Research Article

Evaluation of Forging Die Defect by Considering Plastic Deformation and Abrasive Wear in a Hot Forged Axle Shaft

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Abstract
In the hot forging process, an abrasive wear is a major problem in the manufacturing process which may possibly happen together with the plastic deformation. Both effects are difficult to distinguish in the real tooling. Finite Element Modeling (FEM) is a tool that use to simulate those phenomena in the hot forging process. However, some unknown factors are not directly obtained from the actual measurement. Thus, the sensitivity analysis is applied together with FEM to approximate those parameters. This research was to evaluate the die defects of the hot forged axle shaft process which were the plastic deformation and the abrasive wear. The reliable simulation modeling was developed by conducting the sensitivity analysis of the unknown parameters; heat transfer and friction coefficient, and compared the results with the experimental results. Then, the evaluation of the defects was performed by considering the effect of the plastic deformation and abrasive wear separately. The plastic deformation would be determined by comparing the effective stress with the yield strength of the die material at the same temperature. To predict abrasive wear in 3D space the die profile from the actual process was measured by CMM and then it was compared with that obtained by FEM. Archard's model was used to predict the abrasive die wear in FEM. The variation of the K-values was significant to the wear prediction. According to this study, the average K-value obtained from different positions gives the best representative than considering only a single point K-value.

Keywords: Hot forging die defects, Plastic deformation, Abrasive wear, Wear coefficient determination

1 Introduction

Die life in hot forging process is the most crucial parameters in designing a successful process, because the forming die will absorb a significant forming load and temperature during operation to conform an initial shape of the workpiece to be a product. Many factors, i.e. die material, die design and forging conditions, influence directly to the die life [1]. Common failures are catastrophic fracture, wear, mechanical and thermal fatigue and plastic deformation The most occurred failures almost 70% is die wear [2], [3]. The effect

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of the die wear occurs when the volume of the die changing which leads to the forged part out of tolerance. Common wears are abrasive and adhesive wears. The abrasive wear frequently occurs. The cause of the abrasive wear comes from scratching, shearing and bumping of the rigid stuffs on the surface. The adhesive wear seldom occurs in the hot and warm forging because the interface between lubricant film (graphite layer) and oxide film will act as a protective shield to prevent the adhesion. Not only the high forming load will cause of the die wear, but also during the hot forming the dies and workpiece exchange the heat and result in increasing die temperature. This effect will make die become soften and prone to be weared easily [4]–[8]. In addition, the die defect may come from the plastic deformation because of the high contact load and temperatures existed on the die surface continuously in each step [6]. The plastic deformation starts when the forging load makes the die effective stress be higher than the yield strength of the die material at the apparent temperature during each step [8].

Numerous researchers have been studied and tried to develop technique and mathematical models to predict the abrasive wear [9]–[11]. Even though many mathematical models were developed, those models were modified from Archard's model as shown in Equation (1) [12].

$$W = \int K \frac{p^a \times v^b}{HRC^c} dt \qquad (1)$$

Where W is a wear depth at 1 cycle, K is a wear coefficient, p is normal contact pressure, v is sliding velocity, HRC is hardness as a function of temperature and (a, b and c) are constant coefficients.

To apply the wear model all the coefficients (K, a, b and c) need to determine directly from the experiment. The wear coefficient (K) is extremely sensitive to the amount of wear rate, while the constants (a, b, and c) are dependent on the type of die materials [9]–[11]. Generally, K-value is determined from sensitivity analysis of different K-values by simulation. Then, the actual worn die was compared with that obtained from the simulation to determine the K-value. However, in reality, this value cannot predict the abrasive wear for the entire forging die, because of the deviation of the contact pressure, relative velocity and hardness. Thus, some regions could have more errors than others. This would be difficult to justify which K-value is suitable for the process.

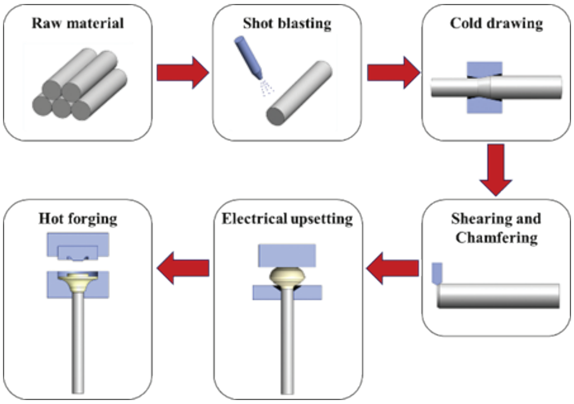

Figure 1: Hot forging process of the axle shaft.

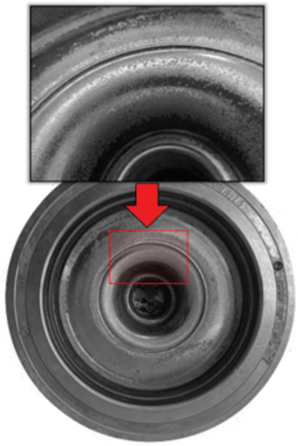

Figure 2: Abrasive wear on the die surface.

