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Research Paper

Investigating of Manufacturing of Titanium Hip Prosthesis by Cold Forging Process via FEM Analysis

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Abstract

The forging process is a typical process to manufacture industrial parts that are subjected to fatigue stresses. The forged parts have equiaxial grains, and crack propagation occurs at a lower rate. A part's mechanical properties stem from its manufacturing process and initial materials. One of the applications of the forging process is manufacturing different kinds of metallic prostheses such as hip prostheses, which are very privileged in medical and rehabilitating issues. Hip prostheses undergo various types of stress, i.e., fatigue stress, indicating its significance in manufacturing. Cold forging is a promising method to produce high-strength parts with high fatigue life. Titanium alloys are widely used in prostheses due to their corrosion resistance. This study investigates the feasibility of manufacturing hip prostheses via cold forging. To analyze the behavior of materials during the forging process, the FEM simulation by ABAQUS software is applied. The press force is a significant factor in achieving the final geometry in which raw material fills the forging die within one stroke. In addition, the strength of the die is noticeable during the forging process.

Keywords

Cold Forging, FEM, ABAQUS Simulation, Hip Prosthesis, Titanium Alloy

1. Introduction

Life expectancy and quality rise have increased patient requests for better and customized solutions. One of the biomedical products is prostheses such as hip prostheses (Figure 1). This piece is very consumable, especially among older patients. Due to the bio-compatibility of hip prostheses, they should be made from special materials, i.e. titanium alloys.

Figure 1. Kinds of hip prostheses [1]

Several processes have been introduced to manufacture hip prostheses, such as casting, machining, additive manufacturing, etc. However, the forging process is more considered because of fatigue stresses imposed on the hip. In the forging process, the grains of the material become aligned. Hence, more fatigue strength is obtained. In addition, cold forging results in more strength than hot forging. This survey investigates the feasibility of cold forging of titanium hip prosthesis to obtain maximum strength.

Fiorentino et al. presented a new method of designing the hip prosthesis by comparing other studies and FEM simulation. They outlined the concept of an ideal prosthesis. Moreover, new solutions were identified and tested using FEM simulations to evaluate their mechanical resistance in static and dynamic working conditions [1]. Viceconti et al. described a new software environment (HIPCOM design environment, HIDE) to design custom-made total hip replacements. Their devices are frequently designed using general-purpose mechanical computer-aided design (CAD) programs using a set of bone contours extracted from computer tomography (CT) images as anatomical reference [2]. Kourra et al. developed a method based on an innovative hip prosthesis acetabular cup prototype with a prescribed non-uniform lattice structure forming struts over the surface, with the interconnected porosity encouraging bone adhesion [3]. Pimenta et al. identified and evaluated the reasons that led a THR implant to fail prematurely after 2 years of use in a 65-year-old female patient. They concluded that the fractured implant presented a fatigue mechanism due to pits on the surface [4]. It is worth mentioning that the forged parts should be machined to achieve the required accuracy and precision [5-11]. Risse et al. used the high design freedom of additive manufacturing processes in combination with computer-aided engineering (CAE) methods to provide approaches to solve the existing stiffness problem in hip endoprosthetics [12]. Taghimalek et al. investigated the mechanical properties of hot forging in Ti6Al4V alloy. According to their results, experiments and simulations have reached a very close agreement [13]. Park et al. characterized the deformation behavior of Ti–6Al–4V alloy under hot compression conditions in the temperature range 850–1000 °C and strain rate range 0.001–10 s^{-1}. In addition, processing maps were generated using the dynamic material model (DMM) [14]. Levkulich et al. investigated process variables contributing to the development of non-uniform, coarse grains during β annealing following conventional forging of the α/β titanium alloy Ti-6Al-4V using subscale laboratory experiments and simulations of the evolution of the β-phase crystallographic texture [15]. Tomczak et al. presented results of theoretical-experimental forming of hollow shaft forgings from titanium alloys [16]. The finite element modeling (FEM) is a privileged method in predicting the final properties of the products during forming processes [17-19]. Lee et al. employed the thermal-coupled finite element method to examine and establish the relationship between the process parameters and the deformation behavior. In their study, the simulation of the non-isothermal forging of Ti–6Al–4V was performed, and the predicted results agreed well with those from the experiment [20]. Gontarz et al. presented a theoretical analysis of the unconventional forging process of hollowed shafts from Ti-6Al-4V alloy in a three-slide forging press. This method, in comparison with other metal-forming methods, allows for obtaining hollowed products [21]. Luo et al. worked on the key parameter of sliding velocity at the die-workpiece interface in the numerical analysis of the blade forging process. Their results indicated that the friction model matches the experimental results better than the traditional ones [22]. It is worth mentioning that the surface quality of the forged parts should be improved by conventional methods [23-25]. Zhu et al. determined the friction factor of Ti-6Al-4V titanium alloy under a hot forging situation by the combined approach of ring-compression tests and finite element simulations. They employed different heat-transfer coefficients to generate the calibration curves when both lubricant conditions were applied in hot ring compression of Ti-6Al-4V titanium alloy [26]. Chen et al. investigated the influence of forge temperature, ram rate, and starting microstructure on the deformation characteristics of isothermally forged Ti-6A1-4V alloy. They measured yielding and finish forge pressures in the practical range of forge temperatures and ram rates [27]. Odenberger et al. investigated the possibility of designing hot forming tools with acceptable accuracy at short lead times and minimal need for the costly die try-out, using finite element analyses of hot sheet metal forming in the titanium alloy Ti–6Al–4V [28]. There are several other surveys have been conducted on this issue, some of which are introduced in Ref. [29-37]

