Numerical Simulation of Hot Forging Process of KIA Car Brake's Output Shaft

Saeid Hashemian, Peyman Mashhadi Keshtiban*
Faculty of Mechanical Engineering,
Urmia University of Technology, Urmia, Iran
E-mail: itm.hashemian@gmail.com, m.keshtiban@mee.uut.ac.ir, pmkmech@gmail.com
*Corresponding author

Abuzar Es'haghi Oskui
Department of Mechanical Engineering, College of Engineering,
University of Tehran, Tehran, Iran
E-mail: aeoskui@ut.ac.ir

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Abstract: The present study investigates the production process by closed die forging method of one of the sensitive and safe parts of KIA car brake, which is affected by various mechanical and thermal stresses in its operating conditions; therefore, in the present research, the application of this forming method in the Iranian automotive industry has been discussed. In this study, an attempt was made using finite element analysis in ABAQUS software to determine the maximum force required for forging this part. In addition, the influence of various parameters such as the temperature of the part during the forming process, the coefficient of friction between the part and the die, as well as the strain rate have been investigated. The results indicated that the friction coefficient has a significant effect on the maximum required force, and the maximum values of the load increase with increasing the friction coefficient; but the remarkable result is that the effect of this coefficient is negligible from a value onwards. This point is consistent with the observations in practice. Besides, a strong dependence of the results on the loading speed was observed, and the required force has increased with increasing loading speed for reasons such as the strain hardening phenomenon. Also, the force required for forging has decreased with increasing the temperature, which is due to reduced material strength. This reduction from 900°C to 1000°C is less than 2%, while it is approximately 40% from 1000°C to 1100°C, which is consistent with the experimental reports.

Keywords: Hot Forging, Finite Element Simulation, Loading Rate, Friction Coefficient, Temperature.

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Biographical notes: Saeid Hashemian received his MSc in Mechanical Engineering from Urmia University of Technology in 2022. He is also a supervisor at Iran Tractor Manufacturing Company. **Peyman Mashhadi Keshtiban** is an Assistant professor of Mechanical Engineering at Urmia University of Technology, Iran. He received his PhD in Mechanical Engineering from University of Tabriz in 2016. His current research interest includes Metals Forming and Materials Science. **Abuzar Es'haghi Oskui** received his PhD in Mechanical Engineering from University of Tehran in 2020. He's currently a researcher at the University of Tehran, where his research interest includes Fracture Mechanics and Metals Forming.

Research paper

1 INTRODUCTION

Forging methods usually have little or no waste and can create the shape of the final piece in a short time in one or more stages of pressing or hammering. Since these parts are considerably close to the dimensions desired by the manufacturers, the need for material removal methods and machining is significantly reduced, which will lead to a great deal of savings in material and energy consumption. In some cases, it is necessary to perform a series of final operations on the product after forming like various heating treatments to reduce the defects of forging parts. Due to the mentioned advantages, extensive studies have been carried out so far, focusing on experimental tests and finite element simulations of the forging process. Forging operations are usually performed at high temperatures, especially for parts with large dimensions. Therefore, the die's material must have the needed strength and toughness at these temperatures. Besides, these parts must have high hardenability to be exposed to uniform hardening.

It is evident that lubricants also strongly affect the rate of friction and wear between the part and the die. By applying finite element tools, useful information can be obtained about the forging of the desired part and the effect of various parameters on it; finite element simulation enables the necessary changes in the die's geometry, which leads to a significant reduction in costs. Before forging dies are applied in production, they are tested to confirm that the die cavities can be appropriately filled. Due to the high cost of machine tools and reduced productivity in the use of production equipment in new processes, finite element simulation is a considerably important tool for developing new or more advanced processes [1-2]. FEM results demonstrated that, to produce the desired shaft with suitable mechanical properties and geometric forming, it is necessary to identify the material flow, strain, strain rate, required forging force, and temperature history during deformation [3].

The finite element method is a precise and important method for studying the deformation of the material and the conditions of the deformation process in metal forming and is extensively applied to design and predict the forging process [4-5]. In order to simply find the effects of a series of input parameters; the output of the process is presented by finite element method [6]. Zhank et al. (2009) [7] studied the flow lines of a complex-shaped disk in the isothermal forging process. In this study, the material flow has been investigated using a two-dimensional finite element simulation process. The parts of the workpiece with material flow defects such as folding and twisting and internal cutting have been resolved by making changes in the forging process design and initial billet dimensions. In 2008, Lv et al. [3] performed a three-dimensional simulation of the gas turbine compressor forging stages. In this research, the forging stages of the blade from the initial billet to the final blade were simulated and investigated three-dimensionally.