The axle shaft is a component used to transmit torque from the engine to the wheel. Figure 1 shows the process to manufacture the axle shaft. At the beginning, the raw material was cleaned at the surface by shot blasting process. The second step was a cold drawing process which is reduced the diameter of the raw material. Then, the raw material was cut by shearing process and was chamfered to remove the sharping edge which may damage the tools during forming. The head of the billet was deformed and heated up to the temperature approximately of 1,100 to 1,200°C by an electric upsetting process. Finally, the heated billet was forged by a screw press (the characteristic of the press is listed in Table 1) to the near net shape product. The abrasive wear occurred significantly during the hot forging process as seen in Figure 2.

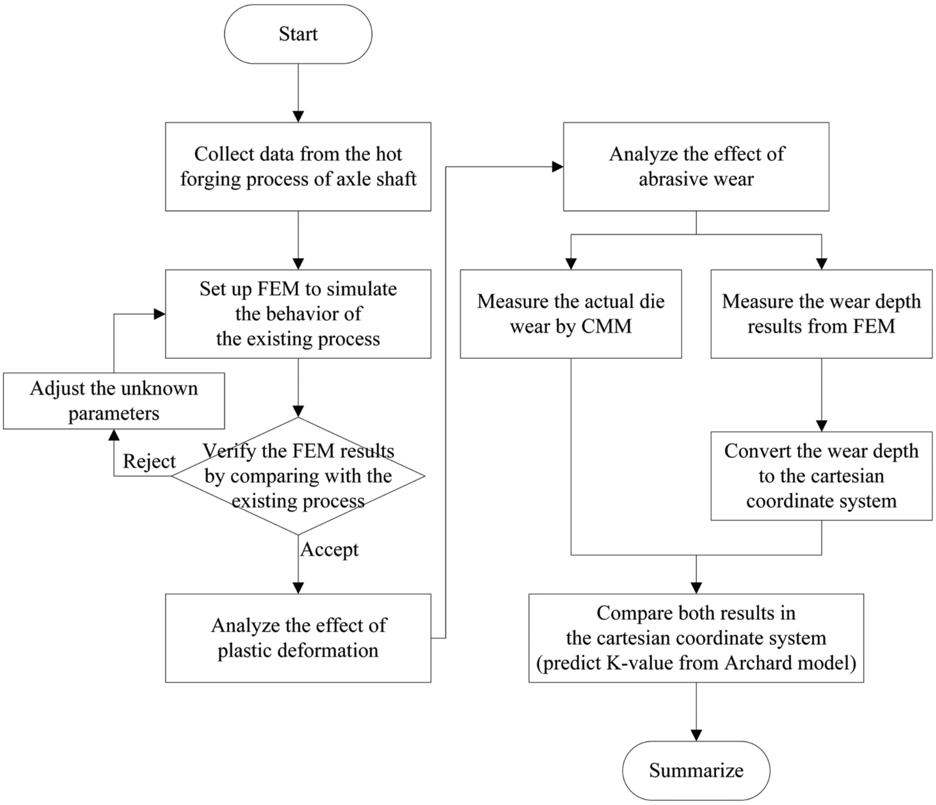

Figure 3: Flow chart of this research.

This research is aimed to evaluate the defects that happened during the hot forging process of the axle shaft. Only 2 defects; a) plastic deformation and b) abrasive wear, were analyzed. For the plastic deformation, the effective stress at the dies would be compared with the yield stress of the AISI-H13 material at the apparent temperature. For the abrasive wear, most of the research would focus only on the evaluation of the die wear in 2D space, which the amount of wear could directly compare between the experiment and simulation results. However, in the case of the axle shaft die the wear profile must be determined in 3D space in which is very difficult to compare with the results obtained from the simulation. Therefore, the technique to determine the suitable K-value and map the results from the simulation to 3D space of the real die profile was also recommended. Furthermore, the recommended technique to determine the suitable K-value by averaging the K-values of each local area is also discussed.

2 Materials and Methods

2.1 *Procedure for predicting die plastic deformation and abrasive wear*

The procedure to predict the amount of plastic deformation and abrasive wear is devided into 5 main steps, respectively, a) collect data from the actual process, b) perform sensitivity analyses to determine heat transfer coefficient and friction value to match between simulation and experimental results, c) predict plastic deformation d) Measure wear profiles by Coordinate Measurement System (CMM), e) determine the suitable K-value to evaluate the abrasive wear. Figure 3 also shows the flow chart of detailed procedure. The assumption to predict both plastic deformation and abrasive wear is that the amount of the surface pressure and relative velocity between the workpiece and die surfaces is repeated constantly throughout the entire process without considering the change in each forming cycle. Therefore, the total amount of the die wear and plastic deformation can be simplified by multiple the number of cycles with the result obtained from the simulation for 1 cycle.

The experimental results obtained from the hot forging of axle shaft were divided into 2 parts: a) forming results to develop the reliable simulation modeling (i.e. forming load, die's temperature at the steady state and part geometry) and b) the die profiles at step number 4,000 to determine the amount of die wear. First, these data were used to determine the unknown parameters in the simulation. The unknown parameters are the interface heat transfer coefficient (h) and shear friction value (m). These parameters were determined by performing sensitivity analysis based on the full factorial design (Designs of Experiments) and compared those results with the experimental data. These unknown parameters were also used for predicting the steady state temperature. This temperature was used later to determine the apparent hardness of the forging die during each forming step.

