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RESEARCH PAPER

Practical Study and Finite Element Simulation of Production Process of the Bush of Gearbox of Mercedes-Benz 10-Wheel Truck by Closed Die Forging

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Abstract

Nowadays, the closed die forging process is extensively applied to produce small to medium parts. The parts produced by this method show high strength, impact resistance, and toughness, which is the main advantage of this method compared to casting. Furthermore, the parts produced by this method are considerably close to the final shape of the designed part in terms of appearance compared to the open-die forging process, and the need for secondary operations such as finishing after the subjected process is significantly reduced. The present work investigates the production process with closed die forging of one of the most important parts of the gearbox of Mercedes-Benz 10-wheel truck, which is affected by various mechanical and thermal stresses in its working conditions. Finite element simulation results in ABAQUS software have been applied to analyze experiments for the purpose of evaluating the extent and type of impact of some important process parameters and also compared with the observed practical results. The results indicated that the initial temperature parameter of the workpiece has the highest effect on reducing the flow stress, and consequently, the required maximum force throughout the process. While the other evaluated parameters, i.e., press speed and mold temperature, have a smaller but undeniable impact.

Keywords: Closed die forging, Hot forming, Finite element simulation, Optimization.

1. Introduction

In any metal forming process, including forging, process simulation is an essential step in designing and preparing the right tools. Doing this procedure allows the production designers in the forging industry to select raw materials with desirable physical properties (such as the fluidity of the material inside the mold, possible process defects such as folding or insufficient amount of raw material in the mold) and predict the production process with high approximation and then by integrating the results of these studies and considering the response to the required expectations of the final product, make appropriate decisions in selecting the main and controllable parameters and operators of the production. Today, despite numerous studies in the field of metals forging, little attention has been paid for recognizing and simultaneously examining the manner and extent of controllable inputs of this ancient process. In the present work, some of these vital parameters and their type of operation on some dependent output quantities have been analyzed in detail and validated by the results of other studies.

Murugesan and Jung [1] optimized the constant coefficients of the Johnson-Cook mechanical behavior prediction criterion for AISI 1045 carbon steel by experimental tests and numerical analysis under different conditions in terms of temperature and strain rate. By numerical and graphical comparison of the results yielded from the experimental data and the obtained structural model, it was concluded that the prediction of the behavior of the material

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by the optimized model is relatively precise under low-temperature conditions and different strain rates. Zhuang et al. [2] investigated the effect of three parameters namely speed, friction, and initial temperature of AISI 1045 steel front axle beam produced by hot roll-forging method on tolerance, temperature distribution, final deformation and process force. They stated in their obtained results from experimental data and finite element method that the initial temperature of the part shows the small effect on tolerance on the contrary to other parameters; however, the highest effect on the temperature distribution is related to the initial speed, and temperature of the workpiece and the friction parameter does not play a significant role in this case. They also pointed out that with increasing the forging part's initial temperature, unlike friction, the force required by the process is reduced, and the speed parameter in this process has an insignificant role in the use of mechanical power. Choi et al. [3] optimized the parameters and design of process molds by finite element and experimental methods through developing a closed-die hot forging method with flash to produce a type of gear made of AISI 1045 steel. They addressed the environmental advantages of production with this method, including the amount of consumed energy and the waste, compared to the production only by the machining method. Kim and Choi [4] evaluated the wear of hot forging mold of H13 material for a type of ball connection socket made of AISI 1045 steel through finite element analysis and applying Goodman & Gerber toughness estimation criteria. They estimated the service life of the use of the mold and proved the consistency of their results with the experimental results obtained by the manufacturer. According to their theoretical results, the wear at the flash aggregation zone of the mold was higher than that in other areas. Kim et al. [5] investigated on the rate of wear and the flow regime of the material in preform and final molds. They analyzed the pressure and temperature distribution of pressing a plasticine material in the form of numerical and physical modeling in isothermal and non-isothermal operating conditions. It was concluded that the distribution of the mentioned parameters during the isothermal and non-isothermal processes are slightly different from each other and the maximum forging force in the final molds is approximately three times more than that in the preform molds. They also approved that with the more proper design of preform molds and the use of appropriate cooling lubricants, the molds' temperature and the forging force are significantly reduced, and consequently, the useful life of the molds is increased. Doege and Bohnsack [6] proposed a new approach to reduce the maximum force and also the specific energy of forging both straight-groove and helical gears during the closing step of molds by dividing the precision forging process into two stages. It was also concluded that the effect of isothermal forging on accuracy, microstructure, fluid stress and ductility of the obtained part is undeniable. Bakhshi-Jooybari et al. [7] investigated the maximum load as well as the heat transfer between the workpiece and the mold in the forging process of the closed mold by performing three-dimensional finite element simulations. Due to the conformity of the simulation results with the experimental data, the proposed structural model was considered appropriate to predict the final shape and process variables. Mori et al. [8] reported experimental and numerical analysis on the effects of hot forging and mold quenching operations of some steel parts of car body. The influence of subjected operations on increasing ductility, dimensional accuracy and strength of the production part by considering the parameters of annealing temperature, rapid cooling temperature and lubrication temperature studied accurately. By presenting a new approach in terms of how to perform this type of heating process, they proposed the subjected procedure to achieve the optimal expected quality of the final product. Pruncu et al. [9] investigated the effects of close hot forging on the porosity, grain size and mechanical properties of austenitic stainless steel parts that have been pre-formed by additive manufacturing. The results showed improvement of mechanical properties including improvement of strength, ductility and formation of homogeneous microstructure. Min and Kim [10] proposed a new idea for the integrated production of a car steering wheel yoke using a precision forging process. By performing experimental tests and using finite element simulation, they investigated the hardness values under heat treatment and lubrication conditions and applied the results of this study in mass production of this part. Wilson et al. [11] applied numerical modeling of heat transfer under variable boundary conditions between the workpiece and mold, taking into account such variables like the type of the physical contact of the workpiece with the mold, the oil film coating and the coefficient of friction in hot forging operations by DEFORM 2D software. Referring to the close correlation of the simulation results with the data obtained from practical experiments, they described the proposed model as more accurate than the type of stable heat transfer. Zhang et al. [12] produced a numerical analysis for hot forging process of the car crankshaft production. By examining different factors such as temperature distribution, microstructure and defects formation in possible positions, they optimized the preform models of the part. They considered this model to improve the life of the equipment and compliance that is suitable with mass production facilities. Łukaszek-Sołek et al. [13] studied on hot forging of isothermal closed molds in the production of a typical steel gear aiming to optimize parameters like initial temperature and achievable strain rate, and noted that the microstructural sensitivity of this type of steel to temperature is more than the strain rate. In addition, due to the occurrence of recrystallization in fine grains, upward strain rates and temperatures above 1000°C have been recommended in the process. In another study, optimization was done on two-stage forging process of airfoil blade by Alimirzaloo et al. [14]. Multi-objective genetic algorithm based on a fuzzy method were used to find the optimal amount of parameters in preform and intermediate dies.