In this study, the feasibility of manufacturing the hip prosthesis by cold forging process is investigated via FEM simulation. To obtain the forging parameters, including the press force and friction coefficient, the process is simulated by ABAQUS software, and then formability, the final shape of the part, the amount of flash, and the maximum tensile stress are obtained through these simulations.

2. Materials & Methods

In this study, the simulations are performed in ABAQUS software version 6.14. The initial model is designed using SolidWorks software. The initial part imported in the Part module is 3D and formable, and the die is solid and non-formable. Figure 2 shows the 3D model of the hip designed in SolidWorks. It is worth mentioning that this model is following the real hip used in the human body.

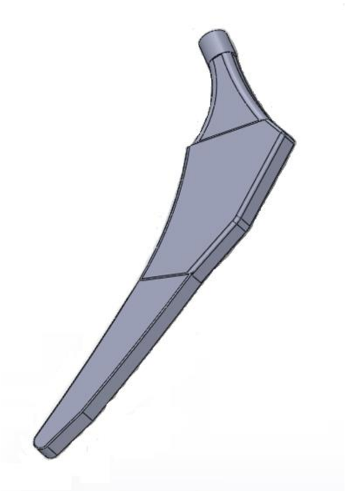

Figure 2. 3D model of the hip modeled in SolidWorks

In this project, the titanium alloy (Ti6Al4V), which is very common for this purpose, is applied. The chemical composition of Ti6Al4V is introduced in Table 1. In addition, the mechanical properties of this alloy used in the Property module of ABAQUS are introduced in Table 2 as well. The engineering stress and strain curves (σ-ε curves) of Ti6Al4V in different temperatures are shown in Figure 3.

Table 1. The chemical composition of Ti6Al4V

Component	**Al**	**Fe**	**O**	**Ti**	**V**
%wt	6	0.25	0.2	90	4

Table 2. The mechanical properties of Ti6Al4V

Poisson's Ratio	**Density (g/cc)**	**Reduction of Area (%)**	**Yield strength (MPa)**	**Modulus of Elasticity (GPa)**	**Ultimate tensile strength (MPa)**	**Fatigue Strength (MPa)**	**Hardness (Rockwell B)**
0.342	4.43	36	880	113.8	950	510	**334**