In this study, only 2 failure modes (plastic deformation and abrasive wear) were analyzed and approximated. The plastic deformation was analyzed and predicted first in each local area of the die. The idea of this analysis is that the material will deform permanently when the effective stress is beyond the yield strength at the operating temperature. The effective stress predicted by the simulation was compared with the yield strength of the die material at the operating temperature. If it is higher, the die material is assumed to have the plastic deformation. The amount of the plastic deformation was subtracted with the measured die profile to remain only the abrasive wear profile.

The unknown parameters are K, a, b, and c. Normally, the coefficients (a, b and c) of the tool steel material (AISI H13) are normally set as 1, 1, and 2, respectively [13]. Only K, which is significant to determine the amount of the abrasive wear, needs to be directly determined from the process. Generally, the sensitivity analysis with different K-values was conducted by simulation and compared the entire profiles of the die wear directly to the experiment in which the K-value provide the minimum error. Then, this value was used as a representative for predicting the die wear for entire die profile. The range of the K-values for performing the sensitivity analysis was come from either the literature review which sometimes it cannot fit for the entire profile. In this research, the sensitivity analyses were performed for each local point of the die to determine the K-value for each local point. Then, those K-values were averaged to find a good representative value for the entire die profile., the sensitivity analyses were performed to generate the linear equation for K-value prediction, and the worn profiles between the simulation and the experiment are compared.

2.2 *Hardness consideration in hot forging and proposed technique for K-value determination*

2.2.1 Hardness consideration in hot forging

2.2.1.1 Hot hardness of die material (H)

Considerable research has been predicted the die wear by adopting the hot hardness to approximate the changing die hardness due to the temperature and contacting time. The hot hardness curve is used to analyze the instant die surface temperature changeably. Lee [14] tested material AISI H13 to obtain the hot hardness function, as shown in Equation (2), in a condition of temperature reaches 500°C by using the micro Vickers hardness in a close chamber which the phenomenon of thermal softening was significant. In this research, the hot hardness was applied in the FE model, yet the tempering parameter was ignored.

$$H(T) = 9216.4T^{(-0.505)} \tag{2}$$

Where $H(T)$ is Vickers hardness and T is Kelvin temperature scale.

2.2.2 A recommended technique for K-value determination

Conventionally, to determine the suitable K-value is required to conduct the sensitivity analysis with different K-values by simulation and compared the entire wear profiles directly to the experiment. The value which could provide the minimum error was selected as a representative value for predicting the entire die profile. Sometimes, this value could fit very well in some region, but other may have more error. The range of the K-values for performing the sensitivity analysis was come from the literature review. Furthermore, most of the research would focus only on the evaluation of the die wear in 2D

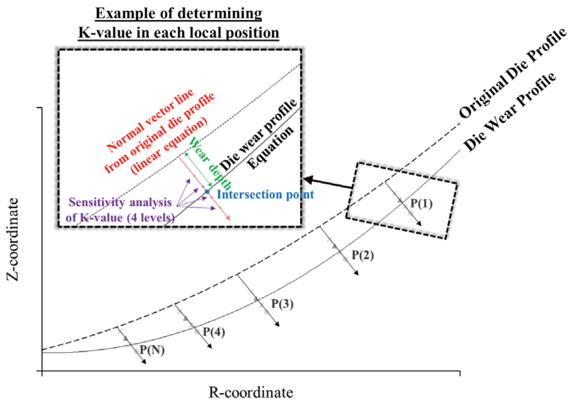

Figure 4: Overview of K-value prediction for each local point.

space, which the amount of wear could directly match between the experiment and simulation results. However, in this case, the wear profile was determined in 3D space in which is very difficult to compare with the results obtained from the simulation. Therefore, in this research, the technique to determine the suitable K-value and map the results from the simulation to 3D space of the real die profile was recommended. The procedure was divided into 11 steps:

1) Fit fifth-polynomial equation of the real die wear.

2) Perform sensitivity analyses of K-values (4 levels) to acquire the wear depth results.

3) Fit the linear equation of the K-value function with respect to the wear depth obtained from sensitivity analysis results in each local position (Figure 4).

4) Generate the normal vector in each linear equation to determine the direction of wear depth (Figure 4).

5) Convert the wear depth obtained from the simulation to the Cartesian coordinates by using a force normal vector to the surface of the die (Figure 5).

6) Determine the intersection point between the linear equation obtained from FEM and fifth-polynomial equation obtained from the experiment in the Cartesian coordinates.

7) Convert the intersection point to the wear depth for each local location.

8) Predict K-value for each local point.

9) Repeat (2) to (8) for each local point to determine the K-values.

10) Average all the K-values.

11) Compare the abrasive wear in the Cartesian coordinates between the simulation and experiment.