In this research, the compressor's blade is made of stainless steel, and Deform-3D has been applied for simulation. Ou et al. (2017) [8] carried out finite element modeling and optimization of the final shape's forming process with uncertainties. In this investigation, Monte Carlo simulation, response surface methods, and probable point analysis were used to quantify the potential properties of dimensional and geometrical errors in the final shape's forming processes. Sadeghi and Khosravi (2008) [9] designed the precision forging dies of gear pinion of the PEUGEOT 405 in a parametric manner. The manufacturing of gears is a significantly specialized work due to their complex contours and high precision that the teeth require. Compared to conventional methods, design and manufacturing of these gears using a precision forging process, saves raw materials and production time and improves mechanical properties.

In this research, different parameters and variables of gear design and the subjected forging process were investigated, and a simple gear pinion was parametrically designed, analyzed, and manufactured [10]. Another study conducted in 2020 by Yazdi et al. [11] investigated the mechanical properties and microstructure of hot-forged aluminum parts. In another study, the tensile and impact behavior of aluminum composite produced by hot forging has been investigated [12]. In another study in 2021, the improvement of mechanical and thermal properties of the material, manufactured by hot forging has been reported [13]. In this study, the material's density, flexural strength, fracture toughness, and thermal conductivity have increased by approximately 2%, 23%, 45%, and 90%, respectively.

It was concluded that forging operations have a great potential to improve material performance. In 2020, Dareini et al. [14] investigated the effect of adding Al2O3 nanoparticles on improving the fatigue behavior of AZ31B magnesium alloy under hot forging. Choi et al. [15] optimized the process parameters and die design by finite element method and expressed the environmental advantages of this production by developing a hot forging method of the closed die with flashes to manufacture a type of gear made of Ck45 steel. Zhuang et al. [16] investigated the effect of three parameters namely speed, friction, and initial temperature of the car front axle beam made of CK45 steel and produced by hot roll-forging method on the process force and tolerance, temperature distribution, and deformation inhomogeneity after completing the process. They presented in their results, which were obtained from experimental data and through finite element method, that in contrast to other parameters, the initial temperature of the part has a negligible effect on tolerance. Also, they concluded that the most significant effect on the temperature distribution is related to the speed and the initial temperature of the workpiece; the friction parameter does not play a significant role in this case.

According to the research background, it can be seen that many studies have been conducted on the hot forging of car parts as well as parts with complex shapes, but the hot forging process of KIA car brake's output shaft, which has been thoroughly investigated in the present study, has not been reported previously. Nowadays, the effect of parameters such as strain rate, temperature and friction in the forging process of the studied piece is one of the questions raised in the Iranian automobile industry that has been tried to answer in this study. Hence, in the present research, it was attempted to determine the maximum process load required for forging this part using finite element analysis in ABAQUS software. Moreover, the number of residual stresses developed in part has been investigated. The effect of various parameters such as the temperature of the part during the forming process, the rate of friction between the part and the die, and the strain rate or loading speed concerning this part made of CK45 steel, have been investigated.

Fig. 1 The forging machine used to produce the output shaft.

(a) (b)

Fig. 2 (a) The final part of the brake's output shaft after machining; (b) The final part of the brake's output shaft after forging.

2 MATERIALS AND TEST METHODS

The production process of the car brake's output shaft starts with closed die hot forging with flashes, and the part is prepared after several stages of machining operations. In the following, a summary of the operations performed on the part is presented. First, the initial piece made of CK45 steel with a diameter of 18 mm and a height of 65 mm is heated to a maximum temperature of 950-1050 °C and is pressed with a 60-ton press machine during the closed die forging operation with flash. After cooling the forged part, turning and tapping are performed in two stages, and then the final part is manufactured. The image of the machine used and the manufactured part are seen in "Figs. 1 & 2", respectively.

The workpiece is made of CK45 steel, and the percentage of the material components was obtained according to "Table 1" by chemical analysis of one of the parts. The temperature-dependent mechanical properties are according to "Fig. 3", which have been used in finite element analysis.