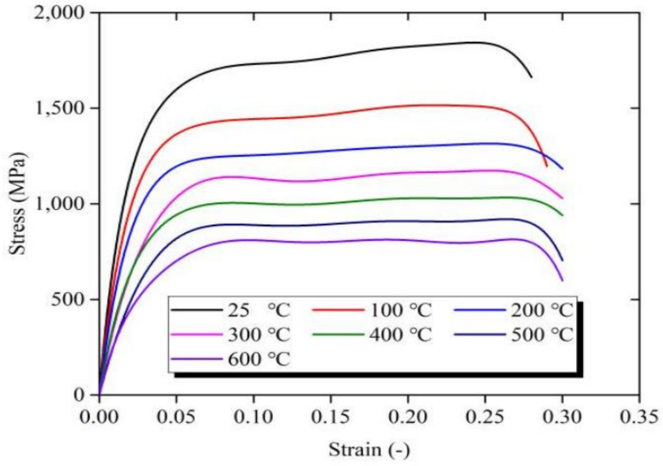

Figure 3. σ-ε curves of Ti6Al4V [38]

Finite element calculations of sheet metal forming processes began to appear in the 1970s. The initial part imported in the Part module is 3D and formable, and the die is solid and non-formable. The dies assembled at the ABAQUS software are shown in Figure 4.

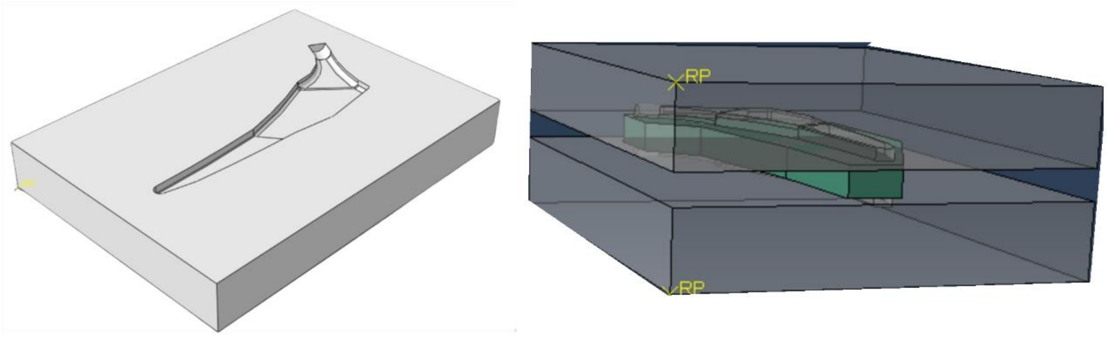

Figure 4. Dies and part (hip) assembly in ABAQUS

The Dynamic Implicit solver is selected at the Step module to solve the problem and perform the simulation. In the Interaction module, general contact matches the parts' related points and die. The oil film with 0.1 coefficient of friction is applied for lubricating.

The 2.5mm mesh size and the hexahedrons 8-nodes (R3D4) mesh type are selected for the raw material in the Mesh module. After increasing the number of mesh elements, the results of the simulations converge. Figure 5 shows the mesh independence diagram for maximum stress in the part. According to Figure 5, after 28000 elements, the stress converges to 1500MPa. In addition, the mass scaling is applied to converge the results. Figure 6 shows the meshing steps of the parts and dies.