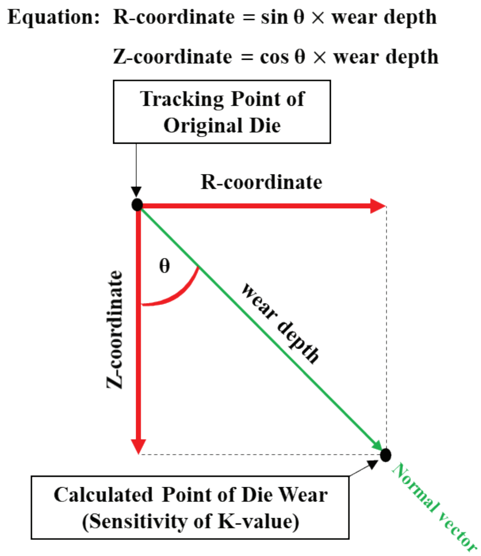

Figure 5: Method to convert wear depth for coordinate system.

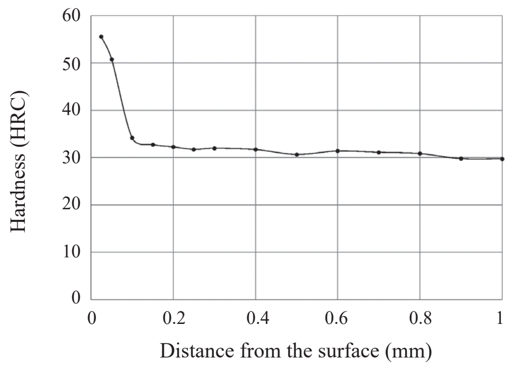

Figure 6: Hardness profile of the die after heat treatment and tempering.

3 Results and Discussion

3.1 *Experimental results*

Data obtained from the hot forging process of the axle shaft were divided into 2 main parts. First, the process parameters are characteristic of screw press (Table 1), the initial die hardness profile (Figure 6), temperature measurement of the workpiece and forging die at the steady state temperature (Table 2 and Figure 7) and forging load. Each condition was collected from 15 samples. The second was the profiles of the forging die after hot forging of 4,000 cycles.

The materials for the axle shaft was made of medium carbon steel (AISI-1045), and both upper and lower forming dies were a hot working tool steel (AISI-H13). The dies were undergone the heat treatment process to increase the surface hardness to around 55.5 HRC. The lubricant was the water-based graphite with the ratio of graphite 5% by volume. The maximum forging load of 19,000 kN was measured from the load transducer installed at the press.

Table 1: Screw press parameters

Parameter	Value
Energy	1.94×10^8 N·mm
Moment of Inertia	3.61×10^9 N·mm·s^2
Lead Screw Pitch	5,000 mm/rev
Blow efficiency	0.8

Table 2: Average data of the initial and final stage

Part	Average Data of Initial Stage (15 Random Samples)	Average Data of Final Stage (15 Random Samples)
Workpiece	Temperature (1150°C)	Flashness (13.5mm) Length (556.5mm)
Upper Die	Temperature (150°C)	-
Lower Die	Temperature (150°C)	Temperature (250°C)
Press Machine	-	Maximum forging load (19,000 kN)

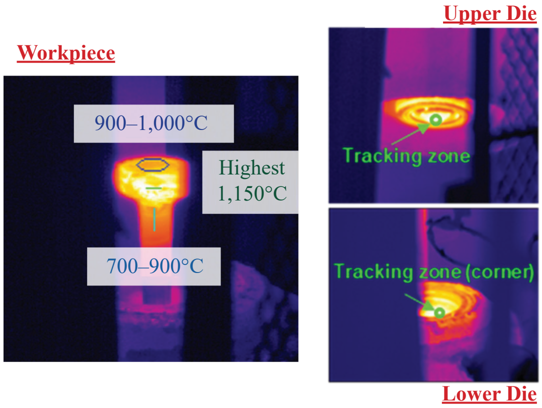

Figure 7: thermal images of the workpiece, upper die and lower die.

Figure 8: Samples of the preform and final form of the product for 3D-scan measurement.

3.1.1 Measurement of the steady state temperature and workpiece profiles

The infrared camera was used to measure the temperature of workpiece and dies after forming as seen the temperature profiles of all components in Figure 7. The maximum temperature of the initial workpiece was 1150°C and both of the dies were 150°C in the initial stage and 250°C for the final stage, respectively.

The workpieces after forming were measured by 3D-scan (Figure 8). The initial workpiece, the balloon-like shape deformed by the electric upsetting process, was used as an input geometry to the FEM, and the geometry of the finished part, namely flashness thickness of 13.5 mm and total part length of 556.5 mm, was used for validating the results.

3.1.2 Die wear measurement

The Coordinate Measurement Machine (CMM) was used to measure the profile of the die. To ensure reliable scans, a standard deviation of the worn die profile must be less than 25 µm. The clamping method is the necessary step to measure the die for preventing misalignment during measuring the dimension. For more precise data, the workpiece should be measured both inside and outside surface to avoid unsystematic sizing. This result from the measurement was provided in the XYZ coordinate for computing the R–Z coordinate for finding the K-value in the wear's model.

