Research Article

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Improvement of forging die life by failure mechanism analysis**

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Abstract: This study analyses the causes of rapid failure at the early stages of hot forging tools. Tool life generally refers to the number of forgings that meet the required geometry, properties and quality produced by a tool. Die failure in hot forging processes are caused by failure modes such as plastic deformation, wear and thermomechanical fatigue. This study focuses on plastic deformation failure. The practical experience was carried out in the upset forge fastener head, having a workpiece material of Ck45 alloy steel and tool made of 56 NiCrMoV7 tool material, which was forged at 950–1150°C, under an 800-ton, horizontal mechanical press. The finite element (FE) software MSC Simufact Forming 16.0 was used to simulate the process. The results showed plastic deformation occurring in the upper and lower dies because the temperature increase progressively reduced the hardness, creating softening effects during the forging process. The optimal forging temperature to form the fastener head was determined to be lower at 1000°C, saving time and cost. The FE method can be efficiently used to enhance the formation and to predict die life.

Keywords: Plastic deformation, die service life, hot forging, MSC Simufact Forming

1 Introduction

In cement mills, a forged fastener head is often used to fix the furnace lining. A closed-die method of hot forging is employed to produce large quantities of fastener heads. The cost of the tools in this approach is assumed to be 15 to 40% of the total manufacturing cost of the forgings [1]. Closed-die forging is a forming procedure that involves a work blank placed inside a closed die cavity under stress; the blank is then and struck with punches until the die cavity is filled with metal [2]. These dies suffer from production problems during the hot forming stages. The use of numerical simulation to validate or enhance designs of forging dies and tools has become popular as a replacement for the prior trial-and-error approach [3].

The research in this paper was conducted to improve the performance and upgrade the productivity of these dies, and the study focused on stress and temperature and failure mechanisms to optimise the hot metal forging process. In previous research, Tavichaiyuth et al. [4] studied die defects, such as plastic deformation and abrasive wear, and examined the hot-forged axle shaft process. Archard’s model was used with the finite element method (FEM) to predict the wear of abrasive dies. When determining plastic deformation, the effective stress and yield strength of the die material were considered. For accurate results, the K-values were across all instances. To estimate the die wear, this knowledge was vital when designing the axle shaft.

Mashhadi et al. [5] studied the effect on the required force, equivalent strain, and flow stress. The closed-die forging technology was used to assess the production process of an essential element of the gearbox of a Mercedes-Benz ten-wheel vehicle. The results showed that the workpiece’s starting temperature had the strongest influence on flow stress and, as a result, the necessary maximum force throughout the operation. While other factors, such as press speed and mould temperature, had only a slight influence.

Hawryluka et al. [6] studied a punch-conscious approach with a procedure of forging a hot cover-type part. The analysis results obtained for instruments after forgery were confirmed for 6000, 9000 and 12,000 forging cycles. The process was carried out in three operations with an
The steel 56NiCrMoV7 is commonly used for the hot forging process and was chosen for this study. This steel features outstanding strength and hardness, good tempering properties, and a high red hardness. It is ideal for the hot forging process due to its excellent mechanical properties. The 56NiCrMoV7 steel is used to manufacture dies for hot forging processes, including the 18-MN crank press. To assure the reproducibility of operational results, three tools were used and WCLV hot work steel (1.2344), according to DIN X40CrMoV5-1, was the forged material. The software used to analyse the punch wear was MSC MARC. The results showed that different wear mechanisms developed in various locations of the evaluated tools.

D’Addona et al. [7] studied the durability of forging and its effect on the cost and quality of forgings. The findings showed the cost of the tools in this approach were 15 to 40% of the total manufacturing cost of the forgings. Die service life is a critical factor in determining the cost of production in the hot forging process.

Additionally, Łukaszek-Solek et al. [8] studied the hot methods of closed thermal briquettes in the production of typical steel gears with the aim of optimising parameters such as initial temperature and achievable deformation rate and discovered that the sensitivity of the microstructure of this type of steel to temperature was greater than the strain rate. Furthermore, since recrystallisation occurred in fine grains, increasing strain rates and temperatures above 1000°C in the process were advised.

