Finite Element Simulation of Ball Joint under Hot Forging Process

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Abstract. Nowadays, the finite element method (FEM) has been widely used to forecast the metal forming process and finding the parameter optimized. This work studied the use of FEM as a tool to design and process optimize a hot forging die for producing an automotive part named Ball Joint that part was made from carbon steel grade S45C. The objective of the study was to increase the efficiency of production and extend the life cycle of the machine by using load not exceeding the machine capability. To achieve this objective, the new parameters must produce workpieces without any defects. The defects regularly found in the forging workpieces are the thickness out of specification, the underfilling, and the crack. The parameter of the rougher and finisher process to studies and optimized that cover is the die gap and forming load. The die gap of 4, 3 and 2 millimeters and the forming load not exceeding 85% of machine capability were used in the hot forging simulation. From FEM simulation results, it was found that the die gap of 3 millimeters of the rougher and finisher process was the best to form workpieces without any defects, workpieces thickness within specification and the forming load not exceeding of 85%. In summary, the simulation and experimental results were compatible.

1. Introduction

Hot forging process is one of the most important process in the automotive part manufacturing industry because it can form a complex part and also control the microstructure [1]. The effects of forming workpieces at high temperature were difficult to control thickness as well as defects of the workpiece such as crack, mechanical properties and under filling etc. [2]. And also improve the hot forging process by optimal the values of processes such as machining, die and others in order to get the quality workpieces, save the time and reduce costs [3]. There are two types of hot forging die, open and close forging dies. The unnecessary waste can be seen in the open die called burr. Currently, the industry competition is very high in terms of cost and quality of workpieces. This work aimed to increase the efficiency of production and extend the life cycle of the machine by using load not exceeding the machine capability, it was necessary to skipped buster process and optimized parameters in the rougher and finisher process by using the FEM to analyze the process and part thickness by using DEFORM 3D ver.11 program to simulate the forming process [4-5]. This simulation program was used to predict material flow in the die to reduce trial and error processes [6-7]. In order to verify the simulation results, this work also conducted experimental studies to compare.
2. Determination of materials parameters and experimental procedure

Material properties. The material of workpiece used in this study is the medium carbon steel S45C. The chemical composition and mechanical properties are listed in Table 1 and 2, respectively.

| Table 1. Chemical composition (% mass) of S45C |
| C | Si | Mn | P | S |
|---|---|---|---|---|
| 0.42% | 0.25% | 0.6% | 0.020% | 0.035% |

| Table 2. Mechanical properties of S45C |
| Parameter | Value |
| Density (kg/m³) | 7800 |
| Young’s Modulus (GPa) | 201 |
| Tensile Strength (MPa) | 569 (Standard) 686 (Quenching, Tempering) |
| Yield Strength (MPa) | 343 (Standard) 490 (Quenching, Tempering) |
| Poisson’s ratio | 0.27 |
| Brinell Hardness (HB) | 210 (Annealed) |

Finite element simulation processes. This work studies used the DEFORM 3D V.11 to simulate the model and design of hot forging Ball Joint workpiece. The manufacturing of the part consisted of three main processes, Buster, Rougher, and Finisher process. While this study will reduce the process of the Buster and study the remaining two main processes, respectively. Which the simulation model with the FEM will include the heat transfer in the air, heat transmission of the workpiece to the die on each process. Fig 1 showed the characteristics of the die used in the hot forging process of the Ball Joint. The top surface of Finisher die that will be higher than the Rougher die surface by about 1 millimeter. The 1350 tons mechanical press with a maximum displacement of 240 millimeters and stroke per minute of 85 was used to form the Ball Joint part.

Flow stress data. The flow stress is a function of strain, strain rate, and temperature [8]. The flow stress of the workpiece metal used from the material library. The equation as indicated in Equation (1) below,

\[
\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}, T)
\]

Where: \( \bar{\sigma} \) is flow stress, \( \bar{\varepsilon} \) is effective plastic strain, \( \dot{\varepsilon} \) is effective strain rate, and \( T \) is the temperature.
Friction factor. Coulomb friction is used when contact occurs between two elastically deforming objects (could include an elastic-plastic object, if it is deforming elastically) or an elastic object and a rigid object. Generally, to model sheet forming processes. The frictional force in the coulomb law is defined by equation (2),

\[ f_s = \mu \rho \]  

Where: \( f_s \) is frictional stress, \( \rho \) is Interface pressure between two bodies and \( \mu \) is Friction factor