Figure 9 shows the location of the measurement. The increment of the measured displacement was 1–2 mm in each point surrounding the die surface. To ensure the repeatability of the wear profiles, 2 sets of forming dies with the same cycles (4,000 cycles) were measured in this study. The die profiles were measured at the critical region with 0, 90, 180, 270 degrees as seen in Figure 9(a). Figure 10 illustrates the comparison between the worn die profile and the initial die profile.

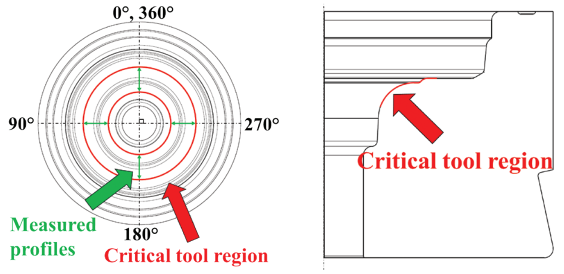

Figure 9: Measurement location of die wear profile at the lower die, a) top view and b) side view.

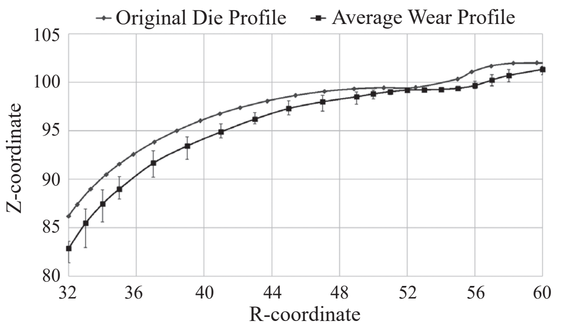

Figure 10: Comparison between the original die and average wear profile of the lower die.

3.2 *Finite element modeling of the axle shaft*

The commercial code, DEFORM-3D, was used to simulate the phenomena in the hot forging process. The simulation model was assumed as nonisothermal for both elastic dies and visco-plastic of the workpiece. The lower die was assumed to be elastic with non-constant temperatures. The upper die and upper die holder were assumed rigid with a constant temperature. Due to the axisymmetric model of the axle shaft only ¼ model was used to reduce the computation time. The tetrahedron element type was used in both billet and dies. The minimum element size was limited to 2 mm which the size would be adaptive during the calculation. The remeshing criterion was defined by the relative interference (0.7) between the workpiece and dies to avoid any penetration of the die and workpiece.

The real dimension of the workpieces and dies were measured directly by the 3D scan and they were used in the simulation. Initially, the temperature of the workpiece and the lower die was simulated and compared to the results obtained from the infrared camera (Figure 11). The movement of the upper die

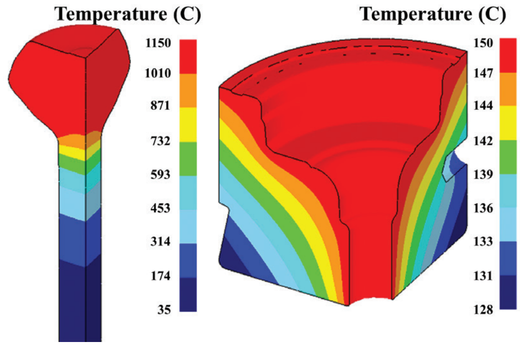

Figure 11: Preheated process of workpiece and lower die in FEM.

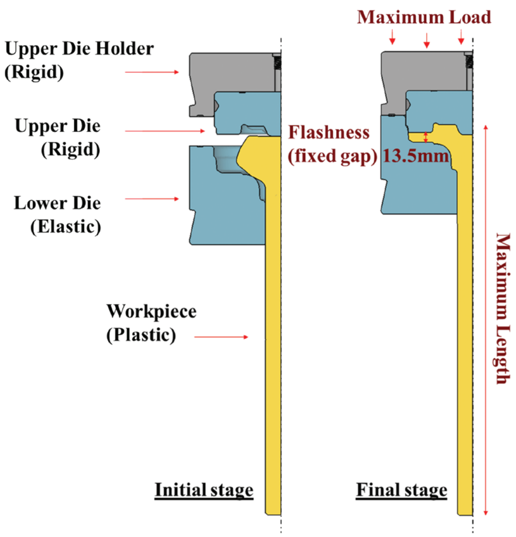

Figure 12: Schematic of the simulation model.

was input according to the characteristic of the screw press as seen in Table 1. The stopping criterion of the press was the gap or flash thickness of 13.5 mm as seen in Figure 12. The flow stress curves of workpiece as a function of the strain rates and temperatures are shown in Figure 13 and the average initial hardness of the base material of the die was 55.5 HRC.

3.2.1 Sensitivity analysis of interface heat transfer coefficient (h) and shear friction value (m)

Two unknown parameters are the interface heat transfer coefficient (h) and the shear friction coefficient (m) which cannot be directly measured from the process. Table 3 shows the conditions and indicators

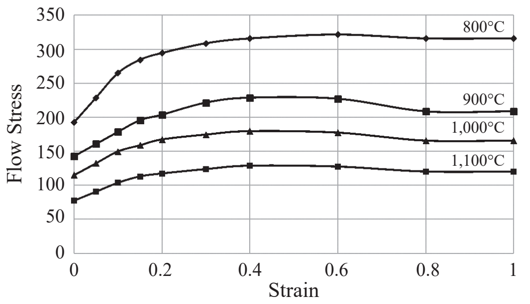

Figure 13: Flow stress curve of AISI 1045 at different temperatures.

for performing the sensitivity analysis to determine the unknown parameters. Table 4 shows the process condition to simulate the FE model.