The present work investigates the production process with closed die forging of one of the most important parts of the gearbox of Mercedes-Benz 10-wheel truck, which is affected by various mechanical and thermal stresses in its working conditions. Finite element simulation results in ABAQUS software have been applied to analyze experiments for evaluating the extent and type of impact of some important process parameters and results were compared with the observed practical outcomes.

2. Materials and Methods

2.1. Experimental Works

The production process of the gearbox bush starts with closed-die hot forging without flash and becomes ready after several stages of machining operations and finishing the surface of the part.

Initially, the first cylindrical part of AISI 1045 carbon steel with a base diameter of 54 mm and a height of 47 mm is heated to a maximum temperature of 950-1050°C and compressed during the closed die forging operation without flash by a 500-ton hydraulic press (Figure 1 (a, b)).

After cooling the forged part, the ejector pin mark at the end of the part is cut, and the part is drilled along its axis in several steps (Figure 2 (a, b)).

In the final step, boring, longitudinal turning, and facing operations are also performed on the semi-finished part, and then the final part is resulted (Figure 3).

a b

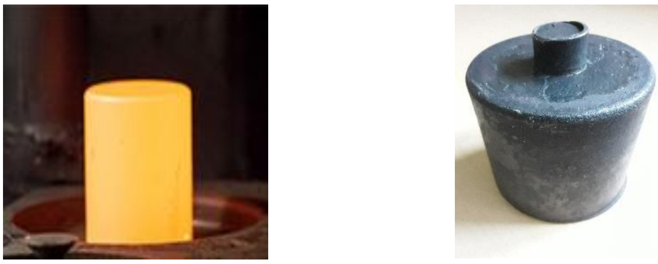

Figure 1. a) initial preheated and b)Final forged part

a b

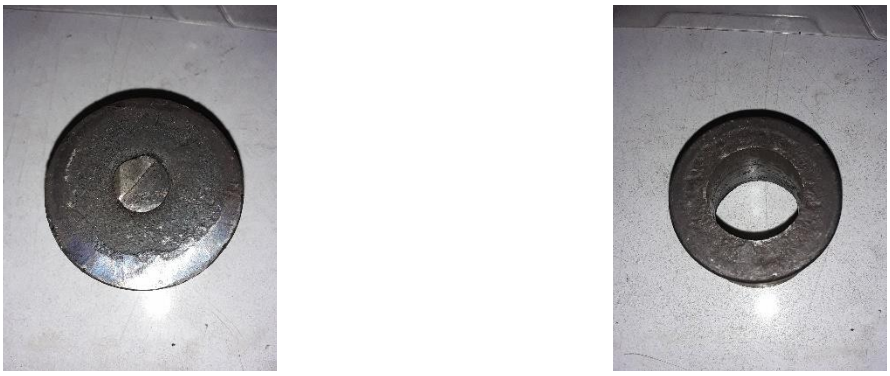

Figure 2. The sample After a) removing ejector pin mark and b) hole drilling in the center zone

