Determination of Optimal Preform Part for Hot Forging Process of the Manufacture Axle Shaft by Finite Element Method

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Abstract

The main objective of this study is to determine an optimal preform part in hot forging process, which can reduce the underfill defect and forging load in hot forging process. The preform design approach was used to design the optimal preform part. The geometrically parametric approach and sensitivity analysis were applied to determine the optimal preform part to form the final part before forging process and the suitable process parameter which have the effect on the material flow by using the non - isothermal condition with finite element modeling (FEM). The fulfilling die cavity was used to be an indicator to determine the optimal preform part. The purpose of this study is to reduce the underfill defect, because the advantage is to improve the productivity rate and production cost at the final forging step. The results of the manufacture axle shaft had been successfully formed by using the optimized preform shape.

***Keywords**: Preform design, Finite element method, Sensitivity analysis*

1 Introduction

A manufacturing process for the axle shaft is manufactured by hot forging process. The hot forging has been used because of high production rate, superior final product strength and near net shape geometry. The manufacturing axle shaft is composed of 2 main processes; a) preform part process and b) final part process. The preform part process is to create an enlarged diameter at the head of a billet by using electric upsetting machine. The final part process is to forge to the desired final part. The method of final part process is closed die hot forging without flash which could fulfill die cavity without minimum loss of material. Figure 1 shows the operation of the automobile axle shaft in this study.

Although the method of manufacture axle shaft in hot forging process is the closed die hot forging without flash, the underfill defect could occur at the final part stage. Normally, the way to solve the underfill defect is improved the preform workpiece geometry. For this study, the preform geometry was designed in order to minimize the underfill defect in the final part process. The difficulty in closed die hot forging without flash was the preform design. In present, the preform is designed by trial and error. Currently, the finite element method has been used to design the preform part. A reverse engineering technique was used to design the process backward by starting from the design from the final stage and trace back to the initial stage by using FEM [1-3]. The two-dimension FEM with the process constraints was successfully designed the forging process of the semi-finished gear part including the indication of the possible defects of the part during forming process [4]. The studies on the geometrical parameters also were successfully investigated by [5] to evaluate the effect of the preform geometry on the precision forging of a compressor blade. Different optimization algorithms, such as Response Surface Method [6], full factorial sensitivity analysis [7] or genetic algorithm [9], were common tools used to symmetrically investigate the effect of the process parameter and the preform geometry on the products.

The objective of this study is to determine an optimal preform part in hot forging process, which can reduce the underfill defect. The operation of this study is composed of 3 steps; a) conduct the geometrically parametric approach to determine the optimal preform shape that can be used to form to a desired part, b) apply perform sensitivity analysis to investigate the effect of the process conditions during preform step on the material flow to the specified part dimensions by using non - isothermal viscoplastic Finite Element Modeling (FEM), c) determine the optimal preform part for minimizing the underfill defect in hot forging step. Finite Element Method has been used to determine the suitable process parameters and optimal preform part geometry in order to reduce the underfill defect.

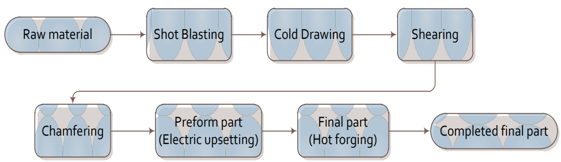


Figure 1: Show the operation of axle shaft

2 Experiment procedure

2.1 *Material properties*

The material of workpiece used in this study is the medium carbon steel (AISI 1045). The chemical component and mechanical properties as list in Table 1 and 2, respectively.

Table 1: Chemical component (%mass) of AISI 1045

C	Si	Mn	P	S
0.48	< 0.40	0.5-0.8	<0.035	<0.035

Table 2: Mechanical properties of AISI 1045

Parameter	**Value**
Modulus of Elasticity	200 GPa
Ultimate Tensile Strength	560 MPa
Yield Strength	275 MPa
Poisson’s Ratio	0.3
Hardness Brinell	166 HB
Elongation	22 %

2.2 *Parameters of process simulation*

In simulation of hot forging process, the process parameters play an important role in predicting the simulation results.