Table 3: Conditions and indicators to perform the sensitivity analysis to develop a reliable FE-Modeling

Unknown Parameter	Indicator
h (1, 5 and 9)	Lower die temp.
m (0.3 and 0.7)	Maximum load
	Maximum length

Table 4: The process condition of simulation model

Simulation Model	Comments	
Simulation Type		Coupled analysis non-isothermal with thermal expansion elastic dies and plastic workpiece
Movement Type		Screw press machine control (Z-axis direction)
Workpiece	Object type	Plastic
	Element size	2mm (minimum)
	Initial temp.	1,150°C (maximum)
Lower Die	Object type	Elastic
	Element size	2mm (minimum)
	Initial temp.	150°C (maximum)
Upper Die	Object type	Rigid
	Element size	2mm (minimum)
	Initial temp.	150°C
Upper Die Holder	Object type	Rigid
	Element size	2mm (minimum)
	Initial temp.	150°C
Boundary condition	Symmetric plane	¼ symmetric
	Friction coef.	sensitivity analysis
	Heat transfer coef.	sensitivity analysis

The analysis was focused first to determine the temperature at the lower die. The interface heat transfer coefficient was varied in three conditions 1, 5 and 9 kW/(m^2 K) which the results of the lower die temperature were 255, 360 and 455°C, respectively as seen in Table 5. The FE model with 1 kW/(m^2 K) was the best fit with the experiment result.

Table 5: Results from sensitivity analyses to obtain interface heat transfer coefficient (h)

Experiment	h = 1	h = 5	h = 9
Lower Die Temp. (250°C)	255°C	360°C	445°C

The friction value is related to lubricant which affects significantly the workpiece dimension, the area of the flash and the forming load. In this case, the maximum length of the formed product and the maximum load were the indicators properly to determine the friction coefficient for validating the simulation model. The flash thickness of 13.5 mm was used as a stopping criterion for this simulation. According to the literature review, the shear friction coefficient is 0.3 approximately in the normal condition but it can be increased by the dry condition. To ensure the less error model, the friction coefficient would be varied between 0.3 and 0.7 for an analytical approach of the significant factors. Table 6 shows the results of the friction coefficient of 0.3 and 0.7, respectively. The maximum load of 19,900 kN and 21,600 kN, the maximum length of 556.4 mm and 555.7 mm for both friction values were compared with the experimental load. The suitable shear friction value from the sensitivity analysis of m value was 0.3 due to both indicators provided a smaller error than that of 0.7. The suitable value of the unknown parameters for a reliable simulation model could be concluded as the interface heat transfer coefficient = 1 kW/(m^2 K) and the shear friction coefficient = 0.3.

Table 6: Results from sensitivity analyses to obtain friction coefficient (m)

Experiment	m = 0.3	m = 0.7
Maximum Load (19,000 kN)	19,900 kN	21,600 kN
Maximum Length (556.5 mm)	556.4 mm	555.7 mm

3.3 *Analyses of plastic deformation and abrasive die wear*

3.3.1 Plastic deformation

Before approximating the die wear, the effect of

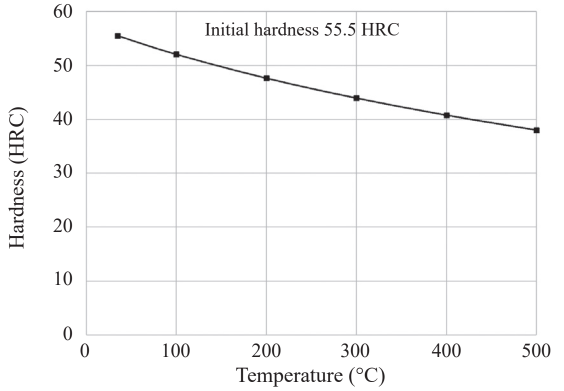

Figure 14: Hot hardness profile of die material.

the plastic deformation is needed to determine first because some areas, such as the corner radius on a die, is hard to separate both phenomena. Typically, the plastic deformation occurs from the level of yield stress higher than the yield strength of the material. The effective yield strength of the die can be approximated from the hardness of the material from Equation (3) [15] and Equation (4) [16], respectively. The hardness of the die material during the hot forging process could be approximated directly from the temperature. The initial hardness of 55.5 HRC at ambient temperature would be decreased rapidly at a high temperature. According to Lee's equation, the hot hardness curve (relationship between hardness and temperature) of the die material is shown in Figure 14. The lowest of the yield strength in the investigated area of the hot die was 1,250 MPa from hardness conversion [Figure 15(a)] while the highest of effective stress of lower die in FE model was 810 MPa [Figure 15(b)] which both would be compared for investigating the plastic deformation effect. Therefore, this research can be summarized that no effect of plastic deformation due to the effective stress are lower than that of the hot yield strength at the operating temperature.

$$HV = \frac{233 \times HRC + 14500}{(100 - HRC)} \quad (3)$$

$$YS = -90.7 + 2.876HV \quad (4)$$

Where YS is yield strength (MPa), HV is Vickers hardness and HRC is hardness scale Rockwell C.

