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Original Article

Process optimization for hot forging of difficult parts by computer experiments and response surface analysis

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ABSTRACT

Closed die hot forging of 304L stainless steel is difficult compared to carbon and micro-alloyed steels in terms of higher forming force and defects. An appropriate combination of design and process factors including cross-section diameter, initial billet temperature, and flash land thickness is crucial to minimize the forming force without causing any under-filling or folding defects. This paper aims to develop an optimized closed-die hot forging process for long, thin, and tubular rail body components used in gasoline direct injection systems. The effects on the forging load are investigated using computer experiments containing the finite element method under a full factorial array of three factors at three levels to obtain the main and interaction effects. Linear and quadratic surface response analyses are performed to define the relation between forging load and input factors, and finally, the simulations are validated with some limited experiments. The simulation results that fit the nonlinear regression model were in close agreement with the experiments, and an optimal set of parameters is conveniently proposed for industrial production.

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INTRODUCTION

Closed-die hot forging is a widespread method in the mass production of parts such as the stainless-steel fuel rail body used in internal combustion engines. This component's hot forging is very hard concerning die wear, under-filling defect, and forging load. Therefore, it is essential to have extensive knowledge and understanding of the effects of process parameters on the forging force. Statistical methods, particularly regression and surface response analysis of experimental and simulation data, are constructive for understanding these relationships.

Figure 1 demonstrates the process flow commonly applied in industrial hot forging [1, 2]. Usually, four die sets need to be employed in a sequence of three or four hammer and/or press stations. The last step "hot calibration" is a step that can be skipped if an effective finisher operation with a well-optimized die set is conducted. A hot forming process without flash is not possible in most cases, because flash is the only buffer that controls and enables a complete die-fill-

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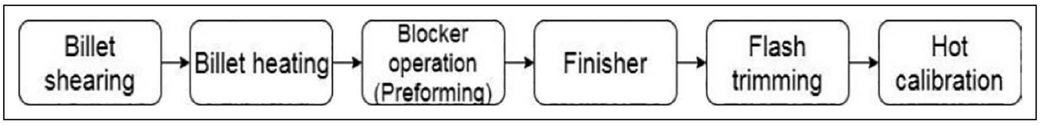

Figure 1. Process flow-chart of hot forging metal alloys.

ing. Flash trimming is considered a mature operation and it is not taken as a research and development issue; however, the design of the pre-forming (blocker) and finisher steps are critical for an economic process with minimized press tonnages and consistent part quality with minimal scrap rate.

There are a few design-of-experiments (DoE) studies on closed-die hot forging in the literature. Most of them use the Taguchi method, which is relatively less complicated than the full factorial method. Full factorial orthogonal arrays can include all possible combinations of input variables and consider the input variables' interaction effects. Therefore, more accurate results can be obtained with the full orthogonal arrays [3]. Taguchi method is commonly utilized in industrial research because it allows the researchers to understand the effects of the input variables on the defined outputs by using a minimum number of experiments, yet the interaction effects are neglected. Another beneficial method for evaluating the forging parameters is the fractional factorial design that ignores some of the input-variable combinations. Forging research involving full factorial, fractional factorial, and Taguchi methods are summarized in the following paragraphs.

Finite element analysis is a strong tool to simulate the hot forging process as well as other metal forming processes. When it was first introduced in the 1970s, both mathematical and material models were weaker along with the computational capabilities. With the advent of computer technology and the gradual development of finite element software, usage of the simulation approach became standard practice in the industry. However, a systematic approach in planning the input variables of the simulations such as the DoE approach followed by ANOVA and regression, or surface response analysis is very helpful to optimize the forming process ahead of the costly die tryouts.

Shahriari et al. [4] examined the effects of flash land thickness, internal and external draft angles, and internal and external edge radii on filling the die cavity, forging load, and workpiece material cost in closed die forging. They used a fractional factorial design to find optimum finisher forging parameters. They found out that flash land thickness and external draft angle have the highest impact on the forging load, while internal and external radii do not affect it. Moreover, exterior draft angle, outer radius, and flash land thickness influence workpiece material cost at the highest rate.

Grobaski et al. [5] investigated the effects of friction at the workpiece/die interface, workpiece temperature, die temperature, and press speed on the service life of hot forging dies. They arranged experiments that included four factors at two levels. According to this arrangement, 16 (2^4) finite element simulations were conducted. The forging process had an upsetter, a preform, and a finisher operation. They calculated forces in the Z direction, finished workpiece temperature, net energy, effective stress, shear velocity, and contact stress when these factors are at their maximum levels. They found that the factor affecting shear velocity is the ram speed according to the standard probability curve. Therefore, they observed that as the ram speed increases, the workpiece flow rate increases. Parallel to this, they observed that deformation-rate raised die wear according to all wear models.

Durukan [6] studied the effects of induction furnace parameters on workpiece temperature using a DoE with 2^3 full-factorial orthogonal array. He used furnace energy rate, conveyor speed, and coil box hole diameter as input variables at two levels. He prepared ten billets for each experiment and then calculated these billets' averages after heating. Accordingly, the furnace energy rate is the most influencing factor in the resultant billet temperature. The interaction effect of furnace energy rate and coil box hole diameter significantly impacts billet temperature at the furnace outlet.

Al-Omari et al. [7] examined the influence of the diameter and height of the forging die and workpiece dimensions on stress and strain distributions on the dies. They conducted 27 (3^3) FE simulations arranged in a full factorial orthogonal array. Consequently, they observed that workpiece dimensions significantly influence the total work needed to complete the forging operation.

Xuewen et al. [8] examined five independent factors regarding their effects on the forging load. They used a Taguchi orthogonal array to attain the optimal parameter combination that minimizes the forging load. They discovered that flash gutter thickness is the most significant factor; the billet diameter-to-length ratio is essential, and the flash gutter length is not considerable.

Ohdar et al. [9] investigated the effects of workpiece temperature, forging die temperature, friction coefficient, and flash land thickness on the effective die stress using Taguchi L9 orthogonal array. They found that flash land thickness, workpiece forging temperature, and friction coefficient are the critical input variables. As a result, they obtained the best combination of input variables in terms of effective die stresses.