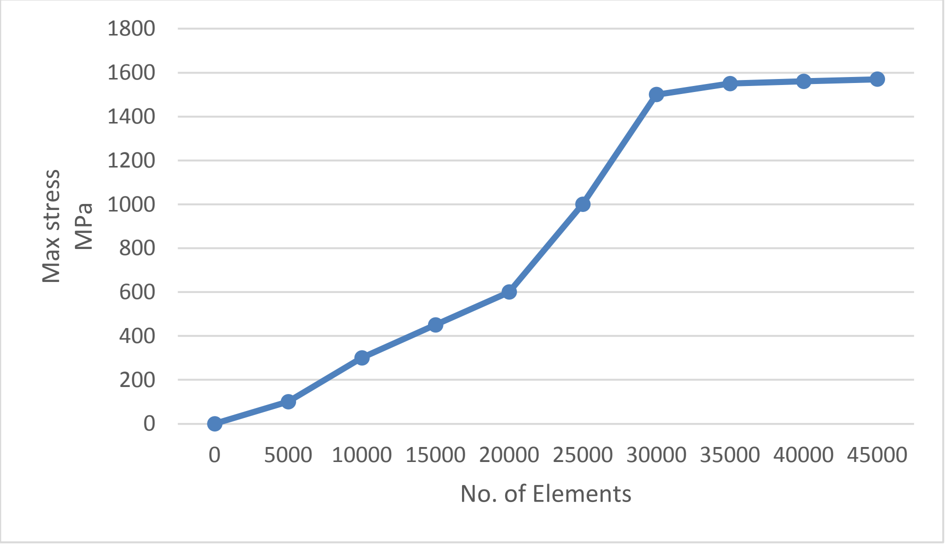

Figure 5. Mesh independence study

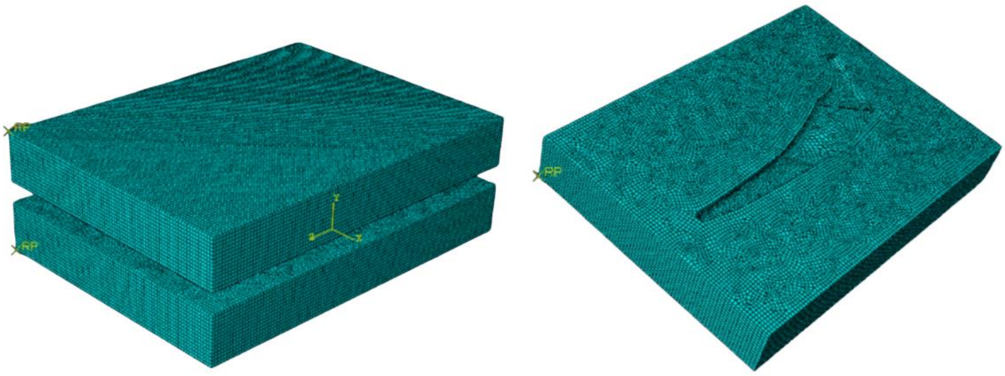

Figure 6. Meshing of parts

3. Results and Discussions

In this study, the feasibility of manufacturing the hip prosthesis by cold forging process is investigated via FEM simulation. As explained below, the maximum stress, strain, and displacement were obtained via simulation.

According to Figure 7, the maximum stress obtained from FEM simulation is about 1500 MPa which means that the sheet metal ultimately shows a plastic behavior to fill the shape of the die. As it is evident, the final shape of the billet is entirely under the geometry of the desired part (hip prosthesis). As expected, the maximum stress has occurred in the flash section of the hip. The press force is obtained at 120kN, so a 15-ton press is appropriate for this project.

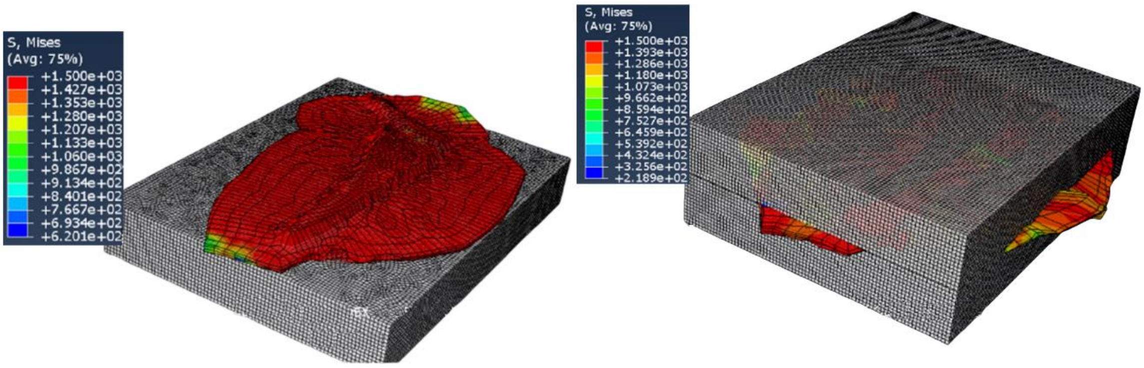

Figure 7. Von Mises stress in hip prosthesis

Figure 8 shows the strain obtained from the FEM simulation. As it is evident, the strain is very high, and the maximum strain occurs in the flash section. Because the material shows plastic behavior, this strain value cannot be explained clearly.