Table 1 Chemical composition of CK45 used in car brake's output shaft

Components	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
Weight Percentage (%)	0.46	0.38	0.45	0.018	0.004	0.38	0.03	0.08	0.00

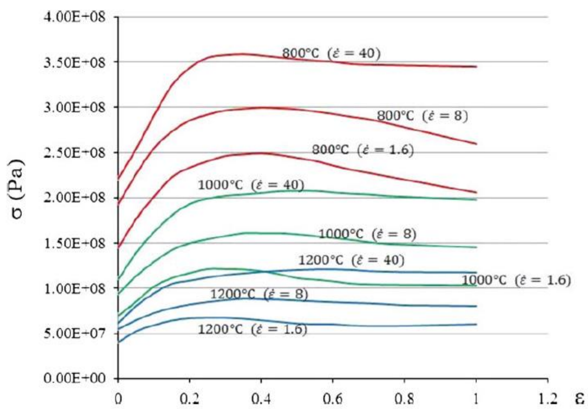

Fig. 3 Stress-strain curve of CK45 alloy steel at different temperatures and strain rates [11].

The first step in modeling is to extract the material's properties at all other required temperatures and conditions. In the present research, first, by fitting a surface on the given materials' properties, the function related to the material properties can be extracted. For this purpose, Design-Expert software has been applied, and the three-variable model has been employed with the variables temperature, strain and plastic strain rate, and yield stress output. The output result of a three-variable surface equation will be according to "Eq. (1)", which can extract the yield stress in any condition by placing the inputs.

$$\sigma_y = 1233.5 - 1.96\ T + 10.04\ R + 282.42\ PS - 3.5\times10^{-3} T\times R - 0.09\times T\times PS + 1.18\ R\times PS + 7.88\times10^{-4} T^2 - 0.12\ R^2 - 183.32\ PS^2 \quad R^2 = 0.9697 \tag{1}$$

Since hot forging is desired in the present study, changes in mechanical properties with temperature are required. In order to facilitate the use of these properties in finite element analysis, the equation governing the values of Young's modulus is in accordance with "Eq. (2)" by fitting the curve, the change of which along with the variations in the yield stress are presented in "Fig. 4". It is noteworthy that the Poisson's ratio and the density of the alloy were 0.3 and 7800 Kg/m^3, respectively.

$$E(T) = -2\times10^{-5} T^2 - 7.27\times10^{-2} T + 214.7 \quad R^2 = 0.99 \tag{2}$$

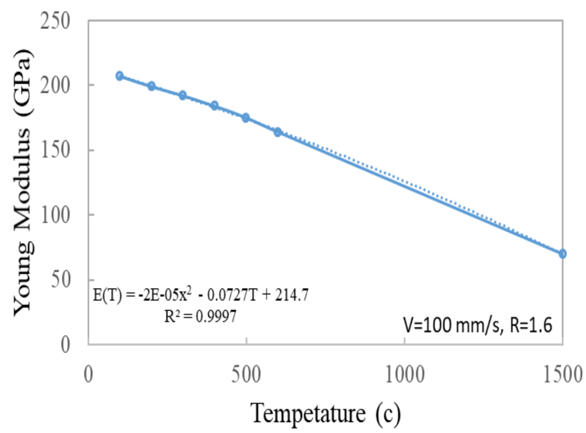

Fig. 4 Changes in the values of Young's modulus at different temperatures.

The curve of yield stress change in terms of these three variables is as follows and the corresponding curve are presented in "Fig. 5".