Chand et al. [10] examined the input variables' effects on the forging defect ratios. According to the tests that utilized Taguchi L9 orthogonal array, billet temperature is the most influencing factor that causes forging defects. Forging die tem-

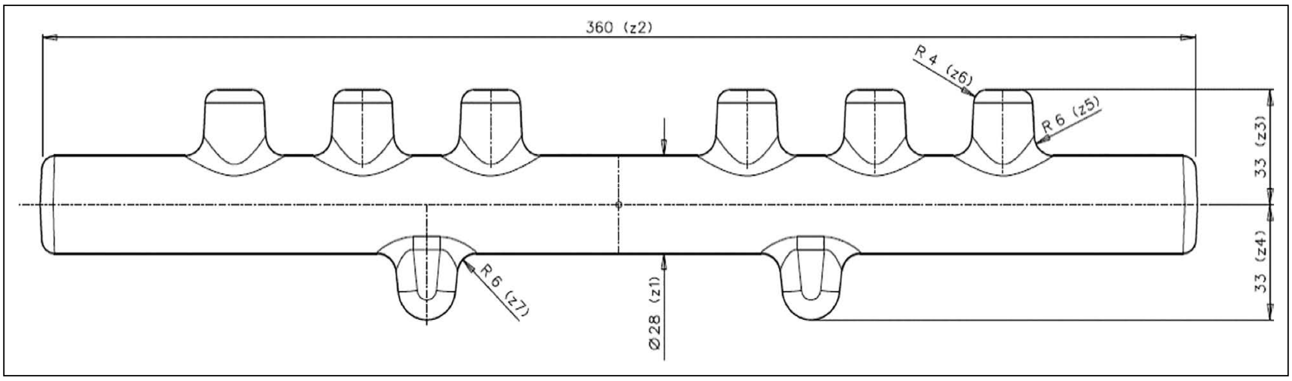

Figure 2. Nominal part dimensions after forging at room temperature.

perature and billet mass are the significant secondary variables; yet, forging time has the least effect on the forging defects.

Marinkovic et al. [11] investigated the relationship between factors that primarily affect the die land dimensions. They formed regression models for the height of the die land and the die land's width and height ratio. Furthermore, they tested these models and discovered that regression models agreed with the experimental data.

Alimirzaloo and Biglari proposed regression response functions in their research related to the hot forging of a gas turbine blade [12]. They generated regression models to minimize flash volume, vertical and lateral forces, etc. They used the ANOVA method to determine significant parameters that they used as input variables. However, their methodology is only limited to input parameters related to a couple of preform geometries, though it is well known that forging process parameters also play a crucial role in the value of the responses taken. Furthermore, they managed to reduce the flash volume and forging force by optimizing a gas turbine blade's preform shape thanks to creating regression models for these responses.

In [13], regression analyses were performed to obtain a model for the response of billet weight (called "job weight") of an axisymmetric automotive part. After a DoE with the Taguchi method, the ANOVA method was employed to find the essential parameters concerning their effects on the forging weight. Billet weight, heating temperature, and heating time were considered input variables, and results obtained from the experiments were used in the regression analyses. They successfully formed a multiple linear regression model for forging weight, tested the model with different input variables' values, and validated it.

In [14], the effects of the input parameters such as deformation temperature, die speed, and friction coefficient on the output variables, maximum tensile stress, and forging force, were investigated using the Taguchi method, ANOVA, and regression analysis subsequently. They found out the experiment level, which consists of the best input variable combination in optimum output responses. Moreover, they have discovered the significant input parameters that play an essential role in the responses' values. Finally, they have built regression models to demonstrate the relationships between input variables and output responses.

Another study optimized process variables to provide easy material flow in the forging die cavity [15]. They chose billet size, billet temperature, and friction coefficient as input variables, and they considered effective strain rate, die wear, and material flow rate as output variables. They built multi-variable and non-linear regression models for each of the responses.

The first goal of the study is to develop a closed die hot forging manufacturing system for long, thin, and tubular rail body components which is used in gasoline direct injection systems. The second aim of this research is to investigate the effects of the forging parameters, including billet temperature, cross-section diameter, and flash land thickness on the forging. The third goal is to propose an industrially effective methodology in using finite element analysis to minimize the time and effort spent during die tryouts. In addition to these main goals, some of the important considerations as post-processors, such as temperature distribution, maximum temperature values, and strain rate values on the workpiece, are examined. Finally, suitable experiment(s) will be chosen to produce samples and to compare some results of those samples and those taken from simulations. A commercial part is taken as the case of this investigation (Fig. 2).

DESIGN OF EXPERIMENTS

The full factorial experimental design including all possible combinations of three factors (workpiece temperature, flash thickness, billet diameter) at three levels (3^3) was utilized in this investigation [3, 16]. This scheme is beneficial to demonstrate the main and interaction effects of the predefined factors on the forging load simultaneously. 27 (3^3) FE simulations were conducted as computer experiments (Table 1). The Taguchi method is a more economical approach to cover the main effects; however, in the simulation environment where there is no repetition and the main cost

Table 1. Design of experiments

Experiment number	W/P temperature (°C)	Flash land thickness (mm)	Billet cross section (mm)
1	0	0	0
2	1	0	0
3	2	0	0
4	0	1	0
5	1	1	0
6	2	1	0
7	0	2	0
8	1	2	0
9	2	2	0
10	0	0	1
11	1	0	1
12	2	0	1
13	0	1	1
14	1	1	1
15	2	1	1
16	0	2	1
17	1	2	1
18	2	2	1
19	0	0	2
20	1	0	2
21	2	0	2
22	0	1	2
23	1	1	2
24	2	1	2
25	0	2	2
26	1	2	2
27	2	2	2

is the computation time, the comprehensive approach of the full-factorial design is more effective. Taguchi method is the best in costly production shop tests, and it may be applied in the validation phases of new products and processes.

Figure 3 demonstrates the process and die design methodology employed in this study. The finite element model and simulations are used as a tool to eliminate the costly die tryouts. This process and die design method combine the vast experience of the company with the accurate prediction power of the finite element method. The DoE approach systematizes the use of the FEM and evaluation of the simulation results so that rational design decisions can be made.

