7 0.3	 (-) (-)
2. Conduction heat transfer coefficient between contact H	11	(N/sec/mm/°C)
3. Convention heat transfer coefficient h	0.02	(N/sec/mm/°C)

3.2 *Initial billet size*

Normally, the mass of an initial billet in a hot forging process can be calculated by Equation (1). The mass of material required is equal to the summation of the mass of a finished forging part, the mass of a flash, and the mass of oxide scale [9].

$$m_{req} = m_f + m_{fla} + m_{sc} \quad (1)$$

where m_{req} is the mass of the material required or the initial billet. m_f is the mass of the finished forging part. m_{fla} is the mass of the flash, and msc is the mass of the oxide scale. However, for a new forging process, it is quite difficult to compute the mass of the flash and the oxide scale. Thus, the mass ratio factor in the following Equation (2) is more practical to determine the mass of material required [9].

$$m_{req} = W \cdot m_f \quad (2)$$

where W is the mass ratio factor, which depends upon the geometrical shape and the mass of the finished

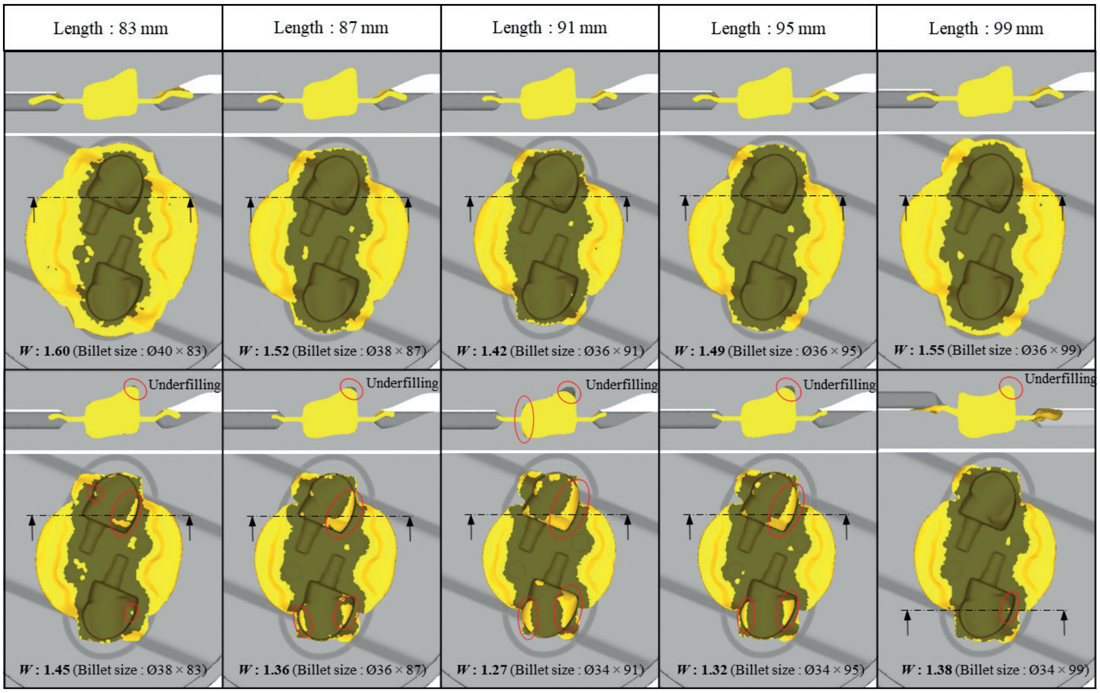

Figure 5: Comparison of the finished forging part at the last step in the FEM.

forging part. The mass ratio factor (*W*) can be selected from the table in the textbook [9]. In this study, the mass ratio factor (*W*) was 1.5 because the mass of the finished forging part, which included the left and the right sides of the talar body prosthesis, took up 0.52 kg, and the geometrical shape was classified in the group of the large change in cross-section. To study the effect of the mass ratio factor on complete metal filling in the die cavity, the mass ratio factor (*W*) was varied from 1.1 to 1.9 (0.60 to 0.99 kg) with the different diameter and lengths of the initial billet in the FEM. The FEM was conducted for 20 cases, with four different diameters (Ø34, Ø36, Ø38, and Ø40 mm) and five different lengths (83, 87, 91, 95, and 99 mm) of the initial billet. Moreover, the FEM results were used to determine the optimal size of the initial billet for the hot forging process of the talar body prosthesis, which includes two criteria. The first criterion is that the initial billet had to be the smallest size in order to complete the metal filling in the die cavity. The second criterion is that the flash of the workpiece after the last forming step had to be covered on the flash land of the forging die because the flash was long enough for the trimming dies in order to cut the flash out.