The failure dies in the hot forging process are typically based on failure modes such as plastic deformation [9], wear [10], oxidation and thermal and mechanical fatigue [11, 12].

A first essential step in this direction is the use of tool steels, such as 56NiCrMoV7 (DIN 1.2714), with a process-dependent heat treatment to adjust the tool hardness. Hardness is closely connected to ductility and toughness [13]. The changes in the surface layer of tools caused by various failure mechanisms must be accurately described in order to increase the tools’ durability used in hot and warm forging processes [14]. Ductility is more effective than toughness in tool life [15].

FEM, which provides significant data, such as the temperature distribution and equivalent stresses in tools, can be useful in understanding the mechanism of failure of forging tools. This study developed a method for estimating tool life in hot forging processes and for predicting the plastic deformation of a tool. The maximum possible production quantity, which describes the useful life of the die, is assessed based on the fluctuations in the initial temperature of the billet and the die’s hardness [16]. Warm/hot forming methods are frequently used to create more deformability and complex shaping [17]. The objective of this research is to study the plastic deformation failure and optimise the hot forging process using FEM.

## 2 Materials and methods

### 2.1 Die life depending on plastic deformation

Because of the contact between the die and hot deforming material, the temperature rises during the hot forging process. The rate of temperature rise can be attributed to several factors, including initial die and billet temperatures, contact time, pressure, conditions of die material and surface treatments. The thermal softening caused by this temperature increase gradually reduces the hardness of the die and leads to die failure by plastic deformation [18].

The Holloman-Jaffe’s (parameter $M$) equation describes the effect of tempering on steel hardness, as shown in Eq. (1), which indicates the effect of the change in die hardness on the contact temperature and time successive forging cycles [7, 19].

$$M = T(C + \log t) \times 10^{-3}$$  \hspace{1cm} (1)

where $M$ is the tempering parameter, $t$ is the tempering time (h) at the tempering temperature $T$ (K), and $C$ is the Holloman-Jaffe constant, a material-dependent constant. The constant $C$ decreases linearly with increasing carbon content, and a value of 19.5–20 for regular carbon and alloy steels was recommended [20].

The tempering temperature $T$ is to be replaced by the temperature equivalent $T_{eq}$, the most critical parameter in the model of plastic deformation caused by tempering on the die. If the maximum and lowest temperature of $T_{max}$ and $T_{min}$ are reached at the same die point, $T_{eq}$, is expressed conveniently by Eq. (2):

$$T_{eq} = \frac{2T_{max} + T_{min}}{3}$$ \hspace{1cm} (2)

where all temperatures are in Kelvin. The die’s lifetime before exceeding plastic deformation can be calculated using Eq. (3):

$$t_h = \exp \left[ \frac{1000M_y}{T_{eq}} - C \right]$$ \hspace{1cm} (3)

where $t_h$ is the lifetime and $M_y$ is the value of $M$ when the hardness of the die exceeds critical hardness. Any behaviour that raises the equivalent temperature reduces die life, owing to plastic deformation [7]. In addition, $M$ is different from material to material. However, common steel grades used for hot forging dies can be found else [21].

### 2.2 Experimental work

The steel 56NiCrMoV7 is commonly used for the hot forging process and was chosen for this study. This steel features outstanding strength and hardness, good tempering
Table 1: Chemical compositions for tool steel and workpiece

| Material   | C%  | Si%  | Mn%  | P%   | S%   | Cr%  | Mo%  | Ni%  | Co%  | Cu%  | Al%  | V%  | Fe%  |
|------------|-----|------|------|------|------|------|------|------|------|------|------|-----|------|
| Ck45       | 0.44| 0.188| 0.64 | 0.0036|0.0185|0.0296|0.0083|0.0182|0.0620|0.0044| -   | -   | 98.4 |
| 56NiCrMoV7 | 0.55| 0.25 | 0.75 | 0.03  | 0.03 | 1    | 0.45 | 1.6  | -    | -    | -    | 0.1 |      |