As input factors, workpiece (billet) temperature (T_b), flash land thickness (t_f), and billet cross-section diameter (D_b) were selected according to industrial know-how and the literature [1, 2]. A minimized billet cross-section diameter is preferable for reduced billet weight. The initial billet section diameters were taken as 37, 38, and 39 mm, where its length (338.1 mm) was kept constant because the forging of long parts is more of a two-dimensional forming process that takes place under plane strain conditions. Deformation in the axial direction is negligible as compared to the cross-section. This is caused by the long friction surface along the part axis. This phenomenon is also observed in the flat rolling process of sheets and plates [2]. Levels of the input factors are shown in Table 2, while the calculated billet masses are given in Table 3.

THE PROCESS AND THE FE MODEL

The two stages which include a blocker (preform) and a finisher were planned, and two die inserts were used. An appropriate blocker design is essential since it allows minimized material flow in the finisher stage and minimum flash mass, trimmed off as scrap. The thickness of the preform was designed approximately 5% higher than that of the finisher model based on experience and as recommended in the literature [1, 2]. Besides, its length and width are approximately 5% lower. These adjustments make the preform about 5% heavier than the finisher, which dramatically helps die filling and material savings.

Blocker and finisher dies were modeled with 3-, 3.5-, and 4-mm flash land thickness and 12 mm flash land width. High edge and fillet radii were applied for a smooth material flow. 3^o draft angles were designed for easy material removal from the die cavity. The parting line was located at the vertical center of the rail body's cylindrical section with the broadest cross-section. The bottom die was designed to accommodate the boss sections to facilitate complete filling in these areas. Some of the solid model images are shown in Figure 4.

Solid models constructed in UG NX v11 were converted to STL file format to run the FE software Forge Nxt v3.0. The finite element method is a numerical approach used for solving complicated differential equations that define complex engineering cases [17]. Tetrahedral elements were used, while the bottom and top dies were selected as rigid bodies to abate the processing time. Billet, lower die, and upper die had 15312, 39677, and 31512 nodes, respectively, in the set-up with 4 mm flash land thickness and 38 mm billet diameter. Other process properties are shown in Table 4. The friction coefficients for the top and bottom dies were set by testing two limit values (0.1 and 0.3) recommended by the software guide [17] and the more realistically predicting Coulomb coefficient of 0.3 was set.

The workpiece material was given as AISI 304L austenitic stainless steel (Table 5) [2]. Due to the high Cr and Ni content in the alloy, flow stresses are relatively high at high temperatures than equivalent micro-alloyed or carbon steels, accelerating die wear.

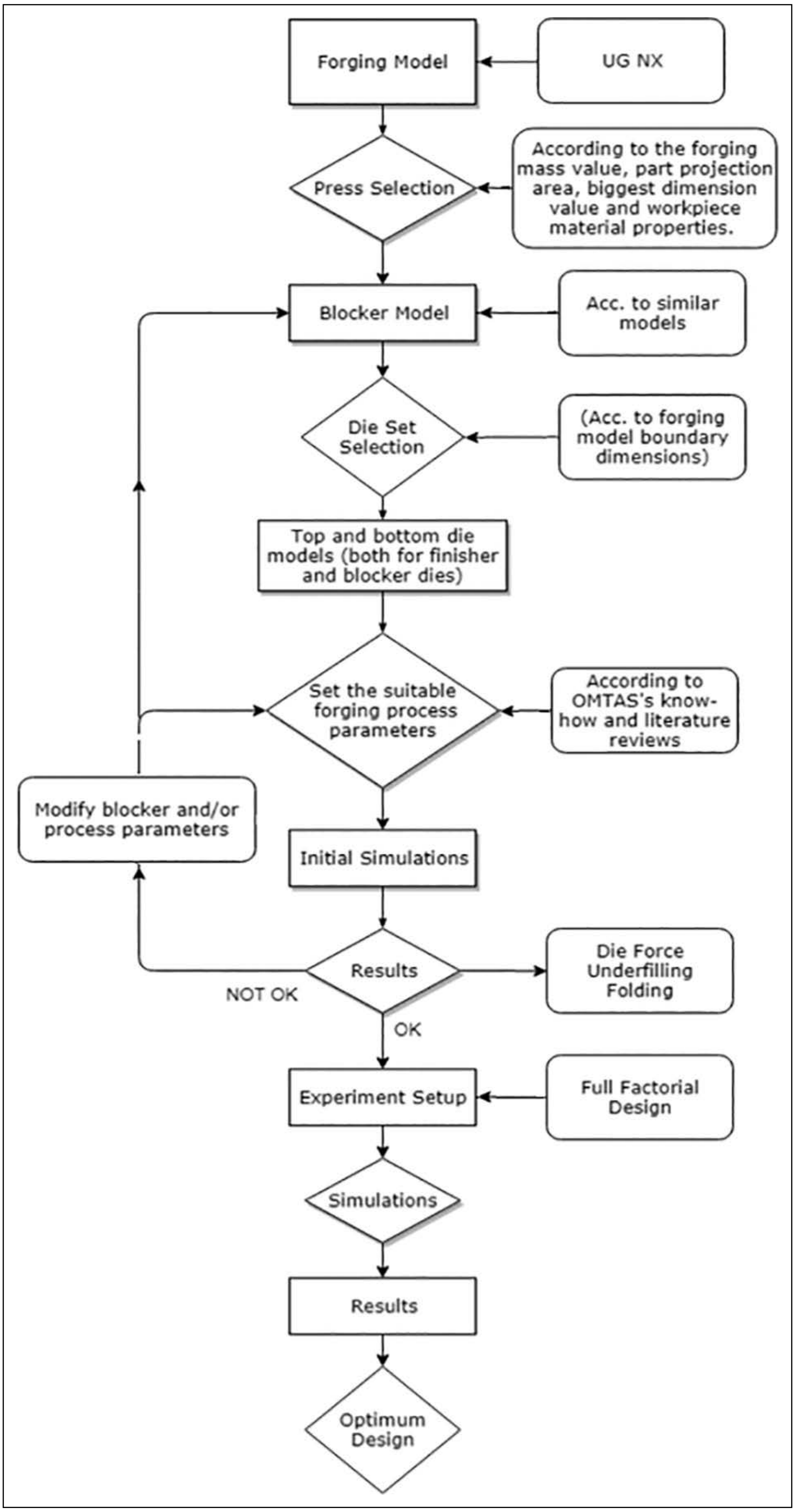

Figure 3. The process design and optimization methodology employed.