2.2.1 Flow stress data

The flow stress is a function of strain, strain rate and temperature. The flow stress of the workpiece metal was assumed to be a governed by Power Law Equation as indicated in Equation (1) below,

$$\sigma = K\varepsilon^n \dot{\varepsilon}^m \tag{1}$$

Where: K is constant, ε is strain, n is the strain hardening index, $\dot{\varepsilon}$ is the strain rate and m is the strain rate sensitivity index.

2.2.2 Friction factor

This forming process was conducted under the high contact pressure. The most commonly use of friction model for hot forging analysis. This is the constant-shear friction model. Friction model was applied at the boundary condition (S. Guy, .et al, 2002). Therefore, the simplified shear friction model was assumed to describe the friction as behavior between the workpiece and die. The shear friction equation is shown in Equation (2) below,

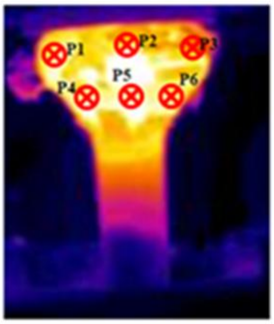
$$\tau = mk \tag{2}$$

Where: m is the friction factor and k is the shear yield stress of the material

In this study, the friction factor “m” was assumed to be constant at different temperatures and contact pressure and the sensitivity in friction coefficient “m” value was conducted to determine the suitable of the shear friction value.

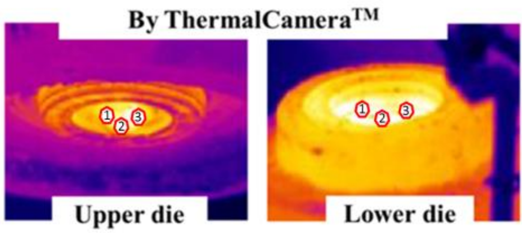
2.2.3 Thermal properties

The thermal properties of this study were constant parameters throughout the investigation. The initial temperature of the upper, lower dies and preform were measured directly from the experiments by using thermal camera as seen in Figure 2 and Figure 3.



By Thermal Camera TM	
Point	Temperature °C
1	1,010
2	1,020
3	1,000
4	1,010
5	1,020
6	1,000
Avg	1,000

Figure 2: The initial temperature of preform part from Thermal Camera



No	Upper	Lower
P1	145	105
P2	155	110
P3	155	105
Avg	150	100

Figure 3: The initial temperature of upper die and lower die from Thermal Camera

2.3 *Hot forging system*

The closed die forging without flash was adopted in the final step to form the final part. Figure 4 show schematic of the experimental set up for the hot forging process which is consisted of a preform part, a upper die, a lower die and a holder die. The equipment used for providing the relative velocity was a screw press machine. The relative velocity is the relationship between pressure and velocity.

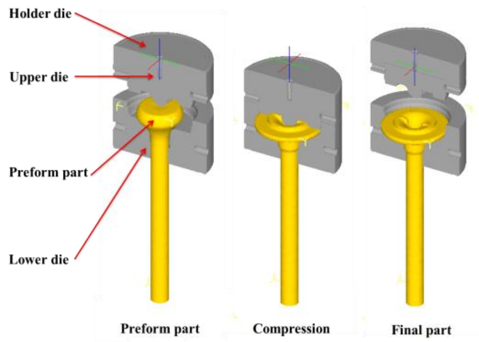


Figure 4: Schematic of the experimental set up

The hot forging process was consisted of three steps; a) after preform part was performed and heated up by electric upsetting process, then the preform part was transferred to the forging die by a robot arm, b) the upper die was moved down by ram speed in order to forge the preform that to be a final part, and c) the water-graphite base mixture was applied for lubricating and cooling after the final part was formed.