Mechanical press. The Mechanical Press type replicates the cyclic motion of a mechanical press. The parameters required to simulate the motion are the total displacement of the press \( (D_{\text{tot}}) \) relative to the current displacement \( (D_{\text{cur}}) \) and the number of strokes per unit of time \( (S') \). Using these parameters, it can compute the die speed at any point of the travel of the die. The movement direction can only be specified in the X, Y, Z, -X, -Y or -Z directions. The equation to derive the die speed is defined by equation (3),

\[ v = 2\rho S'D_{\text{cur}} \sqrt{\frac{D_{\text{tot}}}{D_{\text{cur}}} - 1} \]  

Where: \( v \) is the die velocity, \( \rho \) is pi (3.14159), \( S' \) is strokes per second, \( D_{\text{cur}} \) is current amount of displacement and \( D_{\text{tot}} \) is the total die displacement from top dead center to bottom dead center

In the manufacturing, the material used to produce the Ball Joint part was medium carbon steel grade S45C and Ø46 x 260 millimeters for the hot forging simulation model, the material was used in the software namely S45C. The forming temperature of the initial workpiece was 1200 °C. The temperature of the upper die and the lower die was 250 °C. The friction coefficient between workpiece and forging die was 0.3 and heat transfer coefficient was 11. The element number of the workpiece was 40,736 elements with a minimum element size of 1.75 millimeters. The condition of the mechanical press machine was the total stroke of 240 millimeters, stroke per second of 1.416 and connecting rod length of 900 millimeters. The aim of this work studies to increase the efficiency of the production process and reduce the trial and error process at the beginning of the production. The Buster process was removed from the current process while to optimize of the die gap. The die gap between upper die and lower die as shown in Table 3.

| Process   | Die gap (mm) |
|-----------|--------------|
| Rougher   | 4.00         |
| Finisher  | 4.00         |

To obtain the optimal of the die gap to produce the parts and the part thickness within specification. And forming a load of the mechanical press not exceeding 85% of machine capability.

3. Results and discussion
Result and accuracy of simulation program. The result of the simulation model of the Rougher process was the shape and thickness of the workpiece as shown in Fig 2(b). At the die gap 4, 3 and 2 millimeters, the part thickness per specification requirement was 14.50 – 15.00 millimeters on a critical point in Fig 2(a). When the die gap decreased, the thickness of workpiece decreased, and the forming load was increased as shown in Fig 3.
Figure 2. Workpiece (a) Critical point (b) Workpiece burr out and thickness of rougher process

Figure 3. The forming load of rougher process

In Fig 4 and 5 showed the simulation resulted from the Finisher process. Which the thickness of the workpiece was 14.20 – 14.50 millimeters and the workpiece demonstrate the final under filling defect and contract area. The forming load result that required similar to the Rougher process.

Figure 4. Workpiece burr out and thickness of finisher process
The workpiece thickness within specification and without defect was obtained at the die gap 3 millimeters and the forming load result was 1072.29 tons.

![Figure 5. The forming load of finisher process](image)

**Result of Trials.** In the trial process, the die gap was 3 millimeters. It was found that the trial and simulation result was similar to part thickness and forming load. However, the actual forming part showed more burr than of the forming simulation, possibly due to the difference of the die friction and heat coefficient as shown in Fig 6. The result of the workpiece thickness and forming load showed the error about 2.00% and 12.88%, respectively. The higher complexity of forming shape result in a higher error in the workpiece thickness and forming load as shown in Table 4.

**Table 4. Comparative workpiece thickness and forming load**

| Detail        | Thickness (mm) | Load (Ton) |
|---------------|----------------|------------|
|               | Rougher | Finisher | Rougher | Finisher |
| Actual        | 15.50   | 14.50    | 1010    | 877      |
| Simulation    | 15.21   | 14.21    | 1070    | 990      |
| %Error        | 1.87%   | 2.00%    | 5.94%   | 12.88%   |

![Figure 6. Comparative shape of workpiece](image)
4. Conclusion
In this research work, the simulation result showed that the best condition of the die gap for Rougher and Finisher process was the die gap of 3 millimeters. The simulation result shows that the die gap of 3 millimeters can produce the automotive part named Ball Joint, which the part thickness and shape within specification and qualities. The forming load not exceeding 85% as required. However, the forming load used in the forging process exhibited a maximum error about 13% it because of the condition set in the simulation model programmed was slightly different from the condition of the actual forming. The more complex shape of the workpiece resulted in a higher error of the forming load. The final shape of the workpiece is shown in Fig 7.

![Figure 7. The final shape of workpiece (a) Simulation part (b) Actual part](image)

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