Table 2. Factors in the DoE and their levels

Factors	**Low (coded=0)**	**Medium (coded=1)**	**High (coded=2)**
W/P temperature [°C]	1100	1150	1200
Flash thickness (mm)	3	3,5	4
Billet cross section (mm)	37 RSB	38 RSB	39 RSB

Table 3. Billet weights

Initial billet diameter	**Mass [kg]**
37 Round steel billet	2.85
38 Round steel billet	3
39 Round steel billet	3.16

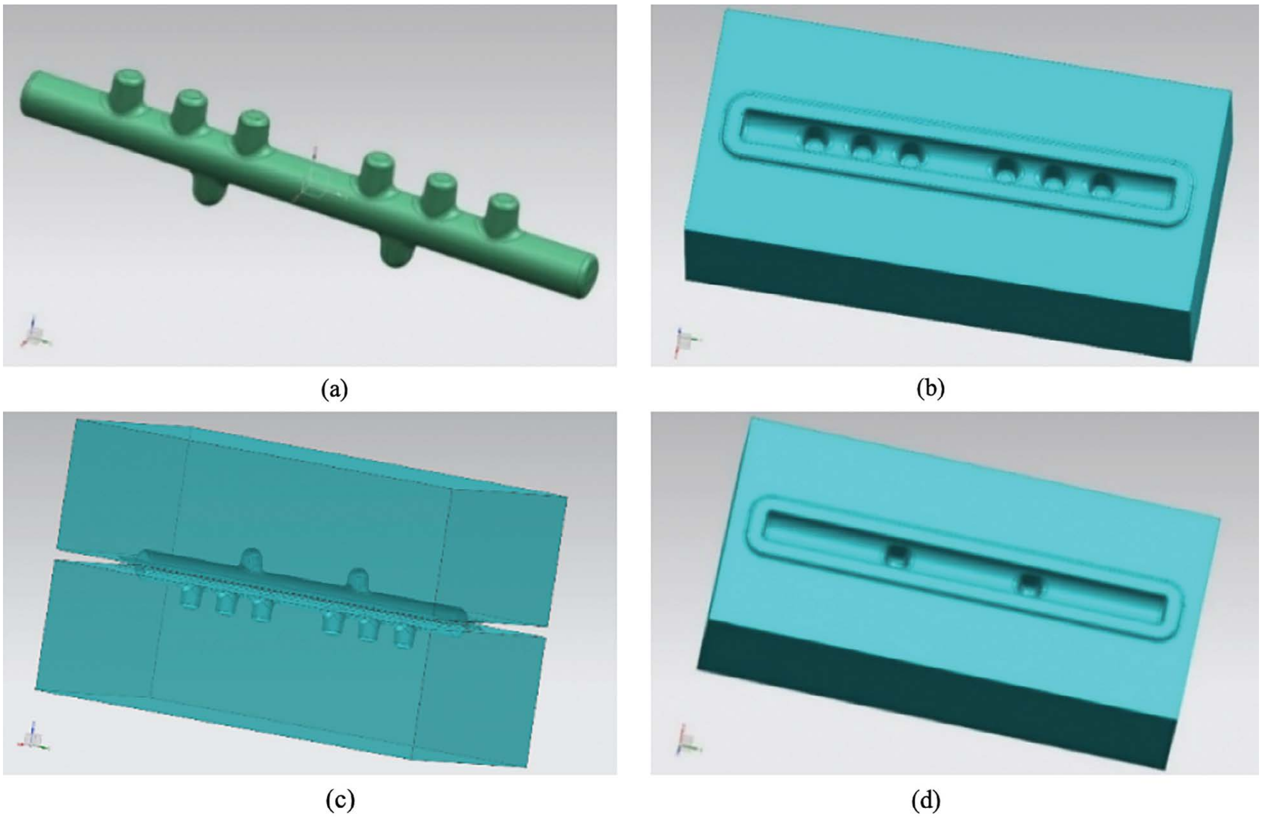

Figure 4. Solid models **(a)** Forging model, **(b)** Finisher bottom die t_f=3 mm, **(c)** Finisher top die t_f=3 mm, **(d)** Finisher die set t_f=3 mm.

Forge Nxt program uses the Hensel-Spittel law for 304L stainless steel (1) c.

$$\sigma_f = A\, e^{m_1 T}\, T^{m_9}\, \varepsilon^{m_2}\, e^{\frac{m_4}{\varepsilon}}\, (1+\varepsilon)^{m_5 T}\, e^{m_7 \varepsilon}\, \dot{\varepsilon}^{m_3}\, \dot{\varepsilon}^{m_8 T} \qquad (1)$$

In this equation, σ_f is the material flow stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, A is the material optimizable regression coefficient, and m_1 to the m_9 values are the other optimizable regression coefficients for the material. m_5, m_7, m_8, and m_9 are selected as 0. m1 is the regression coefficient used to identify the material's sensitivity characteristic to the changing temperature values, and it was optimized as -0.00368 for 304L. m_2 and m_4 are the coefficients used to determine the material's sensitivity characteristic to the changing strain values, and their values were optimized as 0.00037 and -0.04229, respectively. m_3 is the coefficient used to identify the material sensitivity to the changing strain rate values, and this value is optimized as 0.1048. According to these regression coefficients, flow stress-strain curves at 10^{-1} s^{-1}, 1 s^{-1}, 10 s^{-1} and 100 s^{-1} at 1100, 1150, and 1200 °C can be seen in Figure 5.

NUMERICAL SIMULATIONS

Based on the above part and process design parameters, 27 blocker stage and 27 finisher stage simulations were conducted to investigate the input parameters' effects on the forging load. Die filling and folding defects were also considered to find the best parameter combination. As can be seen in Table 6, no folding defect problem was predicted in all simulations. Predicted forging loads were all acceptable for the 20 MN mechanical press. The minority of the simulations demonstrate some under-filling.