2.4 *Simulation model and conditions*

The FE simulation, the commercial package DEFORM-3D™ was applied to simulate the hot forging process with each preform part under the same conditions as list in Table 3.

Table 3: The process condition for FE simulation

Parameter	Value
Flow stress data	$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m}$
Shear friction factor	0.25 and 0.7
Heat transfer coefficient	5 MW/(m^{2}k)
Ram speed of upper die	515 mm/sec
Process temperature	1,000 ^{o}C

The flow stress data model of AISI 1045 obtained from the compression test at different temperatures among 20 to 1300^{o}C with different strain rates were applied to simulation software. For example, the high temperature with different strain rates as seen in Figure 5. The shear friction factor has been varied in order to determine the suitable friction value for hot forging model in this study. The ram speed of upper die and process temperature were selected based on the actual experiment.

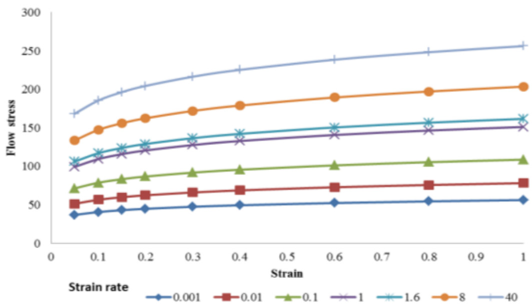


Figure 5: Show the flow stress data at temperature of 1000 °C with different strain rates

Since the preform part and dies (upper, lower and holder die) were non-axisymmetric system, the three-dimension (3D) for the geometrized model was used. The upper die, lower die and holder die were assumed to be rigid-body objects. That means it would allow any elastic deflect on occurring during forming. On the other hand, the preforms were assumed by the visco-plastic formulation, which is only considered plastic deformation behavior. The tetrahedral element was used in the preform geometry model. In order to reduce computations time and obtain accuracy results, the fine meshes was generated at the complex area, such as corner area. The total number of element used to model preform was 60,000 elements as seen in Figure 6.

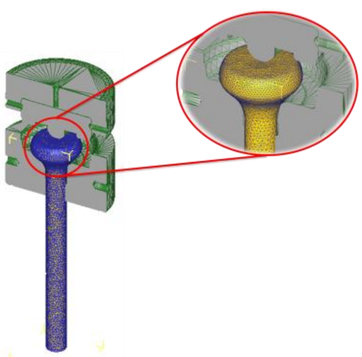


Figure 6: Shows the element of preform part

3 Preform design approach

Figure 7 shows the flow chart of this study that used to present the approach for determining the optimal preform part. In the preform design approach, there are two main stages, the first stage is the geometrically parametric approach, that was selected the primitive shape. The sensitivity analysis was conducted in the second stage to investigate the effect of geometry on the material flow.

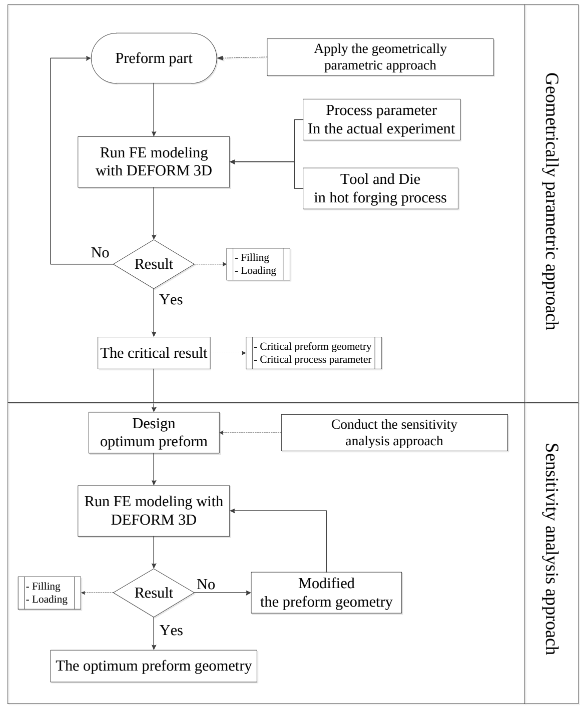


Figure 7: The flow chart of this study

3.1 *Geometrically parametric approach*

In this step, the hot forging simulation starts with the identification of the geometrical preform shape based on the actual experiment. This approach consists of 2 steps; a) determine the critical point on dimension of initial preform in order to determine the accurate shape such as corner at complex area, radial area, which have an effect on the die filling, and b) the process parameter conditions, which concerns on the effect of die filling such as friction factor, which cannot be determined directly from the experiments.