Figure 3. Final part

a b

Figure 4. a) upper and lower jaws and b)punch and matrix modeling

2.2. FEM Simulation

The forging process of the production of this part has been simulated in Axisymmetric two-dimensional form in Abaqus/v2019 software. The main parameters of the process such as press speed, the initial temperature of the workpiece and tools, and the coefficient of friction have been collected from experimental data and valid references and applied as the boundary conditions of the problem throughout the finite element simulation process.

The molds have been designed as male and female form and divided into upper and lower jaws. As shown in the actual image of Figure 4, each mold is capable of simultaneous production of four parts. However, only one piece has been produced in FEM simulation to simplify the model and reduce the time and volume of the calculations.

Due to the axisymmetric geometry of punch & matrix, only their cross-section is drawn, and the three-dimensional shape is created by the rotation of the cross-section around the vertical axis. Figure 5 indicates the cross-sectional and angular maps of punch & matrix.

a

b

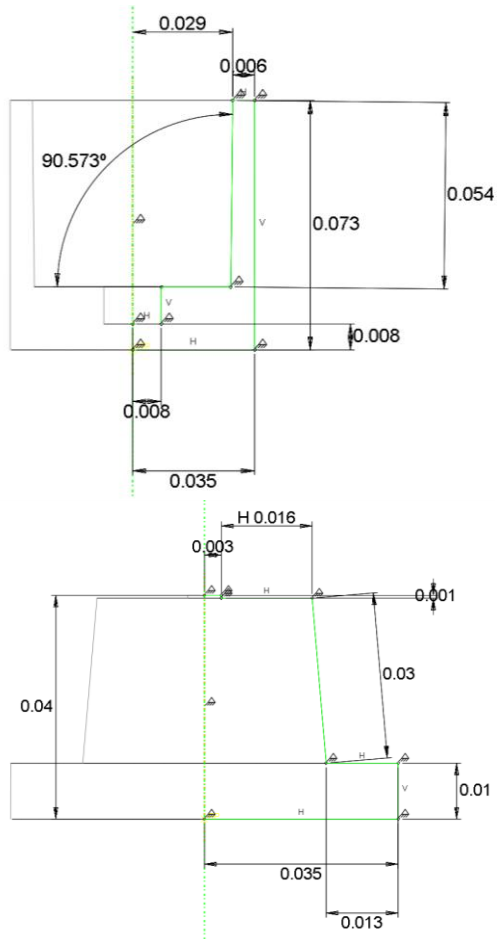

Figure 5. a) Matrix or lower jaw and b) Punch or upper jaw

The forging molds of the production of this part, similar to many hot forging molds, are made of H13 tool steel. The chemical composition of this steel, along with the mechanical and thermal properties used in finite element software, are listed in Tables 1 and 2, respectively.

Table 1. Chemical composition of H13 tool steel [15]

Element	Cr	Mo	Si	V	C	Ni	Cu	Mn	P-S
Content %	4.75-5.50	1.1-1.75	0.8-1.2	0.8-1.2	0.32-0.45	0.3	0.25	0.2-0.5	0.03

Table 2. Physical, mechanical, and thermal properties of H13 tool steel [15]

Properties	Metric	Imperial
Tensile Strength, Ultimate (@20°C/68°F, Varies With Heat Treatment)	1200-1590 MPa	174000-231000 PSI
Tensile Strength, Yield (@20°C/68°F, Varies With Heat Treatment)	1000-1380 MPa	145000-200000 PSI
Reduction Of Area (@20°C/68°F)	50.00%	50.00%
Modulus Of Elasticity (@20°C/68°F)	215 GPa	31200 KSI
Poisson's Ratio	0.27-0.3	0.27-0.3
Density (@20°C/68°F)	7800 Kg/m3	0.282 lb/in3
Melting Point	1427 °C	2600 °F
Thermal Expansion	10.4 E-6 °C	20-100
Thermal Conductivity	28.6 W/mK	215

The workpiece is made of AISI 1045 carbon steel, and its chemical composition and physical and thermal properties are presented in Tables 3, 4, and Figure 6, respectively [16].