3.3 *FEM results*

The FEM results showed that 13 cases from 20 cases completely filled in the die cavity at the last forming step. Figure 5 illustrates the comparison of 10 cases that were the limit between complete and incomplete metal filling for each length of the initial billet. The 5 cases of the complete metal filling are presented on the top row but the other 5 cases of the incomplete metal filling are displayed on the bottom row. To observe the complete and incomplete metal filling, the shaded area of brown color in the FEM indicated the contact between the workpiece and the forging die, which is the same indicator of the previous study [13].

To discuss the FEM results in Figure 5, it can be seen that the mass ratio factors (*W*) at the lower limitations of each length were from 1.42 to 1.60, which were quite close to the guideline, 1.50 [9]. From this point, it can be seen that the mass ratio factor is a very useful guideline for the forging industry because the guideline is practical to use and simple. However, one of the weaknesses is that the guideline does not provide the actual size of the initial billet (size of the diameter and the length). Thus, to determine the optimum size of

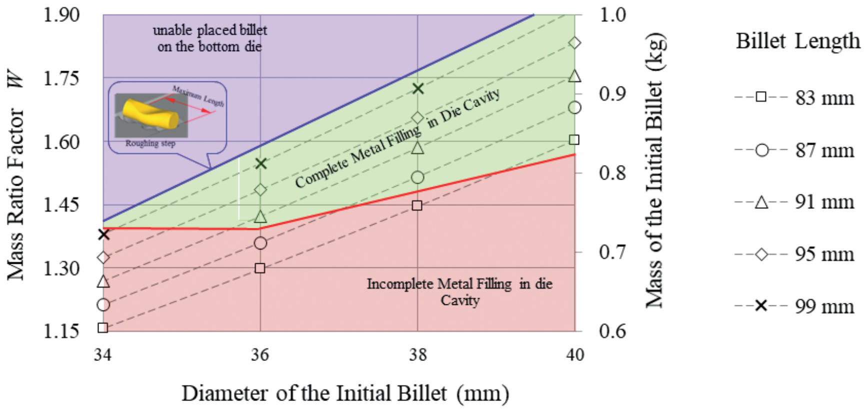

Figure 6: Dimension of the initial billet and mass ratio factor limit diagram for the hot forging process of the talar body prosthesis.

the initial billet for a new process, both the mass ratio factor and the FEM were necessary to employ, as this study, because it will take the advantage and eliminate the weakness of the mass ratio factor guideline.

Another point is that the area of the incomplete metal filling appeared at the top small corner of the workpiece as shown on the bottom row in Figure 5. In those cases, the incomplete metal filling called underfill defect occurred because of the insufficient material to fulfill the cavity of the forging die according to the previous literatures [14], [15]. To sum up, the mass ratio factor significantly influenced the complete and the incomplete metal filling in the die cavity and the optimum ratio between the diameter and the length of the initial billet could also reduce the mass ratio factor or the mass of the initial billet.

To describe more in details, the FEM results were plotted as the limit diagram between the dimensions of the initial billet and the mass ratio factor for the hot forging process of the talar body prosthesis, as shown in Figure 6. The diagram can divide into three areas, which consist of an area of unable placed billet on the bottom die, an area of complete metal filling in the die cavity, and an area of incomplete metal filling in the die cavity. The meaning of the area of the unable placed billet was that the billet cannot be installed on the bottom forging die at the roughing step because the length of the billet was longer than the positioning guide of the bottom forging die. Firstly, the blue line in Figure 6 was the limit curve separating between the area of unable placed billet and the area of complete metal filling. It was the maximum length of the initial billet, being 100 mm. Secondly, the red line in Figure 6 was the other limit curve splitting between the areas of complete and incomplete metal filling in the die cavity. It can be seen that the red line line dropped considerably by decreasing the diameter of the initial billet. This means that the ratio between the diameter and the length of the initial billet also has an effect on the complete and the incomplete metal filling in the die cavity. Therefore, as mentioned before, the optimal ratio between the diameter and length can reduce the mass ratio factor or the mass of the initial billet, leading to the decrease of the material waste in the hot forging process of the talar body prosthesis.