3.2 *The sensitivity analysis*

The sensitivity analysis approach was used to determine the optimal preform part based on the result of the geometrically parametric approach and in order to investigate the effect of the process conditions during preforming step on the material flow to the specified part dimensions.

In order to test the capability of the sensitivity analysis for designing the preform part, the cross-section has been chosen. The geometrical models of the critical section of perform and the dies set are shown in Figure. 8. There are four cross section areas chosen in this study. Each cross section has a great effect on the material flow. The success of determining the optimal preform part should be fulfilled the die cavity on the critical cross section area without underfill and folding defect.

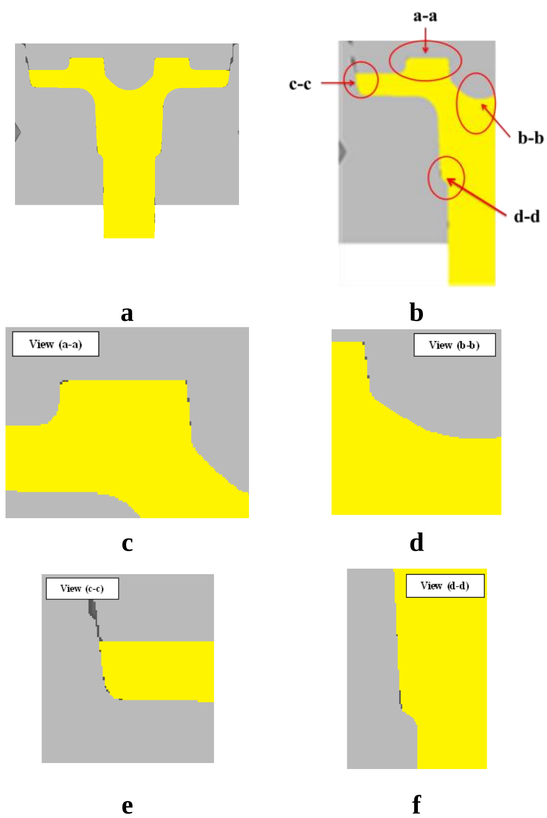


Figure 8: The critical sections of preform for axle shaft; a) the final part with cross section area, b) the critical point area, c) the cross section a-a, d) the cross section b-b, e) the cross section c-c and f) the cross section d-d

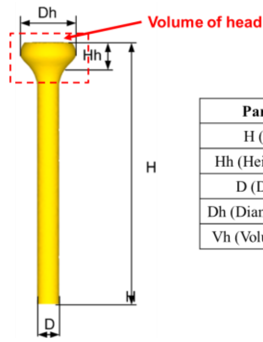
4 Result and Discussions

As mentioned in the section 3 (Preform design approach), the simulation would be conducted in 3 steps. a) the critical point on the initial preform part from the actual experiment, b) with the existing experimental result the process parameters, such as friction factor, would be determined, and c) the geometrical approach would be used to design the optimum preform with the minimum forming loads.

4.1 *Critical point on dimension shape*

The initial preform of hot forging process would be conducted in order to determine the accurate dimension / shape, such as volume of preform, corner at complex area or radius area, affected on the die filling.