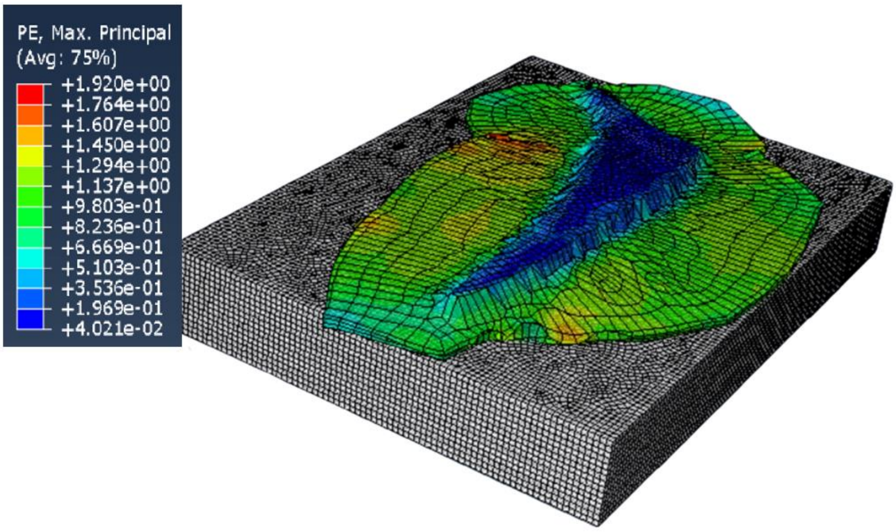

Figure 8. Strain in hip prosthesis obtained from FEM simulation

Figure 9 demonstrates the displacement that happened in the hip prosthesis. According to Figure 8, the maximum displacement occurred in the flash section as expected and was 37 mm.

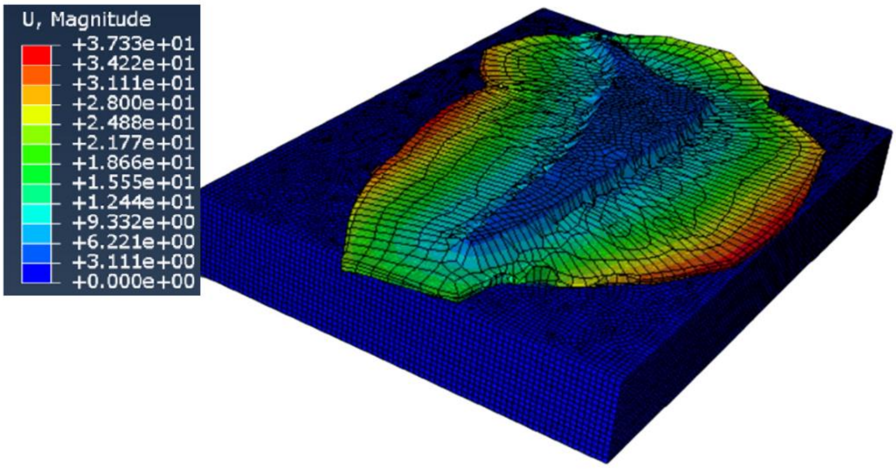

Figure 9. Displacement in hip prosthesis

The results of the present project have been compared with the results of Behrens's study [39]. Figure 10 illustrates the results of Behrens's study as the referenced paper. According to this figure, the maximum stress obtained in Behrens's survey [39] is 1350MPa, which is approximately consistent with the results of the present project. In addition, the steps of the forging of the hip, the final shape of the hip, and the number of flashes are demonstrated in Figure 11.