Table 4. Process properties

1 Billet (workpiece) material	304L Austenitic stainless steel
Forging machine	EUMOCO MP2500 mechanical press
Rotation speed (rpm)	100
r/l ratio	0.13 (for the press connecting rod)
Crank radius (mm)	150
Billet heating temperature (°C)	1100-1150-1200 (3 levels)
Bottom die heating temperature (°C)	150
Top die heating temperature (°C)	150
Environment temperature (°C)	30
Friction condition for top die	Lubrication using water and graphite (μ 0.3)
Friction condition for bottom die	Lubrication using water and graphite (μ 0.3)
Heat transfer condition for top die	Medium interaction (HTC set to 10^4 w/m²k)
Heat transfer condition for bottom die	Medium interaction (HTC set to 10^4 w/m²k)

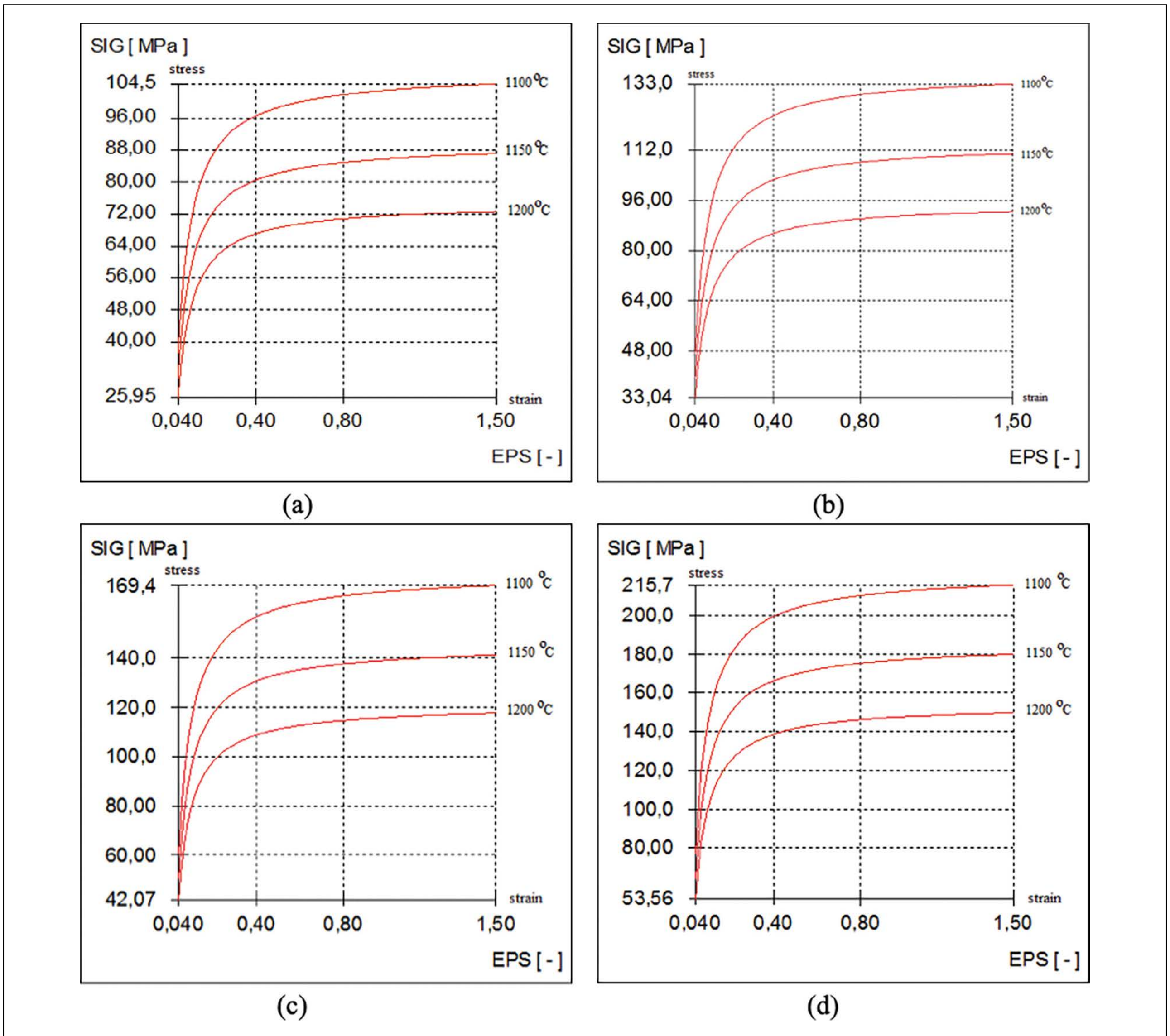

Figure 5. The stress-strain curves for 304L at various strain rates and temperatures **(a)** 10^{-1} s^{-1} **(b)** 1 s^{-1}, **(c)** 10 s^{-1}, **(d)** 100 s^{-1} [17].

Table 5. Chemical composition of stainless steel 304L

Element	Mass percentage (%)
C	0.02
Si	0.66
Mn	1.33
Ni	11.2
P	0.03
S	0.02
Cr	19
N	0.11

Forging load is the main output concerned in this investigation. A low forging load is vital to form components by using an assigned press. In this research, a EUMOCO 2500-ton mechanical press was used; therefore, a maximum load of approximately 1500 tons is acceptable. Due to the uncertainties of the method used to predict the forging force in the software, it is necessary to provide a safety margin. The edge and fillet radii in the preform and finisher models were selected high to attain a reasonable forging load. Also, the total amount of deformation was planned as small as possible in the finisher stage. Furthermore, die cavity boundary radii at the parting plane were selected as high as possible without entailing any defect on the part in the flash trimming stage.

