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Modeling of a Metal Luggage Handle with the Finite Volume Method and Factorial Experimental Design

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Abstract

This research aims to investigate the influence of process parameters during hot forming of SCM 435 material using SKD61 steel molds on both product quality and mold wear. The study employs simulation techniques combined with factorial experimental design (DOE). The modeling process uses Simufact Forming software to obtain test results and predict forming outcomes by creating a finite volume mold model. The model includes 24 base runs, with each run replicated twice/one experimental design, resulting in 48 total case-studied experiments.

The findings reveal that the optimal parameters for hot metal forming involve a workpiece diameter of 13 mm and a length of 155 mm, with the following optimal conditions: workpiece temperature of 1,250 °C, mold temperature of 120 °C, and mold friction of 0.3. These conditions result in a formed volume of 12,828 cm^3 and a hammering force of 104 kN-m. The overall desirability score was found to be 96.96 percent.

Keywords: Finite Volume Method, Metal Forging, Factorial Experimentation

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1.Introduction

Metal forging using molds is a key material forming technology that plays a significant role in enhancing the competitiveness of manufacturing industries. Forging is a manufacturing process in which metal is heated and shaped under high pressure to achieve the desired form. This process involves heating the metal to a specified temperature. Forged products have advantages over those produced by other methods, such as higher strength, durability, and fatigue resistance. One of the technologies addressing these challenges is the use of mathematical models in engineering software. These models focus on analyzing and predicting material deformation under various external parameters. Today, these processes have become more convenient and user-friendly, thanks to the development of specialized software compatible with computers, reducing the complexity of calculations. In this research, Simufact Forming software, utilizing finite volume technology, was selected to study the impact of molds.

2. Research Methodology

The finite volume method is a crucial analytical tool, and its procedures and processes are outlined as follows:

1. Review of Relevant Theoretical Studies which involves examining prior research on simulating the hot-forming process between SCM 435 workpiece material and SKD61 mold material, as well as the design and analysis of experiments. A factorial experimental design technique is applied, along with an investigation of parameters influencing the quality of the suitcase handle workpiece.

Zimniak and Piela [5] studied the use of the finite element method (FEM) for simulating the forming process to improve tool design and product quality while reducing production issues. Using the MARC finite element software, they analyzed the forming of compressor cover components through a multi-platform mold. Problems were observed at the mounting base of the workpiece, which were simulated using a 2D modeling approach. The workpiece material, STW 24 (DIN1016), was 2.5 mm thick.

The researchers found that the issues stemmed from the inappropriate size of the die radius, punch radius, and the number of forming stages. They determined that the optimal forming process required four stages with suitable die and punch radii. These adjustments ensured uniform thickness distribution throughout the forming process and minimized workpiece damage. This study demonstrated that FEM-based simulations can effectively address challenges in real-world manufacturing industries.

Zhang, Wu, Zhouc, and Wang [9] studied the enhancement of precision forming processes for 7050 aluminum alloy rib-webs using the Taguchi method. Rib-web forming can effectively strengthen and toughen the forging while simultaneously improving material utilization. The study revealed that the ratio of the initial temperature and the height-to-width ratio of the billet are the most critical factors affecting the forging quality in the analyzed area. Furthermore, the optimal combination of parameters was identified as A4 (450 °C), B1 (0.1 mm/sec), C4 (H/B=5), and D3 (=0.3). Finally, the production experiments confirmed the accuracy of the predictions quite well.

Yang, Dong, He, and Luo [10] conducted research to optimize the preform shape using RSM (Response Surface Methodology) and FEM (Finite Element Method) to improve deformation uniformity in aerospace forging. In the analysis, the FEM simulation was separated from the optimization program and served solely as a solver for calculating the function. It was found that describing the uniformity of deformation in forging must consider the even distribution of stress.

2. A simulation model was created using the Simufact Forming software to examine the hot-forming process between SCM 435 workpiece material and SKD61 steel mold material.

3. The results of the hot-forming simulation between SCM 435 workpiece material and SKD61 steel mold material were analyzed in conjunction with the design and analysis of experiments (DOE) using the factorial experimental design technique.

4. Summary of Research Implementation and Findings

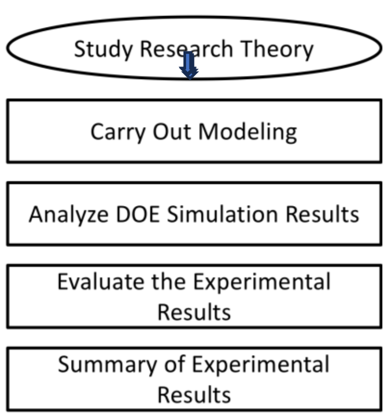

Figure 1. **Research process**

3. Research results

Testing to determine the appropriate element size for analysis and processing using the Simufact Forming software obtained testing results and predictions of the forming process through finite volume modeling. Forty-eight models were studied in conjunction with the Design and Analysis of Experiments (DOE) using the factorial experimental design technique.