$$\sigma_y = 1233.5 - 1.95T - 183.32PS^2 \tag{3}$$

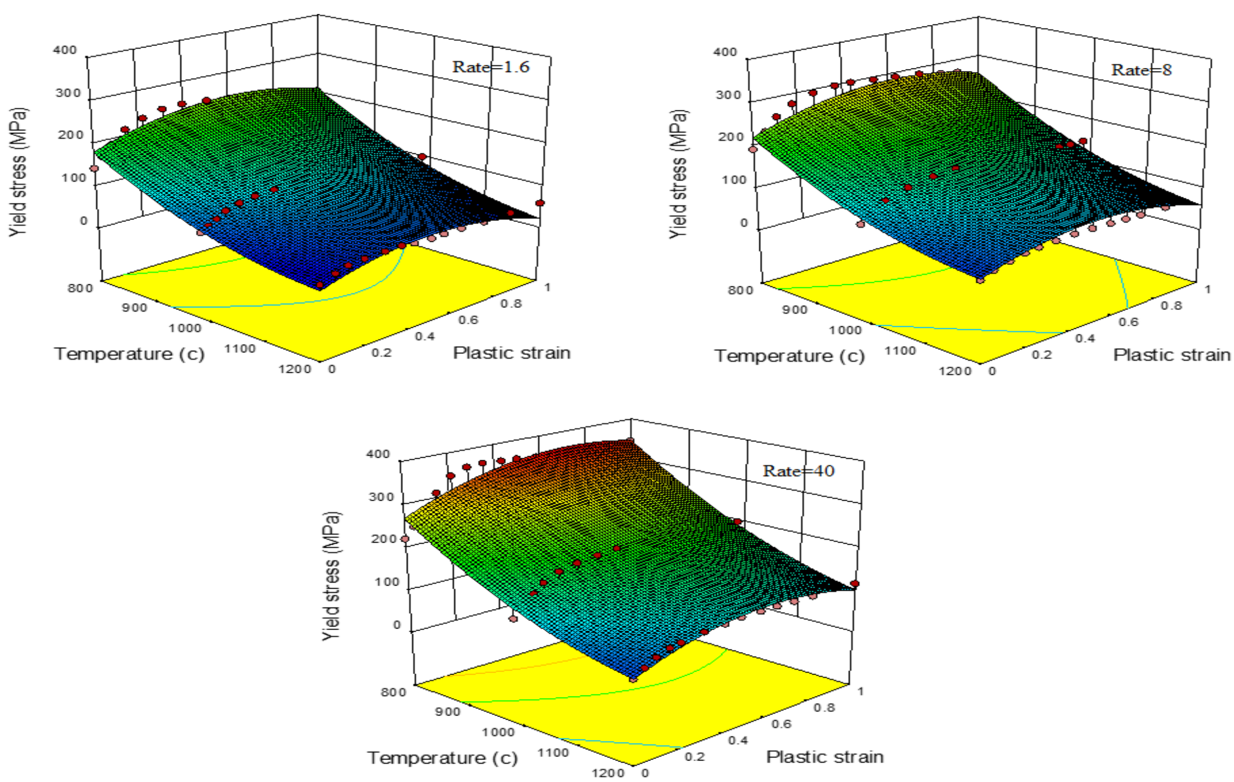

Fig. 5 Changes in the yield stress values in terms of different values of temperature, strain rate, and plastic strain.

Therefore, changes in the parameters required for finite element analysis of the forging process of the desired part are available in different conditions and can be used in the analysis. As a validation, yield stress values in terms of plastic strain are obtained according to “Fig. 6” at a temperature of 900 °C and a strain rate of 1.6.

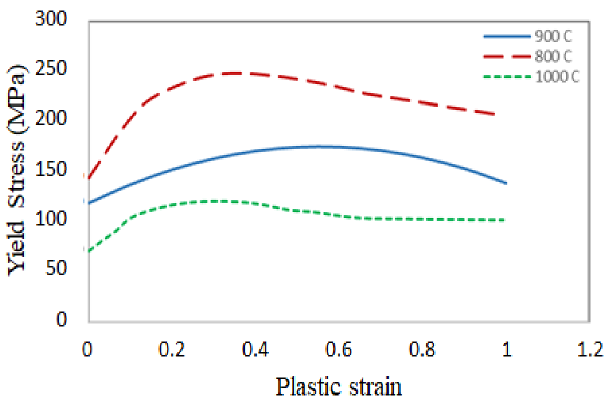

Fig. 6 Comparison of the values calculated by the equation extracted in the present study for the temperature of 900 °C with the values presented in the reference [11].

In order to ensure the validity of the extracted equations, the values related to the temperature of 900°C have been compared with the values presented in the reference [11], which correspond to the temperatures of 800°C and 1000°C; this comparison is presented in “Fig. 6”. As can be seen, the values are significantly reasonable and can be applied in forging analysis at 900°C.

3 GOVERNING EQUATIONS

The maximum force required in forging is one of the primary limiting parameters in manufacturing a part. To achieve the maximum force required in closed die forging with axial symmetry, the “Eqs. (4) and (5)” are obtained using Von Mises criterion and maximum shear stress force (Tresca), respectively [17]:

$$F_{\max} = \sigma_f \pi \left[\frac{a}{4} + \frac{d_G^2}{12\sqrt{3}s} + \frac{2}{3}\mu \left(\frac{a^3 - d_G^3}{8s} \right) \right] \quad (4)$$

$$F_{\max} = \sigma_f \pi \left[\frac{a^2}{4} + \frac{d_G^3}{24s} + \frac{\mu}{12s}\left(a^3 - d_G^3 \right) \right] \quad (5)$$