As shown in Table 6, there is no recognizable pattern between the forging loads of preform and finisher stages in terms of quantity. The preform and finisher stages possess very close forging load predictions, even though finisher stages have low deformation quantity compared to preform stages. The main reason for this, in the finisher stages of the experiments, fillet and edge radiuses are lower than that of the blocker stage, and at the last steps in the finisher stages, there should be more energy or force conveyed through the press to enable workpiece material to fill the intricate re-

Table 6. Simulation results

Case no	W/P T (°C)	Flash land t (mm)	Cross section (mm)	Preform die force Z (Ton)	Finisher die force Z (Ton)	Die filing status	Folding
1	0	0	0	879.94	1011.9	OK	NO
2	1	0	0	731.90	878.00	OK	NO
3	2	0	0	623.67	739.60	OK	NO
4	0	1	0	838.02	804.18	AT RISK	NO
5	1	1	0	695.07	725.47	OK	NO
6	2	1	0	593.19	603.88	OK	NO
7	0	2	0	801.97	664.70	NOT OK	NO
8	1	2	0	661.86	608.87	NOT OK	NO
9	2	2	0	563.24	508.44	NOT OK	NO
10	0	0	1	939.29	1038.9	OK	NO
11	1	0	1	791.29	892.37	OK	NO
12	2	0	1	677.00	743.78	OK	NO
13	0	1	1	849.54	912.03	OK	NO
14	1	1	1	705.90	752.89	OK	NO
15	2	1	1	598.18	637.29	OK	NO
16	0	2	1	818.79	761.79	AT RISK	NO
17	1	2	1	672.62	642.88	OK	NO
18	2	2	1	574.43	564.69	OK	NO
19	0	0	2	1009.7	1058.2	OK	NO
20	1	0	2	884.41	878.99	OK	NO
21	2	0	2	762.50	752.69	OK	NO
22	0	1	2	894.03	925.78	OK	NO
23	1	1	2	746.07	803.53	OK	NO
24	2	1	2	643.64	672.71	OK	NO
25	0	2	2	824.77	813.94	OK	NO
26	1	2	2	686.30	678.70	OK	NO
27	2	2	2	585.61	595.09	OK	NO

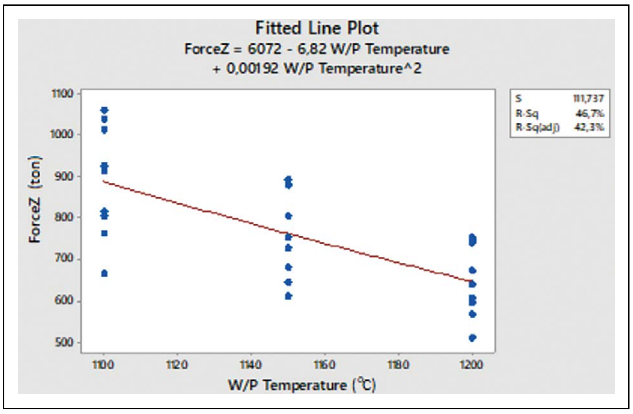

Figure 6. Fitted line plot for forging load-workpiece temperature.

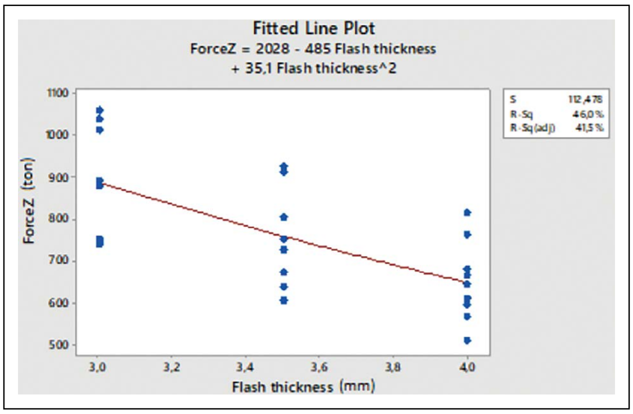

Figure 7. Fitted line plot for forging load-flash land thickness.

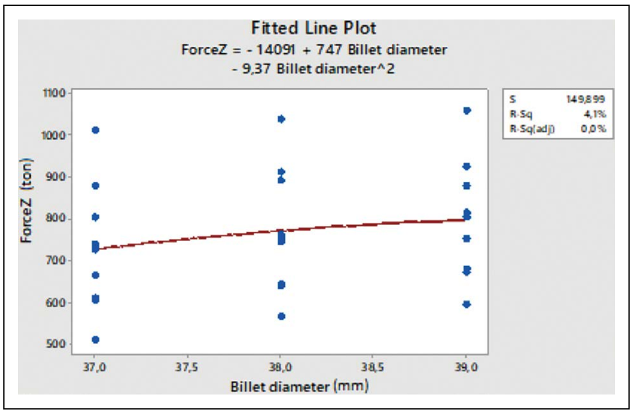

Figure 8. Fitted line plot for forging load-billet diameter.

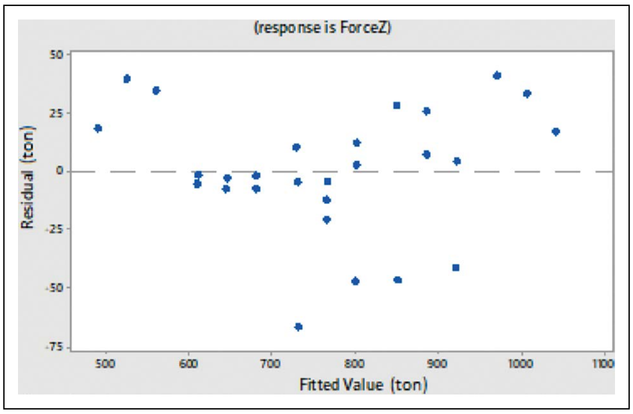

Figure 9. Residuals of the linear surface response fit.

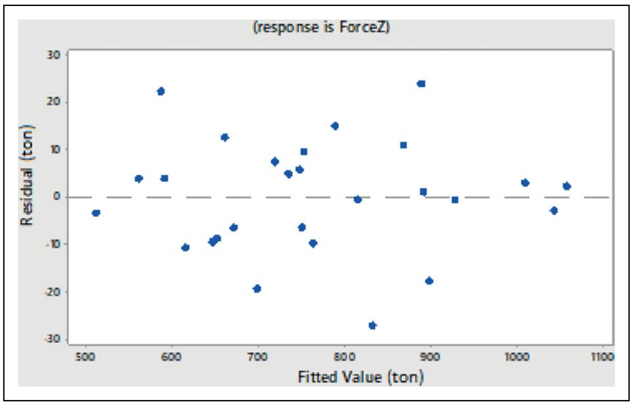

Figure 10. Residuals of the quadratic surface response fit.

gions. The highest forging load among the experiments was observed in the finisher stage of Case-19, which contains 1100 °C billet forging temperature, 3 mm flash land thickness, and 39 mm billet section diameter. This finding was expected because this experiment includes a low level of billet forming temperature and flash land thickness and a high billet diameter level. The lowest forging load was observed in the finisher stage of Case-9 with 1200 °C billet forging temperature, 4 mm flash land thickness, and 37 mm billet diameter. Similarly, this finding is very reasonable since this stage consists of a high level of billet temperature and flash land thickness along with a low level of billet section diameter. However, this level variation cannot be utilized since it can entail an under-filling defect.