Table 3. Chemical composition of AISI 1045 steel

C	Fe	Mn	P	S
0.42-0.50	98.51-98.98	0.60-0.90	≤0.04	≤0.05

Table 4. Physical and mechanical properties of AISI 1045 steel [16]

Properties	Metric Unit
Density	7870 (Kg/m3)
Yield Strength	310 (MPa)
Coefficient Of Thermal Expansion	15 (µm/m. °C)
Poisson's Ratio	0.27
Hardening Temperature (Th)	760 (°C)
Melting Temperature (Tm)	1520 (°C)
Tempering Temperature (Tt)	400 (°C)

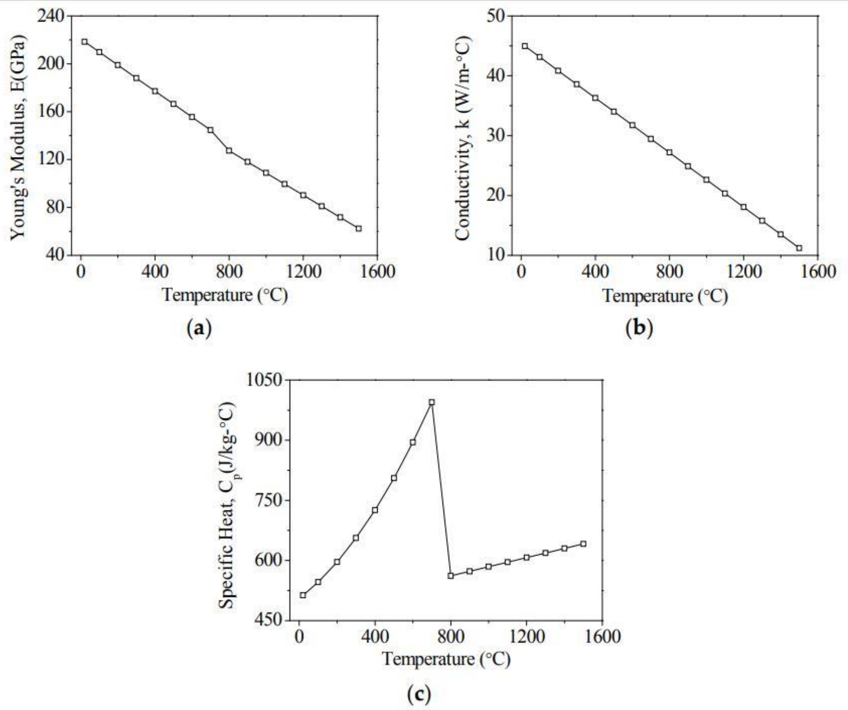

Figure 6. a) Modulus of elasticity, b) Thermal conductivity and c) Temperature dependent specific heat capacity in AISI 1045 steel

The CAX4RT elements abbreviated as square elements with strain and two-dimensional temperature degrees of freedom and four reduced integration points (for the purpose of preventing the common shear locking phenomenon in quasi-static simulations with bending moment) have been used for reaching the initial regular geometry of the workpiece in the Abaqus software simulation. Due to the use of elements with reduced integration points, there is a possibility of occurrence of the Hourglass phenomenon, in which case the element is not capable of feeling the bending force due to improper arrangement of integration points and leads to a significant discrepancy between the analysis results as well as unusual deformations of the element, in order to prevent the occurrence of which, the Hourglass control has been applied in the elements of the workpiece. Due to the occurrence of high and nonlinear deformations in the elements during the formation of the part during the process, the Arbitrary Lagrangian-Eulerian Adaptive Mesh technique, which means the elements adapted to Eulerian and Lagrangian theories, has been used along with the operation frequency and balanced mesh correction in the workpiece area. The use of this technique leads to the material dedicated to the geometry of the workpiece to be easily moved under its elements without creating double distortion.

In the lower and upper molds, quadratic CAX6MT elements with strain and two-dimensional temperature degrees of freedom have been employed along with six integration point of second-order accuracy. For this type of element, the distortion control with a longitudinal performance coefficient of 0.1 has been applied to prevent excessive distortion, especially in the mold's inner wall. The meshed view of the model is illustrated in Figure 7.

2.3. Experimental Design

In the present article, Taguchi's orthogonal arrays method screened with L9 number of experiments has been used to investigate the extent and effectiveness of process controllable variables on responses namely stress, equivalent plastic strain and the force. The levels of evaluated input parameters are presented in Table 5. A comparison has been performed by the responses obtained from the Analysis of Variance (ANOVA). It is noteworthy that all boundary conditions and other input components of the simulated finite element model have been set to be constant during the experiments for accurately investigating the mentioned parameters.