Where, dG is the diameter, s denotes the thickness of the flash, and σf implies the yield stress. The friction coefficient μ is usually considered in the range of 0.3 to 0.5. The explanation of vertical and radial stresses in a pressurized plane is provided by “Eq. (6)” [18]:

$$\sigma_z = -\sigma_f \left[1 + 2\mu \frac{x}{h} \right] \quad (6)$$

Where, x is the distance from the edge of the die and h denotes the height. By an appropriate approximation, the above equation can be used in the form of “Eq. (7)”:

$$\sigma_{z\max} = -\sigma_f \left[1 + 2\mu \frac{r}{s} \right] \quad (7)$$

4 FINITE ELEMENT ANALYSIS

The forging process of manufacturing this part has been simulated as axisymmetric two-dimensional in ABAQUS finite element software due to the symmetry in the geometry and boundary conditions. The main process parameters such as press speed, workpiece temperature, and friction coefficient have been collected from experimental data, a range of commonly used numbers in practice, and other studies and applied during the finite element simulation process [11], [19]. The part and die have been modeled as axisymmetric two-dimensional according to “Fig. 7”. The units used in the model are in millimeters.

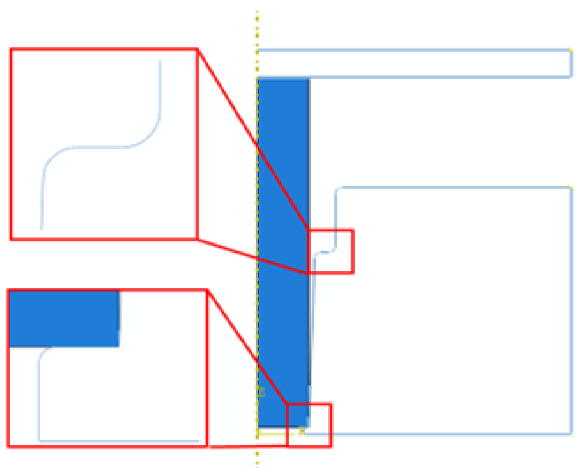

Fig. 7 The part and die modeled asymmetrically.

The samples have been modeled in ABAQUS software and analyzed under the conditions mentioned in the following. The properties of the material are according to the equations extracted in the previous sections, and the analyzes have been performed at temperatures of 900-1050°C and intervals of 50°C. Besides, according to the information collected from the machine used for forging, the strain rates are considered to be 1.6, 8, 20, and 40. Moreover, the friction coefficient values between the part and the die are equal to 0.4 to 0.6 and at intervals of 0.05 to determine the effect of each of these parameters. Also, due to the high strength of the die compared to the part and the purpose of forging, the die has been modeled as a rigid part.

It should be noted that the adaptive mesh technique has been applied to update the mesh at each stage of the analysis to prevent the elements from becoming distorted during large deformations throughout the forging process. The meshing of the piece is shown in “Fig. 8”; eight-node square elements with axial symmetry have been used. The elements have also been considered small enough to allow stress changes to be accurately achieved and obtain mesh independency.

The stress contour of the analysis performed in different sections can be seen in “Fig. 9”. The location of stress distribution, maximum stress, and stress concentration regions are also shown in the figure. The stress changes from the center of the part to the end in different sections are shown in “Fig. 10”.

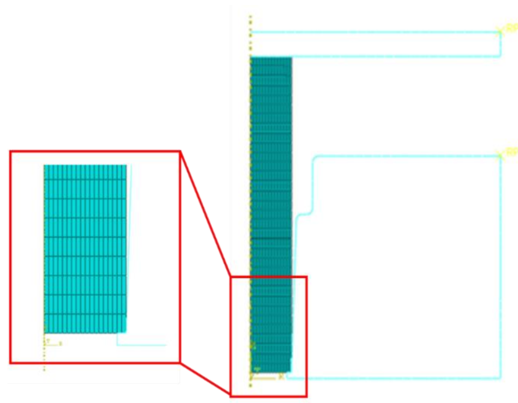

Fig. 8 The meshing used in software simulation.