In this study, the optimal size of the initial billet following two criteria was Ø36 × 99 mm (0.80 kg), in which the mass ratio factor (W) was 1.55. It was selected to implement in the hot forging process because it was the lowest mass ratio factor that the flash of the workpiece covered on the flash land of the bottom forging die at the last forming step in the FEM, as shown in Figure 5. Furthermore, the FEM results provided the highest forming loads at each forming step. The highest loads were 58.96 tons at the preform step, 704.84 tons at the roughing step, and 623.11 tons at the finishing step.

4 Hot Forging Process of the Talar Body Prosthesis

The proposed process design with the optimal size of the initial billet was implemented in the hot forging process for manufacturing of the talar body prosthesis. The experimental results were used to verify the FEM.

4.1 *Implementation in hot forging process*

The forging dies were made from AISI H13 tool steel. Commercial CAM software was used as a tool to generate the NC code for a machining process. Firstly, the raw material was machined to be the geometry of the forging dies with a 0.5 mm offset from the finished shape. Secondly, the forging dies were improved its mechanical properties by hardening and tempering processes, being 50-HRC hardness. After that, the forging dies were machined to the finished shape. Finally, the forging dies were improved the wear resistant property by the nitriding process to achieve 70 HRC of surface hardness.

To conduct the hot forging process of the talar body prosthesis, the mechanical press machine with 1,500 tons in maximum capacity as shown in Figure 7 was used. The characteristic of the press machine was 280 mm of the stroke height and 70 strokes per minute of the ram speed. The initial billet, which was medical-grade AISI 316L stainless steel, was cut to the optimal size, Ø36 × 99 mm (0.80 kg), by the shearing process. Then, it was heated by the induction heater and was subsequently followed by the three-step hot forming process. The temperature of the billets before forging at the first forming step was 1,050 ± 20°C. The highest forming load and the geometries of the workpiece each step were collected from the experiment in order to verify the FEM.

4.2 *Verification results of the FEM*

The experimental results showed that the proposed design for the manufacturing of the talar body prosthesis by the hot forging process was successful.

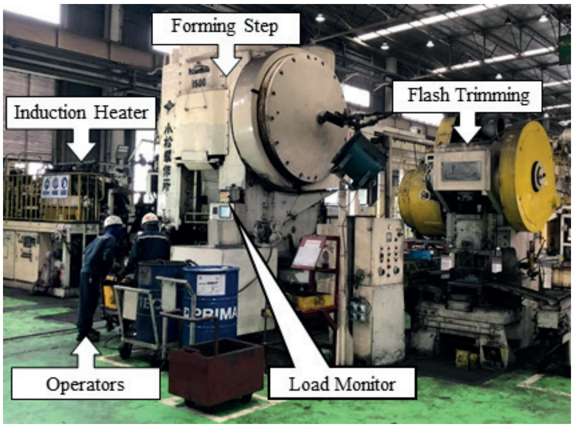

Figure 7: The schematic photo of experimental hot forging tests of the talar body prosthesis.

The material was completely filled in the die cavity without any defects, as shown in Figure 8.

On the first hand, the highest forming loads from the experiment took up 64.0 tons at the preform step, 756.0 tons at the roughing step, and 726.0 tons at the finishing step. To compare the experimental and the FEM results, it found that the FEM provided a similar trend to the experiment. The lowest forming load occurred at the preform step. The highest forming load appeared at the roughing step because the largest degree of the deformation took place at the roughing step. As shown in Figure 9(a), the forming load errors at the preform step and the roughing step were 7.9 and 6.8%, respectively. However, the highest percentage of error was the forming load at the finishing step, being 14.2%. The cause was that the experiment was conducted in the manual production line, in which the workpiece was transferred by an operator, and it was