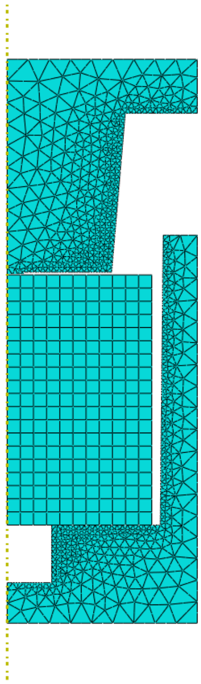

Figure 7. Meshed model in Abaqus software

Table 5. The variable boundary conditions of the process

Parameter / Level	Workpiece initial temp. (°C)	Ram speed (mm/s)	Mold initial temp. (°C)
1	850	30	25
2	950	50	100
3	1050	70	250

2.4. Governing Equations

In order to calculate the maximum force in closed die forging of axisymmetric models using the upper limit and two-dimensional deformation mode and the Von Mises criterion, Equation (1) [17] is used as follows:

$$F_{max} = \sigma_f \pi \left[\frac{a^2}{4} + \frac{d_G^2}{12\sqrt{3s}} + \frac{2}{3}\mu \left(\frac{a^3 - d_G^3}{8s} \right) \right] \quad (1)$$

Besides, Equation (2) [17] is employed for the Tresca criterion as follows:

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

where dG denotes the diameter, s is the flash thickness, and σf implies the flow stress. The coefficient of friction μ is usually considered to equal 0.3-0.5.

For the distribution of vertical and radial stresses in the plate pressure, Equation (3) is presented by Ziebel [18] as follows:

$$\sigma_z = -\sigma_f \left[1 + 2\mu \frac{x}{h}\right] \quad (3)$$

where x denotes the distance from the edge of the mold, and h is referred to as the instantaneous height. This equation can be used with a relatively good approximation as follows: (Equation 4 [18])

$$\sigma_{z\,max} = -\sigma_f \left[1 + 2\mu \frac{r}{s}\right] \quad (4)$$

In the study of industrial processes, the use of Johnson-Cook damage criterion is extensively applied, especially in the finite element forming tools of metals. This criterion has been taken into account by many active researchers in industrial fields due to its relatively well prediction of material behavior and its user-friendliness. However, it is noteworthy that it is impossible to construct a reliable stress model for a wide range of strain rates and temperatures for effective prediction of materials' flexibility behavior.The Johnson-Cook structural equation's relation and coefficients have been applied to define the workpiece's plastic properties into the software, which are demonstrated in Equation (5) and Table 6, respectively.

$$\sigma = [A + B(\varepsilon_p^n)]\left[1 + C ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \quad (5)$$

Table 6. The coefficients of Johnson-Cook plastic properties for AISI 1045 steel

Regular JC Model				
m	C	n	B (MPa)	A (MPa)
0.5655	0.1056	0.5176	176.091	50.103

3. Results

3.1. Finite Element

In order to achieve the desired result in the closed die forging process, it is necessary to observe two conditions: the sufficient amount of the initial blank and its comfortable flow inside the mold tortuosity. The flow of the blank in the pressing operation greatly depends on the shape of the deformation tool. Finite element calculations are usually applied to predict the flow regime and the instantaneous external shape with a high approximation. The flow of material inside the tool starts as the rolling and slipping form and ends by slipping the blank into the mold's empty places.

Figure 8 indicates the extent and type of displacement of elements after the bush's forging process is finished. The area enclosed by the red line represents the jumping level, which has been created as tangential to the ejector pin mark base and at the end of the part (similar to many axisymmetric parts produced by closed die forging). At this surface, the material moves perpendicular to the direction of movement of the upper jaw. This surface also includes plates that separate the elastic deformation from the plastic deformation. Another point to be mentioned about this surface is the change in the material's jumping speed as it moves away from the surface. The vertical black line that divides this plate into two parts is named the Neutral Border. This boundary is exactly coincident to the axis of symmetry of the part, representing the site where the material experiences no lateral movement and can only move in an axial direction. The separation borders are also illustrated by two black arched lines on the workpiece elements in Figure 8. These curved lines represent the area in which the flow of matter is associated with a change in direction.

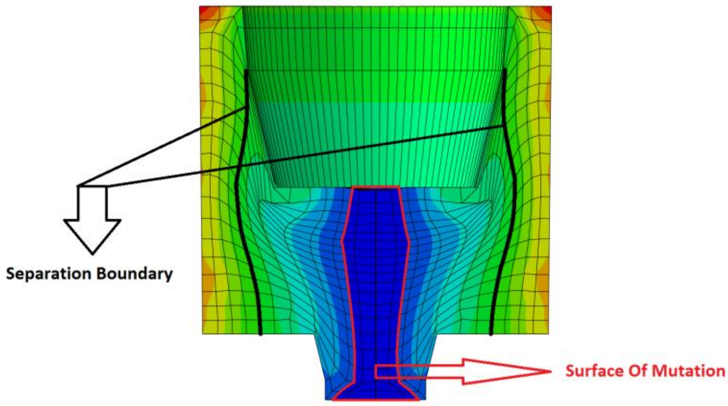

Figure 8. The contour of the flow regime of the material during the process

In closed die pressing, quantitative and qualitative determination of stress components is possible basically by the finite element method at any time and for any deformation position.