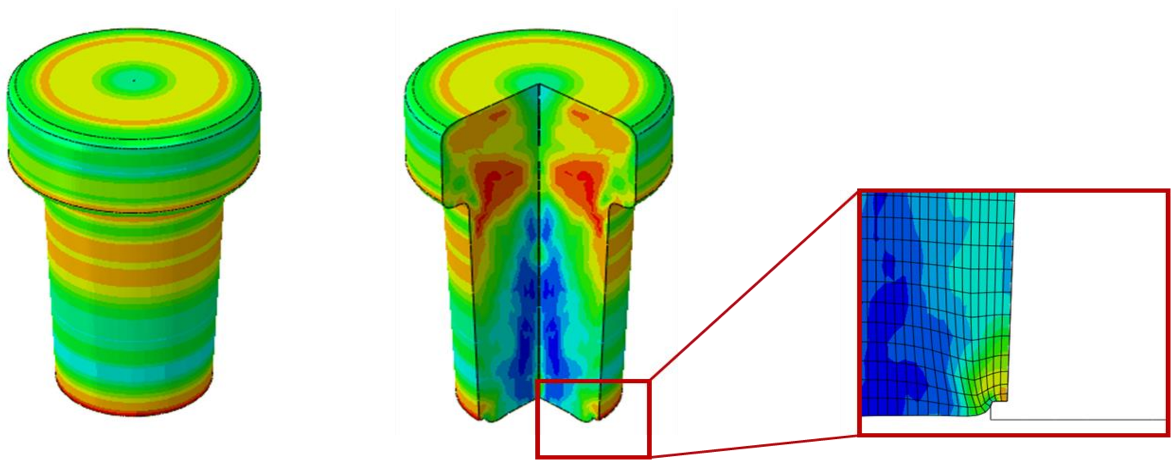

Fig. 9 Stress contour resulting from the analysis of the forging process.

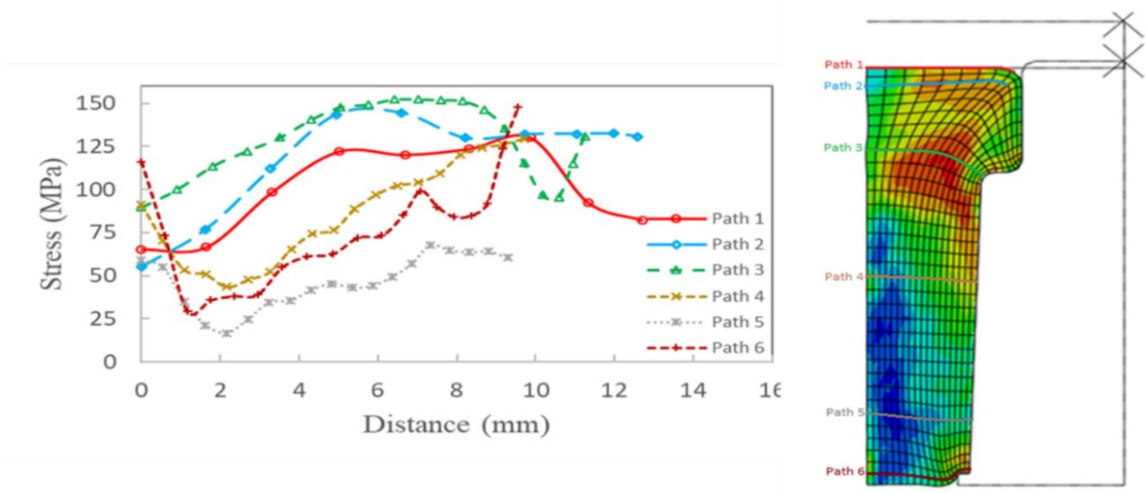

Fig .10 Stress changes in the radial direction at different sections.

However, in forging, the important factor is the maximum force required to forge the desired part under certain conditions. As previously mentioned, different temperature, loading, and friction conditions have been investigated in the present study. An example of changes in the amount of force applied by the jaw of a press machine in Newtons during forging (time in seconds) can be seen in "Fig. 11". Although in this figure, the maximum force is related to the last moment of forging, it should be noted that the maximum force will not necessarily be the maximum load in the last forging step and can occur at any stage depending on the geometry of the die, sample, and problem conditions.

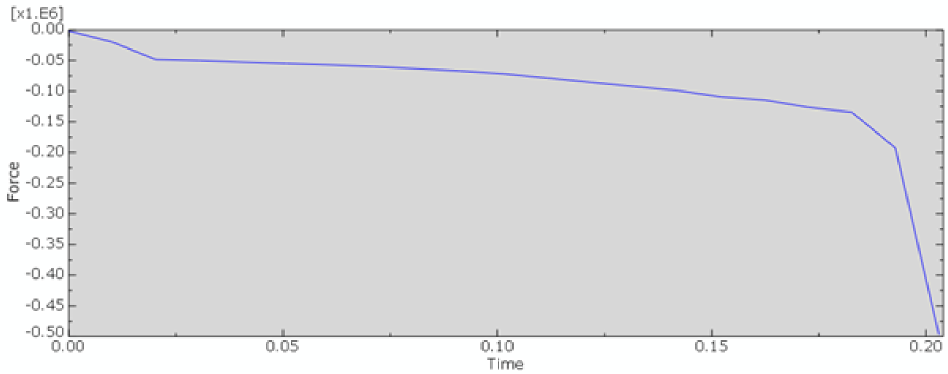

Fig. 11 The changes in the maximum force required to forge the studied part.