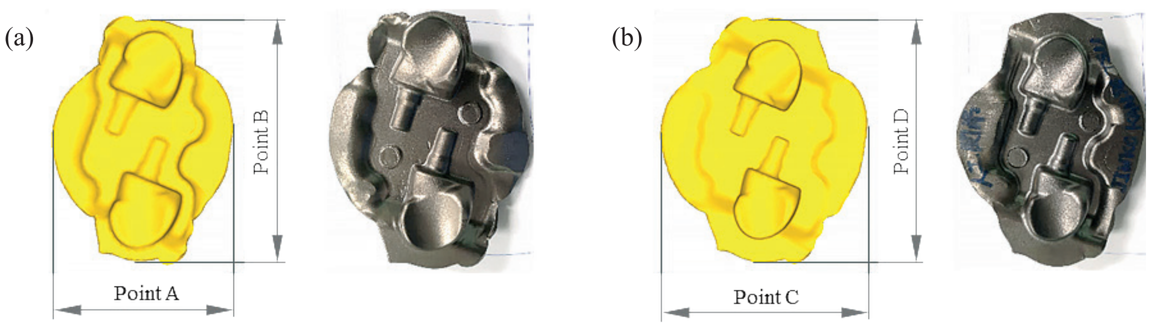

Figure 8: Comparison of the geometrical shapes after forming between the FEM and the experiment at (a) roughing step, and (b) finishing step.

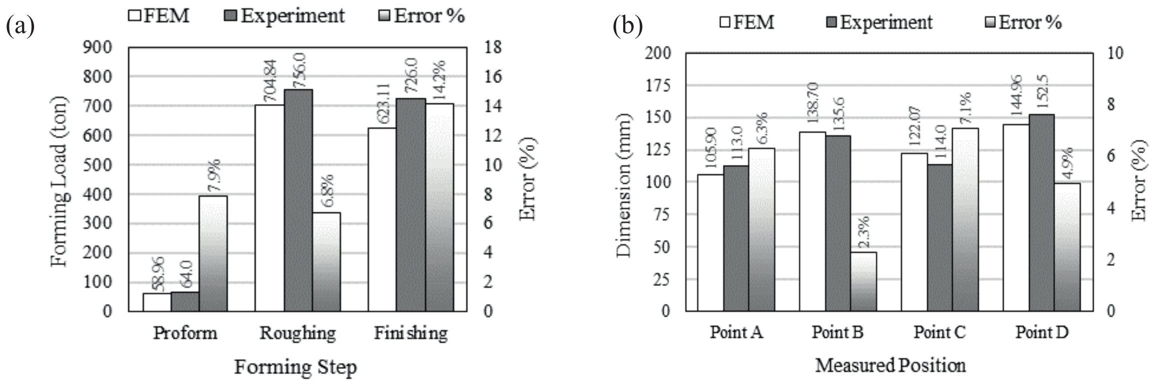

Figure 9: Comparison between the FEM and the experimental results in the hot forging process of the talar body prosthesis (a) The forming load errors, and (b) The geometrical errors.

the first time tryout. Thus, the operator had less skill to transfer and place the new geometry of the workpiece. This led to the transfer time between each forming step in the experiment become longer than the FEM, causing to drop the temperature of the workpiece in the experiment. Due to the lower temperature of the workpiece in the experiment, it resulted in a higher forming load in the experiment than the FEM.

On the other hand, the geometrical errors of the workpiece after forming were investigated in four points, which consist of two points after forming at roughing step and two points after forming at the finishing step. Those points were the deformation of the workpiece outside the die cavity. Normally, the FEM provided that the simulation for the deformation in the die cavity was higher accuracy than outside the die cavity because of the material formed like the shape of the die cavity. If those four points are accurate, the whole geometrical workpiece will be reliable. The results showed that all of the four measured points were less than 10%, as shown in Figure 9(b). The FEM results were quite high accuracy in the geometrical shape. To sum up, the FEM results were in agreement with the experiment in the hot forging process of the taler body prosthesis.

4.3 *Validation results of the finished forging part*

To validate the finished forging part from the hot forging process for the multi-axis CNC machining process, both the optical 3D scanner, ATOS COMPACT SCAN 2M, and the 3D inspection software, GOM inspection, were used as tools. The finished forging part after three-step forming was cut the flash out by the trimming process and then was cleaned the oxide scale by the shot blasting process. After that, it was scanned by the optical 3D scanner and the scanned results were compared to the 3D model by GOM inspection. The 3D models of the finish forging part and the talar body prosthesis were set as the nominal size.