SURFACE RESPONSE ANALYSIS

Regression analyses were conducted on forging load as the output at the finisher stage with the aim of minimization. First, the single-variable quadratic model was fit for each input variable. Figures 6, 7, and 8 illustrate quadratic curves for forging load concerning workpiece temperature, flash land thickness, and billet diameter, respectively. Accordingly, singe-variable regression is not a viable option with the very low (4.1–46.7%) R-square values obtained. Therefore, a more comprehensive approach was needed, and a multi-variable regression approach called the surface response method was adopted.

Linear surface response fit (multi-variable linear regression) was performed (2) and the following model was obtained.

$$\text{Forging Load} = 3041 - 2.41T_b - 239.5t_f + 35.26D_b \quad (2)$$

Table 7. Forging loads as predicted using FEM and the fitted values of quadratic regression

Case no	Workpiece temperature [°C]	Flash land thickness (mm)	Billet diameter (mm)	Predicted forging load (ton)	Fitted value of forging load (ton)	Residuals (ton)
9	1200	4	37	508.44	511.94	-3.5
18	1200	4	38	564.69	560.95	3.74
27	1200	4	39	595.09	591.23	3.86
6	1200	3.5	37	603.88	614.62	-10.75
8	1150	4	37	608.87	586.77	22.1

R-Square of this surface was calculated as 96.6% as a reasonable, yet unacceptable fit. The residuals vs. fitted surface plot is shown in Figure 9. A very maximum residual value of -66.64 is observed for Case-7 and similarly high residuals make the linear surface response, not representative.

Next, a quadratic surface response fit was performed to increase the R-Square value and decrease the residuals (3) and the following model was obtained.

$$\text{Forging Load} = 13599 - 20.5T_b - 9611t_f + 297D_b + 0.00192T_b^2 + 35.1t_f^2 - 9.36D_b^2 + 6.58T_bt_f + 0.267T_bD_b + 210t_fD_b - 0.147T_bt_fD_b \quad (3)$$

The surface modeled by Equation-3 gave an R-Square value of 99.34%, and it is more acceptable in terms of representation of the response. The residuals vs. fitted values plot is illustrated in Figure 10, demonstrating a maximum residual of -27.14, which is much lower than the extremum residual of the linear surface. Indeed, most of the residual values are between +20 and -20.

According to the quadratic surface response fit, five cases with the best input variable combinations in terms of minimum forging load are illustrated in Table 7. Because of the incomplete die-filling in Case-9, it is suitable to select Case-18 as the next-to-optimum combination of the forging load variables. Case-8 simulation gave a prediction of the press load as 564,69 tons and the fitted surface represents this prediction with a low deviation of 3.74 tons.

6 EXPERIMENTAL VALIDATION AND DISCUSSIONS

A limited set of experiments were performed for validation purposes testing the input variable combinations with 3.5 mm flash land thickness, 1,150 °C billet temperature, and 37-, 38-, and 39-mm billet diameters. Yet, there came up some limitations and deviations from the simulations in the sampling phase because of the production schedule on the shop floor. The major limitation is that due to the difficulty of forging austenitic stainless steel, the production crew recommended forming the component 1.5 mm thicker than the nominal diameter to avoid press connecting rod failure due to extreme load at the bottom dead center. Therefore, the press ram was vertically adjusted 1.5 mm higher so that the die set is not closed completely.

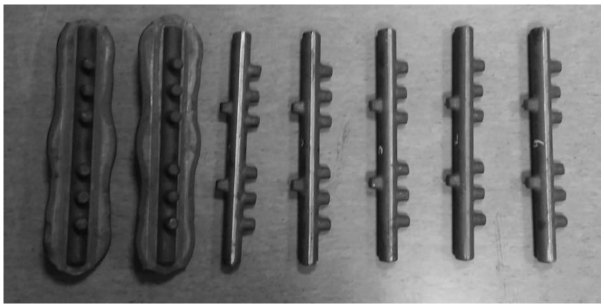

Figure 11. Forged samples during the validation phase.

Figure 12. The shape of a sample after trimming (Case-14, 1150 °C-3.5 mm-38 mm RSB).

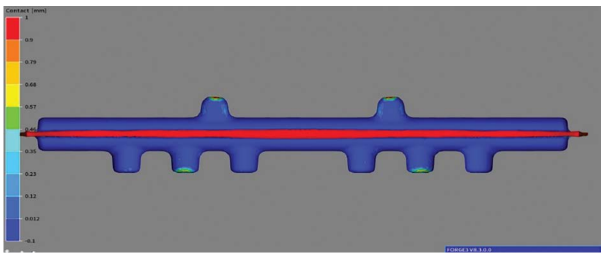

Figure 13. The shape of the component at the iteration at which the part is 1.5 mm thicker than that of the final iteration in Forge Nxt (Case-14, 1150 °C-3.5 mm-38 mm RSB).

304L austenitic stainless-steel bars with a 40 mm section diameter were procured. These bars were cut to a length of 338.1 mm and then transferred to a universal lathe to obtain 38-, 39-, and 40-mm diameters. Die holders for the blocker and finisher stages were heated to provide shrink-fit with forging die inserts, and next, the dies were set on the mechanical press.

Figure 14. Sample with flash (Case-14, 1150 °C-3.5 mm-38 RSB).

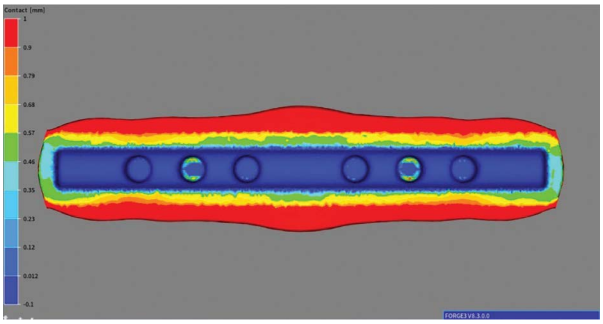

Figure 15. Workpiece geometry at the iteration that is 1.5 mm thicker than the last iteration of the finisher stage (Case-14, 1,150 °C-3.5 mm-38 RSB).