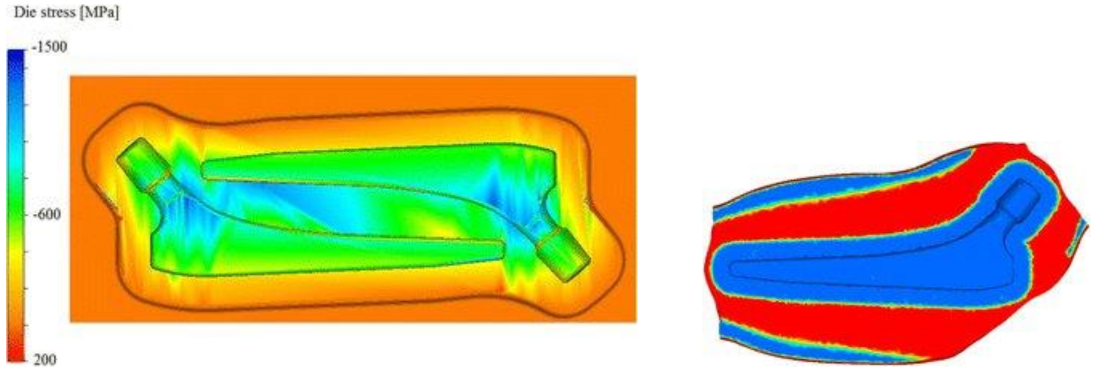

Figure 10. Results of Behrens's survey [39]

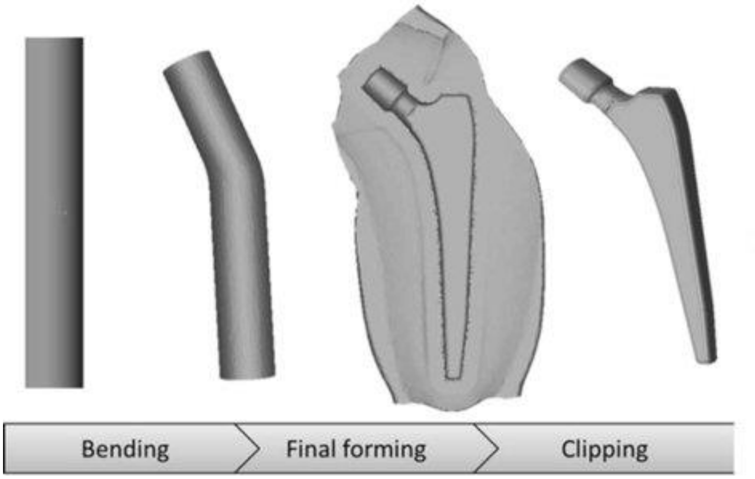

Figure 11. Steps of the forging process of Behrens's study [39]

4. Conclusions

In this study, the feasibility of manufacturing the hip prosthesis by cold forging process is investigated via FEM simulation, and the results are compared to Behrens's study [39]. The maximum stress, the maximum strain, and the displacement were obtained via simulation that are explained as follows:

- The maximum stress obtained from FEM simulation is about 1500 MPa which means that the sheet metal ultimately shows a plastic behavior to fill the shape of the die. As it is evident, the final shape of the billet is entirely under the geometry of the desired part (hip prosthesis). The maximum stress occurred in the hip's flash section as expected. In Behrens's study, the maximum stress was obtained at 1350MPA, which shows the approximate consistency with the present project's results.
- The strain obtained from FEM simulation. As it is evident, the strain is very high, and the maximum strain (1.9 mm/mm) occurred in the flash section of the forged part and Behrens's study.
- As expected, the maximum displacement occurred in the flash section, and it was 37mm. In Behrens's study, this value was obtained at 24 mm due to the minor initial part.

- The press force was obtained at about 120kN, meaning a 15-ton press is needed.

4. Acknowledgment

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