5 RESULTS

First, different analyzes were performed to analyze and recognize the effect of each parameter on the maximum force required for pressing the desired part and the effect of strain rate under the same conditions, the effect of temperature at three different temperatures and the same conditions, and also the effect of friction coefficient under the same conditions are presented in "Figs. 12, 13 & 14", respectively.

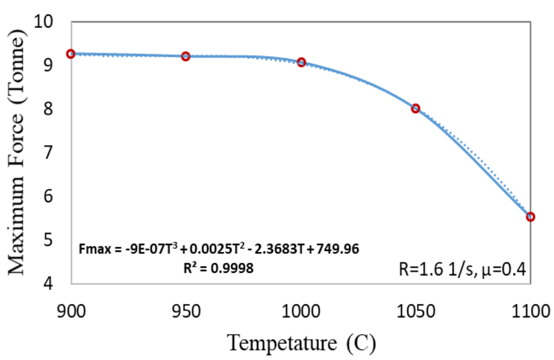

Fig. 12 The changes in the values of the maximum load applied during forging and at different temperatures.

As can be seen, with increasing temperature at a constant strain rate, the maximum force required for forging has decreased, which was not unexpected and was due to the decrease in the strength of the material. However, it is noteworthy that this reduction from 900°C to 1000°C is less than 2%, while it is approximately 40% from 1000°C to 1100°C, which is consistent with the experimental reports observed in the workshops. Moreover, the curve-fitting on it can be seen in "Fig. 12" and "Eq. (8)". The effect of strain rate at a constant temperature of 900°C, friction coefficient of 0.4, and the corresponding curve is shown in "Fig. 13". It is clear that the maximum required load is significantly increased with increasing the strain rate; the main reason for this increase can be interpreted as the occurrence of strain hardening phenomenon in the part.

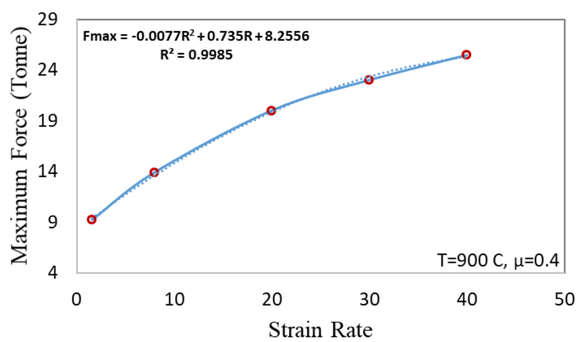

Fig. 13 The changes in the maximum load values applied during forging and at different values of strain rate.

Afterward, according to the reference [11], the effect of the friction coefficient has been investigated in the range of 0.4-0.6, as shown in "Fig. 14". The remarkable result is that, as expected, the maximum values of the load increase with increasing the friction coefficient, but the effect of this coefficient is negligible from some values onwards. This point is also consistent with the observations in practice because, in reality, the surface of the sample and the die are practically locked together with increasing the friction coefficient from a certain extent, and more increasing the coefficient is ineffective.

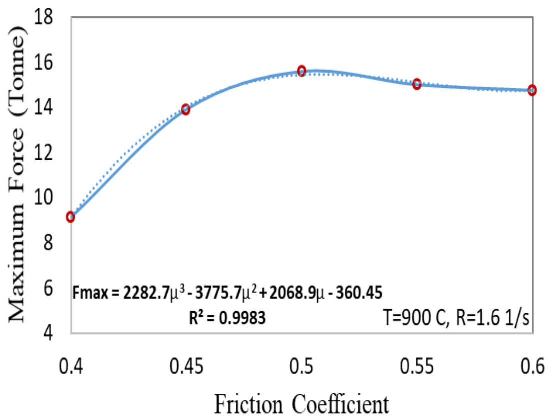

Fig. 14 The changes in the values of the maximum applied load during forging in different values of friction coefficient.

$$F_{max} = -9\times10^{-7}T^3 + 2.5\times10^{-3}T^2 - 2.3683T + 749.96 \quad R^2 = 0.99 \tag{8}$$

$$F_{max} = -7.7\times10^{-3}R^2 + 0.735R + 8.26 \quad R^2 = 0.99 \tag{9}$$

$$F_{max} = 2282.7\mu^3 - 3775.7\mu^2 + 2068.9\mu - 360.45 \quad R^2 = 0.99 \tag{10}$$

Figure 15 indicates the simultaneous effect of temperature and strain rate on the values of the required maximum force as a surface plot in the friction coefficient of 0.4, and "Eq. (11)" is its corresponding equation.