From the test conducted on the forming process of a cylindrical material with a diameter of 13 mm and a length of 155 mm, the average forming force was found to be 104 kNm, with an average element volume of 13,604 cm^3. The force deviation was recorded at 14.30%, and the processing time was 180 minutes. When a smaller element size was used, the force deviation increased to 24.50%, and the processing time decreased to 387 seconds. However, while the percentage difference in force reduced by only 46%, the processing time more than doubled, as detailed in Figure 2.

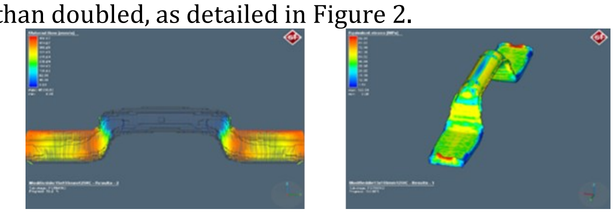

Figure 2: Simulated Model Showing the Complete Workpiece

Figure 2 illustrates the influence of temperature on the curvature. It was observed that the curvature tended to increase at the initial stage, followed by a consistent rise in curvature height. Under optimal parameter conditions—workpiece temperature of 1,250 °C, mold temperature of 120 °C, and friction coefficient of 0.3—the resulting volume was 12,828 cm^3, with a forming force of 104 kNm.

4. Statistical Analysis

The principles of Design and Analysis of Experiments (DOE) were applied using factorial experimental design techniques. Three key parameters were considered: the workpiece temperature (Workpiece-Temp) with four levels (850 °C, 950 °C, 1,150 °C, and 1,250 °C), the mold temperature (Mold-Temp) with two levels (120 °C and 180 °C), and the friction coefficient (Friction) with three levels (0.2, 0.3, and 0.4). The response variables analyzed were volume and forming force.

The experimental design included 24 basic experimental configurations, with each configuration replicated twice, resulting in a total of 48 experiments.

Table 1 provides the experimental results used for statistical analysis of the factorial design concerning volume.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	23	2391550276	103980447	1.08	0.421
Linear	6	1327489001	221248167	2.31	0.067
Workpiece-Temp	3	680619550	226873183	2.37	0.096
Mold-Temp	1	37729440	37729440	0.39	0.536
Friction	2	609140010	304570005	3.18	0.060
2-Way Interactions	11	826789780	75162707	0.78	0.653
Workpiece-Temp*Mold-Temp	3	211892555	70630852	0.74	0.540
Workpiece-Temp*Friction	6	308750504	51458417	0.54	0.775
Mold-Temp*Friction	2	306146721	153073360	1.60	0.223
3-Way Interactions	6	237271495	39545249	0.41	0.863
Workpiece-Temp*Mold-Temp*Friction	6	237271495	39545249	0.41	0.863
Error	24	2300341757	95847573		
Total	47	4691892033			

When considering the volume results in Table 1, the P-values of 0.096 and 0.060, respectively, indicate a marginal risk of having a significant main influence on the volume response. This is because the P-values are slightly greater than the significance level, α = 0.05, suggesting only a minor statistical significance.

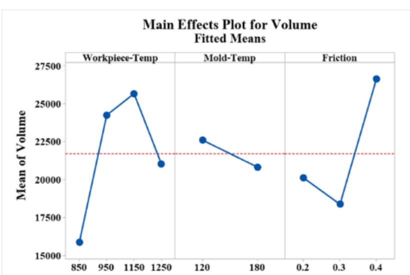

Figure 3: Main Effect Graph on the Response Volume

Results regarding the statistical analysis using factorial experimental design techniques on the response, namely the forming force, indicate that the ANOVA analysis reveals no significant differences in the main effects of all parameters at a significance level of 0.05, as all terms have a P-value > 0.05. The exception is the workpiece temperature parameter, which has a P-value < 0.05, specifically 0.001 < 0.05. Regarding the interaction effects between parameters, including 2-factor interactions and 3-factor interactions, all terms show no significant differences at a significance level of 0.05. The results of the ANOVA analysis are presented in Table 1.

Table 2: Results of the Statistical Analysis Using Factorial Design for Forming Force

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	23	192873	8385.8	9.83	* < 0.001
Linear	6	182491	30415.1	35.65	* < 0.001
Workpiece-Temp	3	180639	60213.1	70.57	* < 0.001
Mold-Temp	1	1344	1344.1	1.58	0.222
Friction	2	507	253.6	0.30	0.746
2-Way Interactions	11	4488	408.0	0.48	0.899
Workpiece-Temp*Mold-Temp	3	1788	595.9	0.70	0.562
Workpiece-Temp*Friction	6	1774	295.7	0.35	0.905
Mold-Temp*Friction	2	927	463.3	0.54	0.588
3-Way Interactions	6	5894	982.3	1.15	0.364
Workpiece-Temp*Mold-Temp*Friction	6	5894	982.3	1.15	0.364
Error	24	20477	853.2		
Total	47	213350			

The consideration of the Interaction Plot between parameters for the statistical analysis using a factorial design on the response volume is shown in Figure 4. It can be observed that all graph lines, analyzed pairwise among the three parameters—workpiece temperature, die temperature, and friction parameter—show no interaction effects between the parameters on the response volume. Although the graph lines exhibit some differences, statistically, it can be accepted that there are no significant differences at a significance level of 0.05. This aligns with the ANOVA results for volume in Table 2, which indicate P-values > α = 0.05 for all terms.