Meanwhile, trimming and hot calibration dies were set on a Ravne-630 trimming press. Die sets were heated to ~150 °C before the operation, the maximum attainable temperature for dies in the plant. Simultaneously, workpieces were heated to 1,150 °C in an induction furnace. Workpieces taken from the furnace were placed in the blocker, finisher, and trimming dies, subsequently. The workpieces were finally delivered to the hot calibration stage to fix the distortions generated during trimming. Examples of formed samples are shown in Figure 11.

Since the experimental workpieces were forged 1.5 mm thicker, the comparisons were made between the sample shapes and the mesh geometries at the time step 1.5 mm higher than the bottom dead center (Figures 12 and 13). Both shapes present a slight under-filling in the boss sections due to the press's intentional insufficient loading. Experimental results are geometrically compatible with the results obtained from the FE simulations.

Figure 14 shows a sample (with flash) formed at a variable combination of 1,150 °C forging temperature, 3.5 mm flash land thickness, and 38 mm billet diameter. This sample was compared with the simulation at the time step 1.5 mm thicker than the end of the finisher stage (Figure 15) in terms of flash shape. The flash morphologies of both forms are very similar except for the areas near the two ends in the axial direction. More flash material is accumulated during the tests. This situation can be attributed to scale formation and insufficient lubrication in the flash area. These two production problems may have deteriorated the smooth flow of the workpiece material inside the boss areas and have forced the material to flow more to lateral flash zones.

Nominal (as-forged) part dimensions at room temperature were illustrated in Figure 2. Selected dimensions on experimental samples and simulated geometries of three cases are compared in Table 8. There are no deviations from the nominal dimensions z2, z5, and z7 for both experiments and numerical results, because these dimensions are determined by early die contact during the forming process. Numerical and experimental results for z1 (part diameter) are 1.5 and 1.3 mm longer than the nominal size, respectively. This is reasonable due to the 1.5 mm less stroke. For z6 (boss nose radius), a slight but acceptable under-filling was observed due to insufficient press stroke. Under-filling occurred for the dimension z4 (boss extrusion length), and deviation from the nominal value is more than that in the other sizes. It was also observed that the impact of the under-filling decreased with increasing billet diameter for the dimensions z3 and z4.

When the geometries predicted by the FE simulations are compared with the averages of experimental measurements (of three samples for each case), they are consistently higher indicating a systematic over-prediction. The reason for that may be the friction model. The μ value of 0.3 used for both dies may have been relatively higher. The higher friction coefficient

Table 8. Selected experimental measurements and dimensions of the shapes taken from the simulations

Dim'n	Nominal (mm)	Case-5			Case-14			Case-23		
		Exp't (average) (mm)	Sim'n (mm)	Error (%)	Exp't (average) (mm)	Sim'n (mm)	Error (%)	Exp't (average) (mm)	Sim'n (mm)	Error (%)
z1	28	29.3	29.5	0.7%	29.3	29.5	0.7%	29.3	29.5	0.7%
z2	360	360	360	0.0%	360	360	0.0%	360	360	0.0%
z3	33	32.99	33.5	1.5%	33.17	33.5	1.0%	33.6	33.5	-0.3%
z4	33	30.09	31.2	3.7%	30.21	32.6	7.9%	30.31	33.6	10.9%
z5	6	6	6	0.0%	6	6	0.0%	6	6	0.0%
z6	4	3.8	4	5.3%	3.8	4	5.3%	3.9	4	2.6%
z7	6	6	6	0.0%	6	6	0.0%	6	6	0.0%

especially on the flash contact zones restrained the outward flash movement, and therefore, the bosses are extruded more than that in the experiments. The FE model includes a fixed Coulomb (sliding) friction coefficient set separately for the upper and lower dies. However, this coefficient is fixed for all surfaces of each die; thus, the variation of the friction conditions depending on the local contact pressure variation is not represented in the FE model. The friction coefficient should be modeled as relatively less than that inside the die cavity.

Validation of the FE model has been made using dimensional comparisons, but another distinct and strong comparison may have been on the press force. The mechanical press used during the experiments is a displacement-limited robust industrial production equipment, but it is not equipped with a load cell-DAQ system to monitor the loading conditions. This is a weakness of this study; however, considering the high tonnages needed to test such an industrial part it may be pardoned. The repeatedly consistent parallelism of the measured and simulated dimensions has shown that the FE method may be used in a DoE and response surface approach conveniently, in a short time, and at a low cost so that the intermediate workpiece geometry after the blocker die may be optimized.

CONCLUSIONS

Linear and quadratic response surface analyses were performed on forging load predictions of a set of computer experiments (finite element simulations) on the hot forging of a long stainless-steel bar based on the full factorial orthogonal array of three factors at three levels. The quadratic response surface gave significantly smaller residuals as compared to the linear one. According to the quadratic response surface analysis, the most practical factor combination to produce minimum forging load without any under-filling was predicted as Case-18. During the experimental validation phase, some geometric comparisons of test samples were made with the FE predictions. Both forms present slight under-filling around the boss sections due to the press's intentionally insufficient loading. Overall, experimental results are in good agreement with the FE simulations, with some over-prediction linked to the friction model and the coefficient.

The DoE approach adapted to run the finite element simulations systematically helped find an optimized solution for the hot forging process of a challenging stainless-steel part effectively and economically. Using this methodology, costly and time taking die tryouts were avoided. The response surface analyses showed that further simulations are not necessary when small parameter variations in practice need to be evaluated in daily production tune-up.

Future studies using the DoE-response surface approach may be conducted further including additional forging variables such as the die temperature, the lubrication conditions, and the press ram speed. Die wear is an important consideration since it accounts for most of the forging failures, and thus it may be another reasonable topic to investigate.

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Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Barış Kabataş: Investigation, analysis, validation, original draft.

Birgül A. Temiztaş: Methodology, review, editing.

Haydar Livatyalı: Conceptualization, methodology, review, editing.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

The study presented in this paper does not have any ethical issues or no ethical approval was needed to conduct the investigation. The work is neither patented nor a trade secret in terms of Mr. Baris Kabatas's company OMTAŞ Automotive Component Industries A.Ş. (Gebze, Türkiye).

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