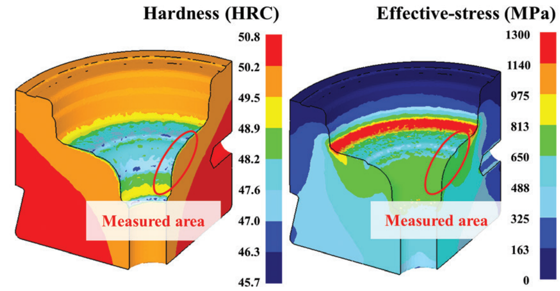

Figure 15: Results of the lower die at the finished stage, (a) Hot hardness and (b) Effective stress.

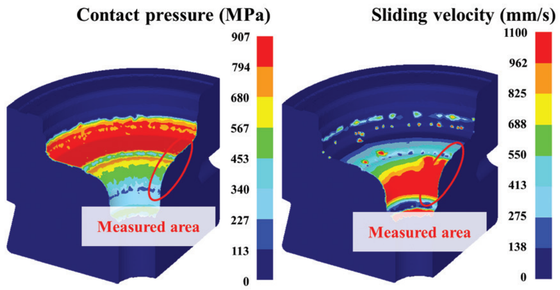

Figure 16: Results of the lower die at the finished stage, (a) contact pressure and (b) sliding velocity.

3.3.2 Evaluation of the abrasive die wear

Figure 16 shows the contact pressure and sliding velocity obtained from the simulation. According to the results, the level of contact pressure [Figure 16(a)] could be obviously divided into 2 regions (1 and 2) which at the area 1 the pressure is in the range of 450–570 MPa while at the area 2 it is above 900 MPa. Furthermore, the relative velocity [Figure 16(b)] could be divided into 2 areas as well which at the area 1 is above 1000 mm/s while at the area 2 it is in the range of 550–700 mm/s. The analysis of the die wear should be divided into 2 areas as shown in Figure 17.

3.3.2.1 Creating equation of real die wear (experiment)

Figure 18 shows the die wear profile obtained from the CMM machine and mathematical fitting model with the 5th polynomial equation. As mentioned before, the analysis of the abrasive die wear was divided into 2 areas to make the analysis become more accurate. The equations for each area are shown in Equations (5) and (6) for the area 1 and 2, respectively.

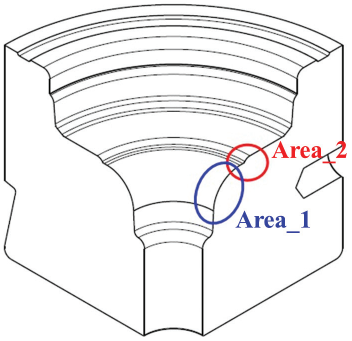

Figure 17: Separation of the measured area for using the sensitivity analysis.

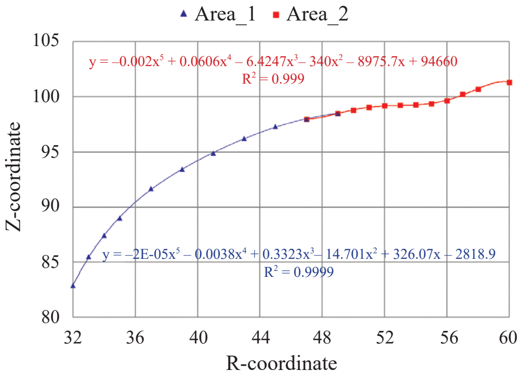

Figure 18: Fifth-polynomial equations of die wear profile.

$$y = 2 \times 10^{-5}x^5 - 0.0038x^4 + 0.3323x^3 - 14.701x^2 + 326.07x - 2818.9 \quad (5)$$

$$y = -0.0002x^5 + 0.0606x^4 + 6.4247x^3 + 340x^2 + 8975.7x - 94660 \quad (6)$$

Where y is Z-coordinate and x is R-coordinate.

3.3.2.2 Sensitivity analysis of K-value (FEM)

The sensitivity analyses were performed by varying the K-values in 4 levels of 1, 2, 3, and $4{\times}10^{-4}$. The simulation results show that the higher the K-value the higher the wear depth. This sensitivity was performed for the 22 positions for each local area as discussed before (Figure 19). Each position (all 22 positions) was fit by the linear equation with the statistic of R-square greater than 99%. As mentioned before, the direction of the wear depth for each position could not be determined

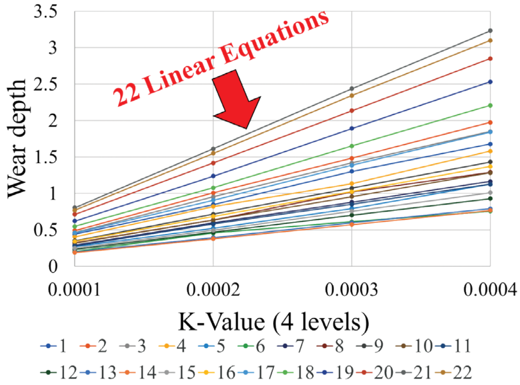

Figure 19: Results from sensitivity analysis as 4 levels.