Figure 1: Billets of Ck45 prepared with dimension (30∅ × 160 L) mm

strength and resistance and heat-treatment dimensional stability [5]. The forging process in this experiment consisted of one cycle finishing stage with two dies – upper and lower – and a punch. The upper die and punch are movable, while a lower die is fixed. The forming process was carried out using a horizontal mechanical eccentric press, with a capacity of 800 tons, from the State Company for Steel Industry.

To supply the amount of metal needed to fill the die cavities, the raw material was prepared to the required dimensions. The volume of raw material required to form the fastener head depends on the shape of the preform in the die.

Hardness is a fundamental element in the manufacture of closed-die forgings to balance hardness with toughness (hard surface + die durability). To resist sudden shocks during the closed-forging process, forging tools require a hardness that can withstand the high temperatures of 950–1150°C, which is achieved by specific heat treatments.

The chemical compositions of the die material, low-alloy steel 56NiCrMoV7, and the billet, AISI 1045, are shown in Table 1. The forging billets, 30 mm in diameter, were trimmed to the desired length of 160 mm (20 workpieces), as shown in Figure 1.

Next, the billets were divided into five groups, four pieces for each group, to be heated to different temperatures by an electric furnace. The five groups were heated to 1150, 1100, 1050, 1000, 950°C, respectively, and then transferred to the 800-ton forging press. The temperature of the billets and tools were measured with an infrared thermometer. The forming process was achieved at all temperatures with little flash, and the time needed to produce one piece was approximately 10 s/cycle.

2.3 Die hardness effect

During the hot framing process, the die material hardness changed with temperature and forging cycles at any point in the die. The initial hardness of the die material after thermal treatment was 42 HRC. The relationship between hardness and the tempering temperature of steel 56NiCrMoV7 is found in Ref [22]. According to this reference, the hardness of the die is inversely proportional to the increase in the tempering temperature, and the critical degree of hardness of this metal was 35 HRC at a tempering temperature of 650°C.

With the increasing number of forging cycles, the surface of the die lost hardness, owing to the tempering effect (die softening) [23]. After completing the forging process at all temperature ranges, the hardness of the upper and lower die was measured at multiple locations, as shown in Figure 2.

Figure 2: Illustration of die hardness measuring

The point 1 in this figure represents the initial die hardness before forging process and point 2 represents die hardness far from deformation reign. Also, points 3 and 4 represent die hardness around the sharp edge and near forming reign. Finally, point 5 shows the die hardness at deformation reign. Unlubricated and uncooled tools result in abrasive wear and plastic strains, common destruction devices. The strain additionally causes the material to be tempered locally, reducing the hardness [24].
2.4 Scale effect

To determine the effect of the scales from the forging material during the forging process on the closed dies, a scanning electron microscope (SEM) was used. During hot forging, some of the scale accumulates on the surface of the tools, and most of it is removed. However, some of the spalling scale remains on the tool’s surfaces, which is collected from forged material, as shown in Figure 3.

![Figure 3: Two sample tested (a) Scale collected from forged metal (b) Powder of scale](image)

An SEM test was performed on two specimens – the scale only and the powder of the same scale after being crushed by a mill. Each specimen was tested for more than one scale size from (40–200 µm), as illustrated in Figure 4.

This technique was adopted to characterise the effect of this scale on the upper and lower dies.

This experiment was performed at temperatures at which scale formation normally occurs. In the subsequent hot forging cycles, the scale effect would be a catalyst for accelerating the process of die failure, acting as an abrasive and increasing the wear of tools [11].