To define the critical point on the initial preform part, there are two preform shapes that obtained from the actual experiment. The specific dimension of the two preform parts were seen in Figure 9



Parameter	Preform 1	Preform 2	Unit
H (Height)	556	556	mm
Hh (Height of head)	44.6	33.4	mm
D (Diameter)	44.5	44.5	mm
Dh (Diameter of head)	115	119	mm
Vh (Volume of head)	430,000	377,00	mm^3

Figure 9: Show the actual dimension of sample preform parts

According to the simulation result, the first preform could achieve to fill the die cavity which is better than that for the second preform at the same condition. The result of the die filling was shown in Figure 10.

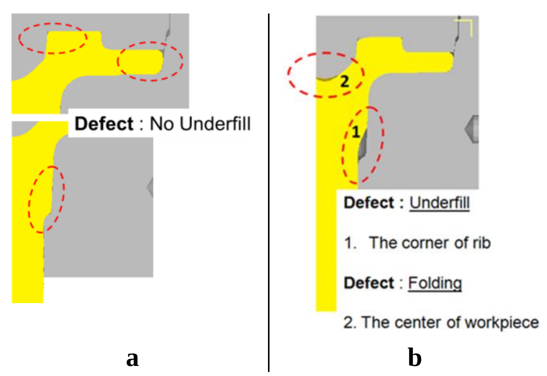


Figure 10: Show the result of initial preform: a) the first preform b) the second preform

In this study, the first preform has been chosen to be the critical dimension, because the result of the first preform part can be fulfilled the die cavity without any defect. In this study, the critical dimension, which has a great effect on the metal flow was the volume of preform. Therefore, the first preform part with it volume would be the critical dimension to determine the optimal preform part in next section.

4.2 *Determination of the suitable process parameter*

The complexity of the manufacture axle shaft in the hot forging process was the determination of the suitable process parameter. Due to some parameters could not directly be determined from the experiment, such as friction factor. Therefore, the simulation would start by simulating with the existing process parameters in order to determine the suitable parameters in the hot forging process.

The friction factor has a great effect on the die filling. Therefore, the various friction factors have been conducted to investigate the effect on metal flow. Two friction factors "m" (equal to 0.25 and 0.7) was defined for this investigation and compared with the real.

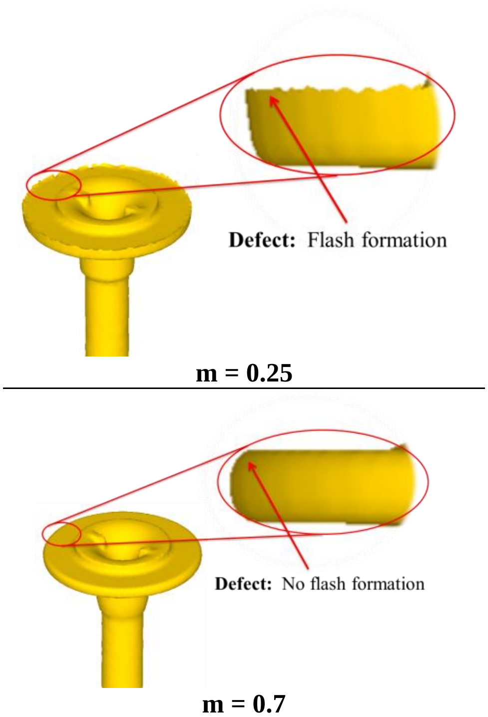


Figure 11: Comparison the friction factor\

The simulation results were presented in Figure 11. The burr and flash deformation was occurred with the friction factor 0.25. The result of the friction factor of 0.25 was different from the experiment as seen in Figure 12. The final part in the actual experiment does not have burr and flash deformation.

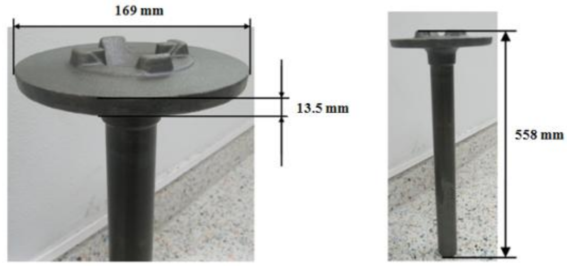
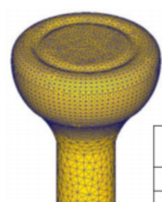
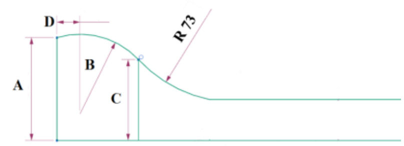


Figure 12: The final part from experiment

According to the sensitivity analysis, friction factor would be 0.7.