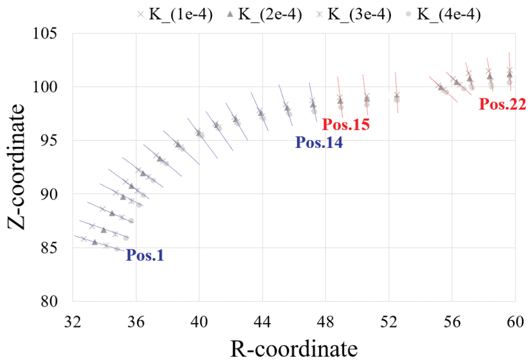

Figure 20: Conversion of the wear depth to the cartesian coordinates for each K-values at different positions.

directly from simulation. Thus, the normal vector from the original die surface was used to represent the direction and convert the wear depth to Cartesian coordinates based on the method shown in Figure 5. Figure 20 shows all the curves fit obtained from the sensitivity analyses of K-values for all positions (22 measurement locations as seen in Figure 10). They were used to determine suitable K-values. Figure 21 demonstrates on how to determine the suitable K-value calculated from the intersection points between the linear curve obtained from the sensitivity analysis and the experimental result. All 22 positions were repeated to determine the suitable K-value for each position.

3.3.2.3 K-value evaluation and result discussion

Figure 22 shows the K-values obtained from each

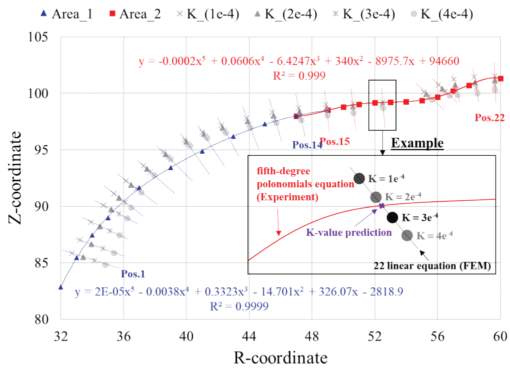

Figure 21: Sensitivity analysis of the K-values for each position.

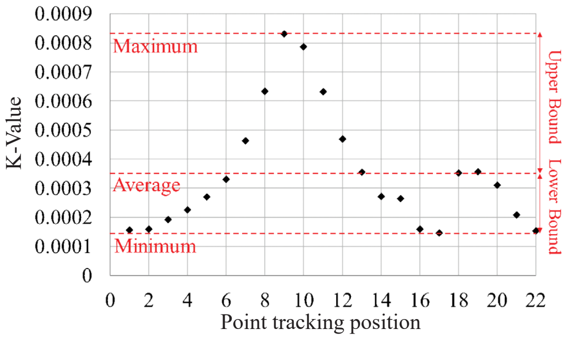

Figure 22: Wear coefficient (K) distributions at the different local point.

position. The average, minimum and maximum of the K-values are equal to 3.51e–4, 1.46e–4 and 8.31e–4, respectively. According to the results, it is very difficult to justify which K-value is suitable for the entire this process due to the variation of the process conditions (contact pressure and relative velocity). The recommended techniques should be discussed. One of the possibilities is to divide the upper and lower bounds by using the average K-value as a middle point. As shown in Figure 22, the upper bound is 9 points, and the lower bound is 13 points. Figure 23 shows the die wear profile when applying with different K-values (average, maximum and minimum values) to show whether which K-value would give the minimum error. According to the result, the average K-value would give the best fit results when comparing to all the conditions. Therefore, during the design, this result should be used to approximate the die wear for the hot forging of the axle shaft.

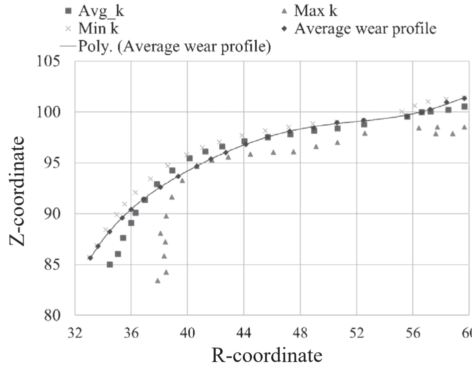

Figure 23: Comparison of die wear distributions with different wear coefficient (K-value).

4 Conclusions

The reliable simulation modeling was developed to evaluate the die defects of the hot forging of the axle shaft. Two kinds of die defects, namely plastic deformation and abrasive wear, were evaluated. The plastic deformation was not occurred at the interested area, because the level of the effective stress at the operating temperature was lower than that of the die material at the same temperature. In this research, the technique to evaluate the die wear in 3D space was discussed. The results of the die wear obtained from the simulation were converted to the Cartesian coordinates to compare to that obtained from the experiment. The suitable K-value to approximate the abrasive wear should come from the average K-value at different locations, not only from the single point. Therefore, it should be recommended to determine the K-value by this technique.

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