The stress distribution on the bush of the gearbox is indicated in Figure 9. It is evident that in the areas of contact of the workpiece with the punch wall or upper jaw, radial stresses (σr) increase with the simultaneous widening and lifting of the blank and as a result of increasing the height of the edges, and also the resultant stress is maximal in the middle areas of the workpiece due to the deformation resistance and axial stresses (σz). The minimum stress is also observable in the lower edge of the lower jaw. In general, it can be concluded that the wear of the punch wall is higher than that in the matrix between the contact areas of the tool with the workpiece.

Figure 10 shows the equivalent plastic strain contour of the hot forging process of the bush. As mentioned previously, the jumping plane and separation borders differentiate the extent and type of deformation in different areas of the part. As expected, the maximum plastic strain occurs in sites with a high amount of blank displacement and especially radial stresses (σ_r)

The deformation resistance especially relates to the filling of edges of deep molds. The force profile of bush production is demonstrated in Figure 11. It can be concluded from evaluating the diagram along with the instantaneous external shape of the forged part that first, the deep areas of the mold are filled, and then other areas are filled with a sharp increase in deformation resistance. Moreover, the punch force gradually increases at the end of the process with the falling of the punch and cooling and filling the edges and the mold's empty spaces. The results of the maximum force applied are in good agreement with the results collected by the product manufacturer, which uses the YHA3_500T model press to produce this part in 4 cavity molds. In fact, in this case, on average, required force to produce each piece at the end of the process and filling the mold is 10^6N. Also, for production by forging method, the part connecting the differential axle to the moving wheel bowl of the car in Nissan Motor Company has obtained a maximum force of 150 tons [19]. It is worth noting that this piece is made of carbon steel with twice the initial bite length and almost equal width, similar to the final geometric shape after the forging process, similar to the gearbox bush piece.

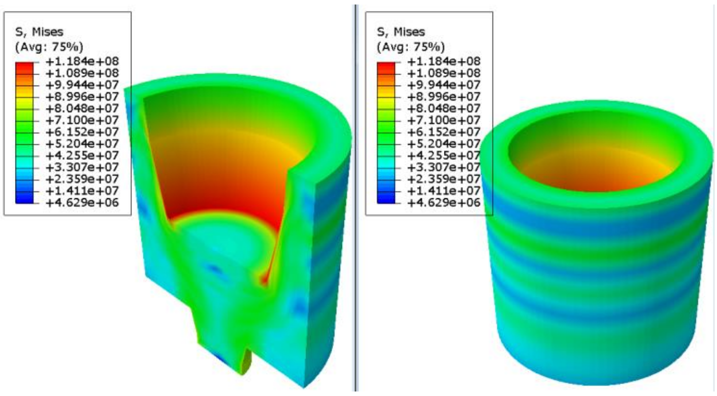

Figure 9. Stress distribution on the workpiece of AISI 1045 steel

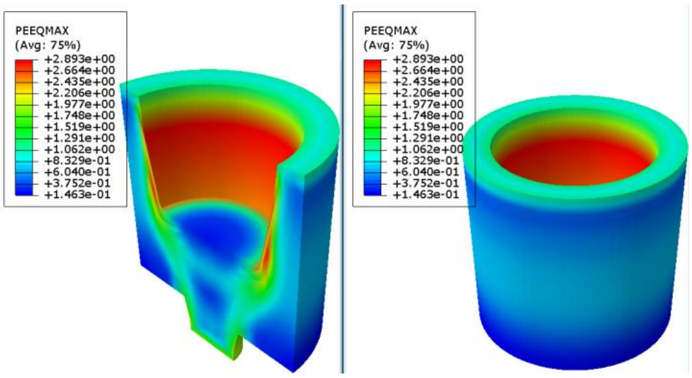

Figure 10. Plastic strain scattering on AISI 1045 forging piece

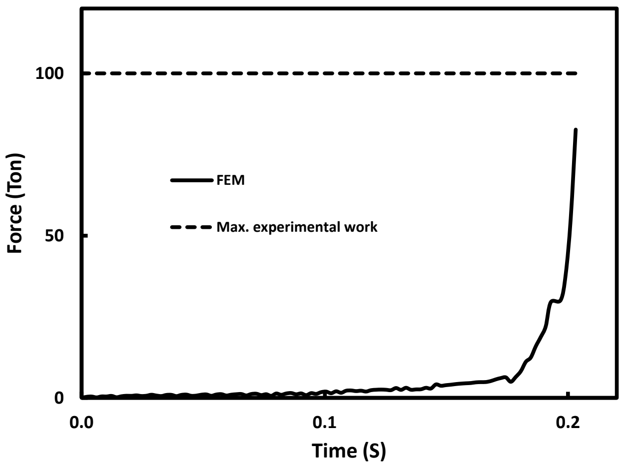

Figure 11. The force profile obtained from FE results

The tendency of the metal to be compressible increases with temperature intensification. The temperature distribution in the forged part at the end of deformation operation depends on the thermal properties of the workpiece, frictional heat, deformation rate, the part's dimensions in its different areas, the part and tool contact time, thermal conductivity between part and tool, and initial temperature of the part and deformation tool.