The effect of strain rate is far greater than the effect of temperature. According to "Fig. 16", it is reasonable that using the maximum temperature along with the minimum strain rate and minimum friction will lead to the minimum force required for forging, but the speed is not controllable in many forging machines, and at best, several specific speeds can be used that there must be a balance between the loading rate and the production speed of the parts. On the other hand, the maximum load decreases with increasing temperature, but according to the results, the maximum applicable temperature in CK45 alloy is 1000 °C in practice, and at higher temperatures, a sharp drop in strength occurs due to structural changes and coarser grains. However, the friction coefficient is one of the parameters that can be controlled in many cases by applying low-cost lubrication methods.

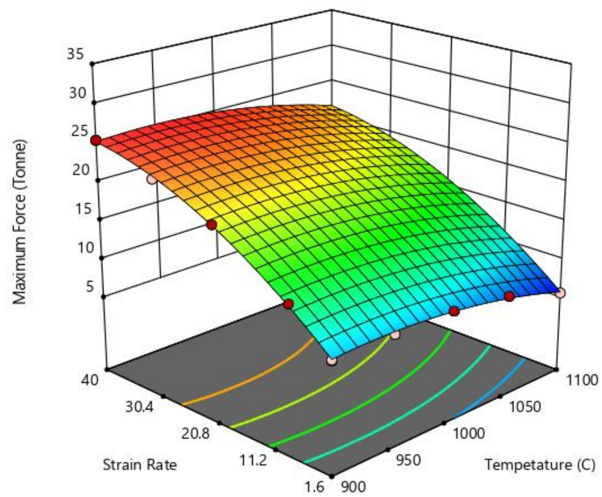

Fig. 15 The changes in the values of the maximum applied load during forging in terms of temperature and strain rate at a friction coefficient of 0.4.

According to mentioned issues, it is observed that experimental limitations usually prevent the freely changing of temperature and strain rate during the forging process, and the use of other methods such as changing the geometry of the part or multi-stage forging along with the mentioned methods might be suitable.

$$F_{max} = -1.51T^2 - 2.90R^2 - 3.59\mu^2 - 1.83T + 7.98R + 2.52\mu + 26.01 \qquad R^2 = 0.99 \tag{11}$$

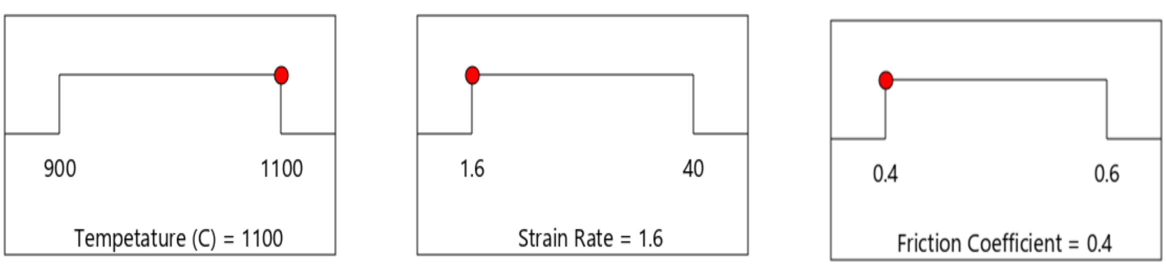

Fig. 16 The values that lead to the minimum force required for forging.

6 CONCLUSION

In the present article, the numerical simulation of the forming process of a particular part in the automotive industry was performed. During the research, the effect of various parameters such as temperature, strain rate, and friction coefficient between the die and the part on the maximum load required for forging was investigated. The result is that the temperature is in inverse relation to the maximum force required, but the alloy experiences a sharp drop in strength as the temperature exceeds 1000°C. Moreover, for reasons such as strain hardening, the value of required force increases with raising the loading rate. It was also observed that the value of the required force increases with raising the friction coefficient, but its effect becomes negligible from some values onwards. Therefore, the friction coefficient is a parameter that can be controlled in many cases by applying low-cost lubrication methods. Besides, a separate equation is provided to estimate the maximum force required in terms of each of the studied parameters, so that future research to be independent of finite element analysis. It is noteworthy that the maximum force of the jaw did not exceed 25 tons in all studied cases. However, the 60-ton press machine is applied to produce this piece. The machines with lower capacities can be used for performing forging operations even with reasonable reliability.

7 NOMENCLATURE

T : Temperature

F : Punch force

V : Punch speed

μ : Friction coefficient

R : Strain rate

E : Young's modulus

S : Flash's thickness

H : Punch height

σ_y : Yield stress

D_G : Punch diameter

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