2.5 FE modelling

Recently, the FEM has been the preferred approach to analyse the mechanical characteristics of materials, structures and coatings [25]. The Simufact Forming software was used for simulation of a hot closed-die forging process, and the upper and lower dies with a punch were drawn in AutoCAD. CAD files were imported and defined to serve as the tool geometries shown in Figure 5. The workpiece geometry was created within Simufact Forming using mostly tetrahedral elements (type 135 for rigid dies with heat conduction). The process consists of the following three steps, each simulated in an individual analysis for all temperatures – 950, 1000, 1050, 1100 and 1150°C:

1. Hot forging
2. Simulation of die load
3. Thermal die analysis

The mesh was created to suit the requirements of simulation. The element size for the billet was calculated as 4 mm based on the geometry. For the die load analysis, the mesh of the die was 25 mm.

![Figure 4: Multilayered of sample no:2 from forging material steel AISI 1045 a) 40µm b) 200 µm](image)
3 Results and discussion

FE simulations with Simufact Forming help analyse the heat distribution inside the dies. The heat conductivity and specific heat capacity are crucial for a thermal analysis [9]. The deformation process was investigated by numerical analysis under different forging temperatures of 950–1150°C. Figure 6(a) shows the die and fixture shapes. Points 1 and 2 represent the sharp edge and critical corners of the upper and lower dies. The stresses and temperatures were analysed at these two points, and Figure 6(b) represents the final product.

During the forging process, as illustrated in Figure 7 and 8, the equivalent stresses were aggregated and distributed over the entire forming area. They increase more around the edges and ends of the dies, particularly around the flash formations at the punching area, causing permanent deformation of the dies. This deformation could result in a large number of damaged and hot work tools in the forging operations. Therefore, the equivalent stress should not exceed the yield stress when designing tools and selecting die metal. As shown in Tables 2 and 3, the equivalent stresses were larger in the lower die at points 1 and 2 than those in the upper die, with the highest maximum equivalent stresses of 143.82 MPa on the lower die forging temperature of 950°C. Because the lower die comes has more contact with the heated piece, it is more vulnerable to high temperatures. The regions of the die that contacts the forged material for longer periods are more severely worn than other areas.

Figure 8 depicts the hardness of the dies gradually decreased because of its exposure to increased temperature. Figure 9 shows the initial die hardness which is represented by number 1 in x-axis largest hardness drop of the dies occurred at point 5 of about 31 HRC which was measured in the forming area of the fastener head, where the upper and lower dies were subjected to plastic deformation. In addition, the hardness degradation of the lower dies was greater than that of the upper die, owing to the lower die having longer contact with the heated workpiece during the hot forging process. This leads to the failure of the dies earlier than expected. Also, the result of the examination of the scale shows that its hardness reached 38 HRC, which was higher than the surface die hardness after the decrease in the edges, especially in the forming area. Region No. 5 in the lower and upper dies were softened from the periodic thermal-mechanical loads. It's action well caused oxidative stress.

Figure 9 shows the master curve of the criterion for plastic deformation of the die (56NiCrMoV7). From Figure 10, an equation is found by using a polynomial fit curve method. The hardness of the die could be calculated by Eq. (4); the value of \( t_h \) could be obtained from Eq. (3) by the FE analysis. The determination of the critical hardness of the die when it causes plastic deformation is crucial. This approach is an improvement in the forming process.

\[
\text{Hardness} = 42 + B_1 t_h + B_2 t_h^2 + B_3 t_h^3 + B_4 t_h^4
\]

where \( B_1, B_2, B_3 \) and \( B_4 \) are obtained from Figure 10 and \( t_h \) is the operation forging time (h).