The results in Figure 10(a) showed the dimensional deviation between the finished forging part from the hot forging process and the 3D model of the finished forging part. The deviation was in the range of –0.63 to +0.93 mm. Additionally, the dimensional deviation between the finished forging part from the hot forging process and the 3D model of the talar body prosthesis, as shown in Figure 10(b). The deviation was in the range of +0.13 to +4.95 mm. Thus, it can be confirmed that the finished forging part from the hot forging process was qualified for the multi-axis CNC machining process.

4.4 *Material utilization of the new proposed process*

To compare the traditional process and the new proposed process, it was found that the material utilization was significantly improved. In the past, the initial billet of the traditional process was Ø50.8 × 65 mm with 1.05 kg, while the talar body prosthesis was 0.18 kg. The material utilization took up only 16.7%. However, the initial billet of the new proposed process was Ø36 × 99 mm with 0.80 kg and it can formed two finished forging parts. Therefore, the material utilization of the new proposed process accounted for 43.66%, which improved by 2.6 times or 261.48% from the traditional process.

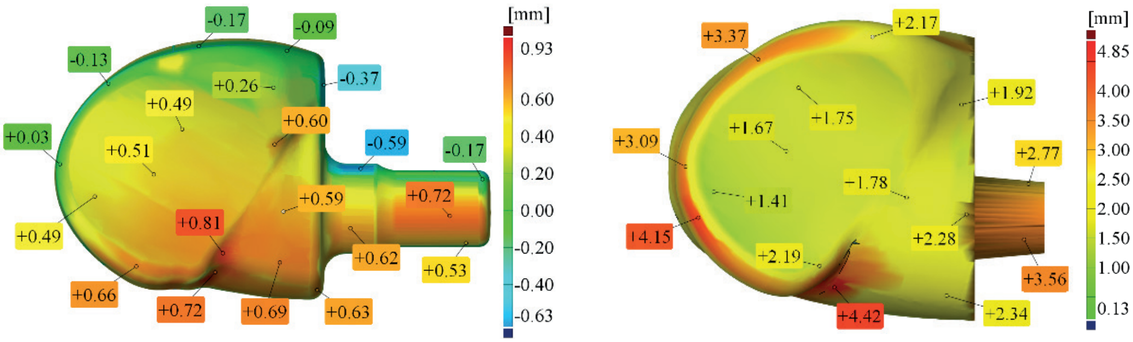

Figure 10: Dimensional deviation between the finished forging part and the 3D model (a) 3D Model of the finished forging part, and (b) 3D Model of the taler body prosthesis.

5 Conclusions

The results of this paper can be concluded as follows:

- The FEM was verified as a reliable model because the FEM provided the simulation results according to the experimental results in the hot forging process. The trend of both the forming loads and the geometry was similar between the FEM and the experimental results.
- The mass ratio factor is a very useful guideline to determine the size of the initial billet for a hot forging process. The FEM results showed the mass ratio factor significantly influences the complete and the incomplete metal filling in the die cavity and the optimum ratio between the diameter and the length of the initial billet could also reduce the mass of the initial billet, leading to a decrease of material waste in the hot forging process of the talar body prosthesis.
- The experimental results in the hot forging process showed that the proposed process design with the Ø36 × 99 mm (0.80 kg) of the initial billet is achieved in order to manufacture the talar body prosthesis without any defects.
- The dimensional deviation results between the finished forging part from the hot forging process and the 3D model confirmed that the finished forging part was qualified for the multi-axis CNC machining process.

Future works will be carried out for the heat treatment process, the multi-axis CNC machining process, and the electro-polishing process for the manufacturing of the talar body prosthesis. Finally, Both contamination and biocompatibility tests must be conducted following the standard for the talar body prosthesis from the new proposed process.

Acknowledgments

The authors would like to thanks Mr. Taweesak Pornsawangkul from IT Forging (Thailand) Co., Ltd. and Mr.Paisan Emdist. Special thanks is also extended to Thossart Harnroongroj, M.D and Thos Harnroongroj, M.D. from Department of Orthopaedic Surgery and Department of Anatomy, Faculty of Medicine, Siriraj Hospital, Mahidol University for their valuable comments and advice. Also, this research was funded by King Mongkut's University of Technology North Bangkok. Contract no. KMUTNB-62-GOV-05.

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