The temperature distribution contour after finishing the forging process of the bush is illustrated in Figure 12. As can be seen in the production process of this part, the local temperature at the end of the deformation operation is higher than the initial temperature of the material before initiating the process due to the high thickness and deformation percentage in the contact site of the blank with the punch wall. In particular, the temperature in some areas has even exceeded the melting temperature of the workpiece, which usually causes a boiling point, and the part adhesion to the tool in such areas. A common solution to prevent this from happening is to speed up the process as much as allowed. In general, it can be concluded that the temperature is higher in the areas of the blank exposed to high tangential stresses.

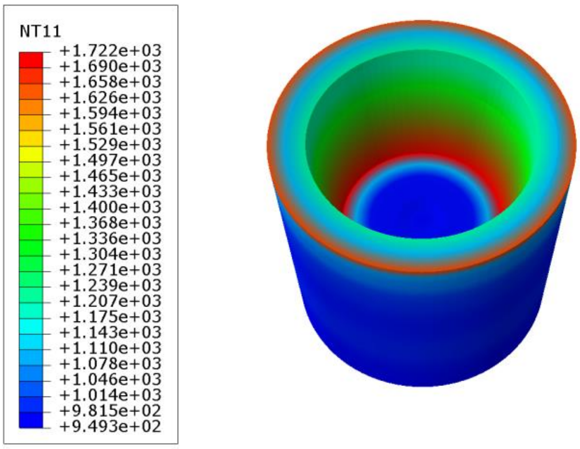

Figure 12. The temperature distribution on the bush of the gearbox after the forging process is finished.

3.2. Experimental Design

The results for the input parameter levels listed in Table 5 are displayed in Table 7 after simulation. In the next step, the responses obtained from the simulation have been compared by the Analysis of Variance (ANOVA) to determine the extent of the impact on the target parameters.

Table 7. Results of finite element tests

Tool Temperature (°C)	Workpiece Temperature (°C)	Plunger Speed (mm/s)	Max Stress (Pa)	Equivalent Plastic Strain	Max Force (N)
25	850	30	170200000	3.774	747400
25	950	50	140300000	3.283	665700
25	1050	70	134100000	2.909	596200
100	850	50	164100000	2.960	794900
100	950	70	139400000	2.996	736200
100	1050	30	111000000	4.163	448200
250	850	70	142900000	2.745	795100
250	950	30	121500000	3.913	604100
250	1050	50	108400000	3.532	537600

Figure 13 indicates the signal-to-noise ratio of the change of control parameters on the stress response variable. This diagram follows the “Smaller Is Better” relation, which means that it is desirable when the corresponding response variable is minimum. As shown in the diagram, the flow stress decreases with increasing the tool and workpiece's temperature parameters, while the flow stress increases with raising the press speed. The percentage of effects of three parameters press speed, tool temperature, and workpiece on the mentioned response variable are equal to 8.88, 33.3, and 57.77, respectively, which can be inferred from the high slope of the temperature parameter of the workpiece compared to other components.

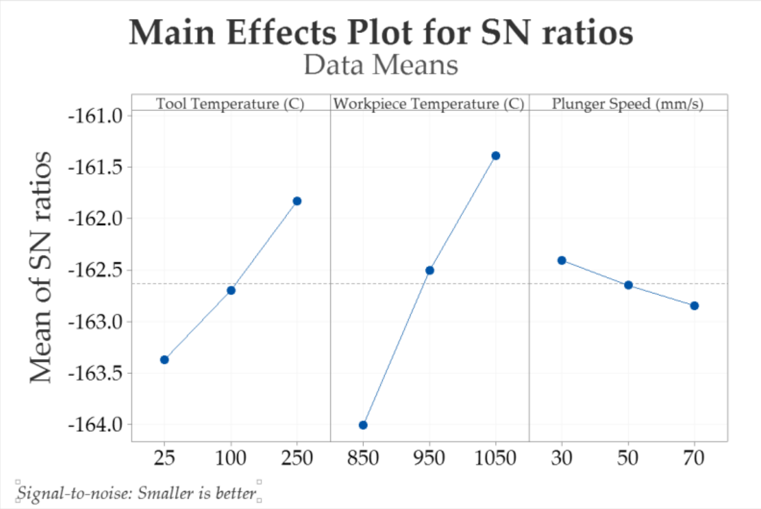

Figure 13. The signal-to-noise ratio of the effect of input variables on flow stress

The effect of inputs on the force has been analyzed in Figure 14, that similar to the stress, it is desirable when the output is minimum. It is evident that the maximum force required to finish the process decreases with increasing the temperature parameters, but the required power of the process raises with increasing the press speed. In terms of the required force of the process, the press speed inputs, the tool temperature, and the blank temperature have affected the mentioned response by 29.63%, 7.41%, and 62.96%, respectively.