By reviewing and analysing the data obtained from the analysis, the die service life can be specified, which mainly depends mainly on the temperature distribution of the dies, the stress point concentrations, and the hardness values at these points. In reality, when the time required to replace old equipment is included, as well as situations of unanticipated tool damage, these costs can increase by 30–50% [26]. This approach represents an achievement in predicting failure and allows for the possibility of carrying out the necessary treatments to avoid the occurrence of an early failure.
(a) Forging temperature 950°C – lower die (temperature – equivalent stress)

(b) Forging temperature 1000°C – lower die (temperature – equivalent stress)

(c) Forging temperature 1050°C – lower die (temperature – equivalent stress)

(d) Forging temperature 1100°C – lower die (temperature – equivalent stress)

(e) Forging temperature 1150°C – lower die (temperature – equivalent stress)

Figure 7: Analysis of temperature and equivalent stress of lower die at points 1 and 2
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Figure 8: Analysis of temperature and equivalent stress of upper die at points 1 and 2

(a) Forging temperature 950°C – upper die (temperature – equivalent stress)

(b) Forging temperature 1000°C – upper die (temperature – equivalent stress)

(c) Forging temperature 1050°C – upper die (temperature – equivalent stress)

(d) Forging temperature 1100°C – upper die (temperature – equivalent stress)

(e) Forging temperature 1150°C – upper die (temperature – equivalent stress)
### Table 2: Lower die service life in terms of plastic deformation

| Initial die temperature (°C) | 950 | 1000 | 1050 | 1100 | 1150 |
|-----------------------------|-----|------|------|------|------|
| Equivalent die temperature (K) | 552.58 | 596.41 | 553.2 | 614.51 | 552.65 | 581.53 | 551.4 | 582.63 | 546.22 | 561.31 |
| Equivalent stress (MPa) | 143.82 | 131.2 | 136.11 | 134.26 | 112.23 | 142.28 | 116.19 | 123.04 | 118.43 | 119.38 |
| Tempering parameter M | 11.37 | 12.1 | 11.27 | 12.47 | 11.38 | 11.98 | 11.36 | 12 | 11.36 | 12 |
| Life time (h) | 1.78 | 1.33 | 1.83 | 1.82 | 1.823 | 1.823 | 1.83 | 1.81 | 1.826 | 1.815 |
| Product quantity (P) | 1066 | 796 | 1096 | 1090 | 1092 | 1092 | 1093 | 1087 | 1093 | 1087 |

### Table 3: Upper die service life in terms of plastic deformation

| Initial billet temperature (°C) | 950 | 1000 | 1050 | 1100 | 1150 |
|-----------------------------|-----|------|------|------|------|
| Equivalent die temperature (°C) | 623.27 | 578.38 | 595.3 | 573.83 | 590.77 | 565.73 | 585.57 | 565.94 | 578.16 | 559.61 |
| Equivalent stress (MPa) | 116.9 | 119.52 | 98.97 | 106.4 | 109.95 | 118 | 99.78 | 103.18 | 109.13 | 98.76 |
| Tempering parameter M | 12.84 | 11.915 | 12.26 | 11.822 | 12.17 | 11.65 | 12.06 | 11.66 | 11.91 | 11.53 |
| Life time (h) | 1.824 | 1.823 | 1.81 | 1.825 | 1.822 | 1.8 | 1.813 | 1.82 | 1.82 | 1.828 |
| Product quantity (P) | 1092 | 1092 | 1084 | 1093 | 1091 | 1083 | 1086 | 1091 | 1091 | 1095 |

### Figure 9: Upper and lower die hardness

### 4 Conclusions

As a result of this research, a helpful strategy has been developed. The simulation of plastic deformation in forging dies was performed with FEM. Die hardness rapidly decreased as die temperatures rose as a result of the contact between the dies and the heated workpiece. Having more contact, the lower die lost more hardness than the higher die. Additionally, the hardness was very low at the forming area, region number 5, less than the critical hardness of the dies, which ultimately led to plastic deformation at these spots. The optimisation of the forming process is possible by adjusting the forging temperature once the plastic de-
formation has been evaluated using FEM. When heated to 1000°C, the lower die was most productive, and the upper die was most productive when heated to 1150°C. Therefore, 1000°C was determined as the optimal temperature for producing the fastener head. This represents time and cost savings by reducing the forging temperature. To optimise the formation process and anticipate die operational life, FEM is a valuable tool.

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