4.3 *Geometrically sensitivity analysis of the optimal preform part*

In order to determine the optimum preform shape, four types of the preform were designed in different geometries based on the constant volume. These preform were illustrated in Figure 13. The constants volume and radius used to design was approximately 430,000 mm^3 and 73 mm, respectively.

	R (Radius) mm	V (Volume) mm^3	A mm	B mm	C mm	D mm
Preform 1	73	430,000	56	43	44	13
Preform 2	73	430,000	44	46	44	15
Preform 3	73	430,000	49	23	44	25
Preform 4	73	430,000	46	52	44	15

Figure 13: Show the different of preform geometry

The different preform geometry based on initial preform shape and constant volume was tested under the same conditions. The simulation result indicates that the die cavities were incomplete die filling at in the end of process as seen in Figure 14.

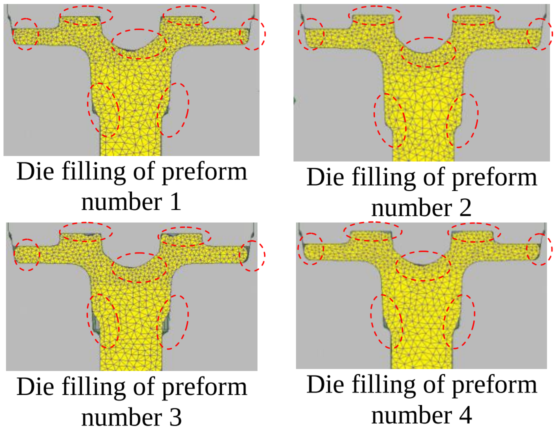


Figure 14: The result of all preform shape in effect of die filling and folding

The forming load required for the hot forging process could be predicted by the simulation software. The forming load from simulation software was verified by the actual experiment load. Figure 15 show the verification of forming load for each trial preform in simulations and the actual experiment.

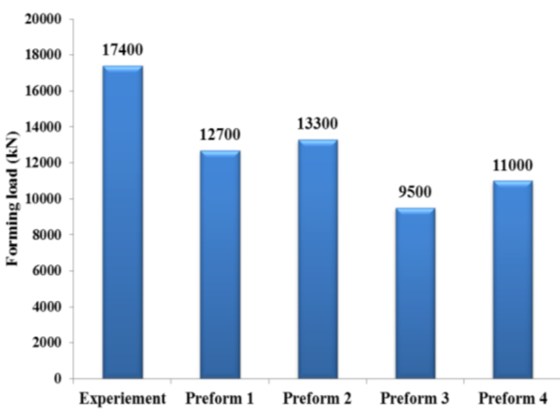


Figure 15: Show the forming load for each preform in the actual experiment and simulations

Based on the simulation result, the preform number 2 could be considered for the most suitable preform part because it could be achieved the completed filling better than that of other designs. The preform number 2 associates with process condition provided the satisfactory final part formation. Therefore, it was selected as the optimal preform part which could fulfill die cavity in hot forging process.

5 Conclusions

The determination of an optimal preform shape based on initial preform shape by using geometrically preform design approach, sensitivity analysis and Finite Element Modeling for hot forging process of axle shaft, has been carried out successfully. In this research of hot forging process for axle shaft, the preform number 2 was selected to be conducted on the preform sensitivity analysis because it geometry could be achieved the die fill in the final part process. The process parameter especially for the friction factor is very important in this study, its effect was significant on die filling, and the effect of geometry of preform was significant in the case of the fulfill the die cavity.

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