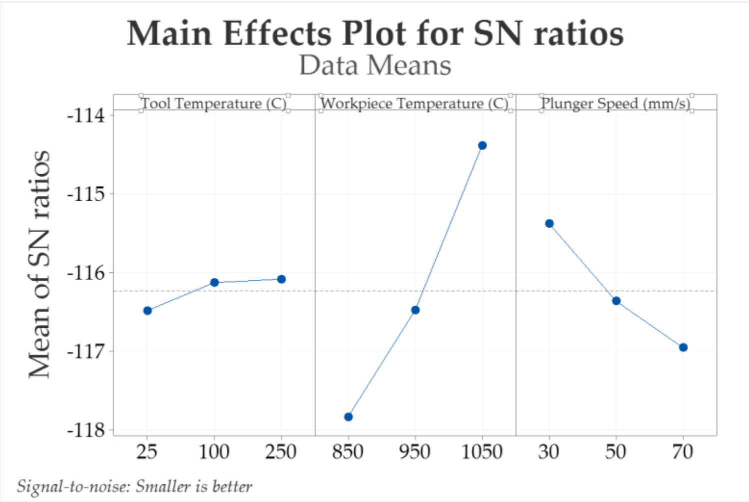

Figure 14. The signal-to-noise ratio of the effect of control variables on the force

In the case of investigation of the equivalent plastic strain, as can be seen from the curves in Figure 15, the process speed had the most significant effect by 70.33%, and also the initial part temperature and the initial tool temperature have affected the plastic strain by 24.72% and 5%, respectively. This diagram is optimized as “Larger Is Better” in contrast to the previous responses, and it can also be deduced from the diagram that the plastic strain raises with increasing the temperature of the mold and tools, while the plastic strain significantly decreases with increasing the press speed.

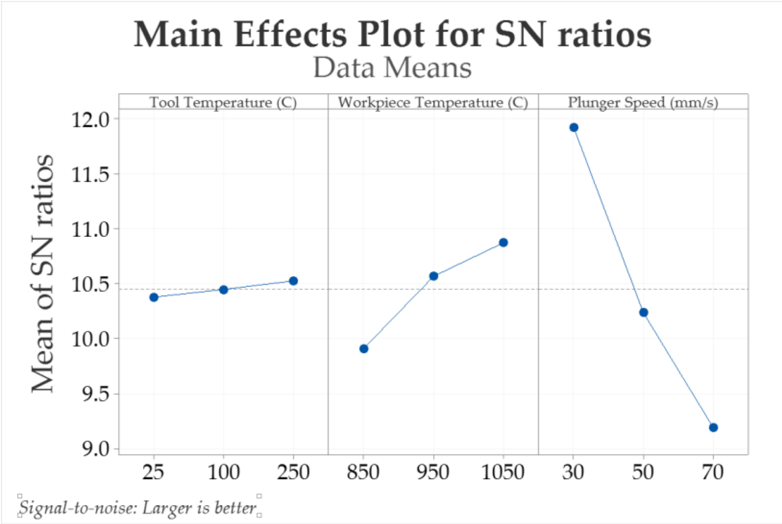

Figure 15. The signal-to-noise ratio of the effect of independent variables on the equivalent strain.

4. Conclusion

The production process of one of the most important parts of the gearbox of the Mercedes-Benz 10-wheel truck has been evaluated by the closed die forging method. The finite element simulation was performed in ABAQUS software. Taguchi method was applied to determine the extent of process parameters’ effect on the required force, equivalent strain, and flow stress. The following results were obtained after analyzing the experiments.

1. In closed die forging, it is possible to achieve many advantages such as producing finished and semi-finished parts with the highest tolerance, minimum energy consumption for finishing, as well as homogeneous filamentous and mechanical structure by optimizing the process parameters appropriate to the type of product and production facilities.

2. The distribution of temperature and shear stresses in different parts of the workpiece are nearly similar, and it can be concluded that the temperature distribution is maximum in areas with higher shear stresses. By all means, the effect of friction, deformation work, and axial stresses on the increase of temperature is undeniable.

3. The closed die forging force increases sharply as the blank lifts and gradually cools because of contact with the mold wall and filling the long edges of the mold.

4. The equivalent plastic strain at the contact point of the piston with blank is maximum due to high deformations in that area.

5. The increase of the mold temperature would reduce the flow stress and force required by the process and also increase the plastic strain in the final part. In practice, this also prevents structural damage during long contact times of parts and tools in many metals. Certainly, it should be pointed out that the advantages mentioned above do not significantly affect the process-dependent parameters, and the economic and time efficiencies of this operation must be taken into account in accordance with the type of production part and its assigned tasks.

6. The raw material's temperature significantly affects the amount of flow stress and the maximum power required to complete the process. However, the punch speed has the greatest impact on the equivalent plastic strain.

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