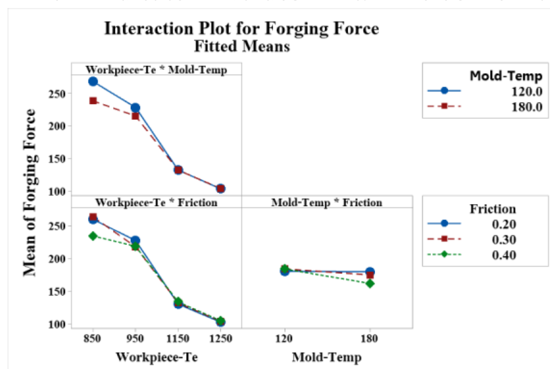

Figure 4: Interaction of Parameters on the Response of Forming Force

Figure 5 illustrates the optimization of three parameters: workpiece temperature (850, 950, 1,150, and 1,250 °C), die temperature (120 and 180 °C), and friction (0.2, 0.3, and 0.4). The response variables include volume and forming force, analyzed using the Response Optimizer. The results reveal that the optimal conditions are a workpiece temperature of 1,250 °C, a die temperature of 120 °C, and a friction value of 0.3. These parameters yield a response volume of 12,828 cm^3 and a forming force of 104 kNm, achieving an overall satisfaction level of 96.96%, as shown in Figure 5.

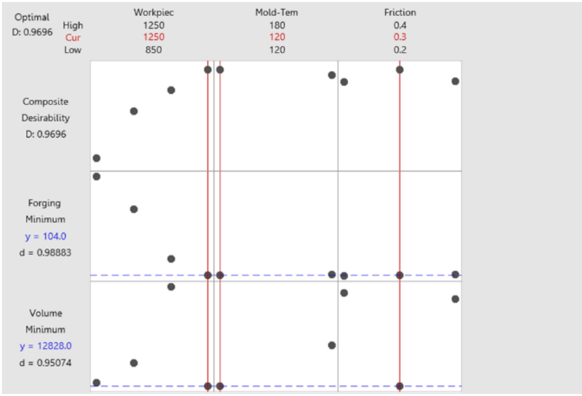

Figure 5: Optimal Condition Analysis of the Three Parameters

5. Discussion

5.1 This research focused on determining the initial size and dimensions of test specimens for production. However, the hot forging process [4], [13], [19] involves additional elements that can be further studied for optimal results. Examples include temperature, the use of lubricants, and alternative initial workpiece shapes beyond the cylindrical form used in this study. These elements provide opportunities for future case studies in parameter [4].

5.2 The use of Simufact Forming software, based on the finite volume method (FVM), emphasizes the importance of element size determination [14]. For material models of large size or complex shapes, the computation time can be extensive. To achieve results with minimal error, high-performance computers are crucial for efficient and effective model analyses.

5.3 The application of FVM, as detailed in international academic journals, in designing metal forming processes significantly reduces product development time. This is particularly beneficial for expensive real-world experiments. It allows designers to explore innovative ideas at low cost while providing rapid feedback to meet the demands of a dynamic market. The use of Simufact Forming in metal forming industries [4], [11], [17] has been validated through comparisons of tryout die analyses and predictive evaluations using various computational models.

5.4 The analysis of optimal parameters in closed-die metal forming using FVM reduces wrinkling and lowers production costs for commercial luggage handle manufacturing. This has a direct impact on extending the die wear life [7], [8], [15], thereby improving overall efficiency.

6. Summary

6.1 The simulation result of forging simulation conducted using the Simufact Forming program, which applies the finite volume method, analyzed 48 sample cases. The results indicate that the optimal initial test specimen dimensions for manufacturing luggage handle components are a diameter of 13 mm and a length of 155 mm.

6.2 The test results of hot forging using closed-die simulation revealed that the initial test specimen with a diameter of 13 mm and a length of 155 mm can be successfully forged into a product with complete dimensions and size integrity. This finding aligns with the predictions made using the Simufact Forming program, which is based on the finite volume method, showing consistent results [15].

6.3 The stress analysis performed on the workpiece following the forming simulation using the Simufact Forming program indicated that the initial test specimen can be safely forged. After undergoing plastic deformation [16], [20], the resulting stress does not exceed the ultimate strength (maximum stress before material fracture) [14], [16]. Consequently, the products can be manufactured with high quality and safety.

6.4 The optimal statistical conditions of the three parameters were found to be: workpiece temperature of 1,250 °C, die temperature of 120 °C, and a friction coefficient of 0.3. Under these conditions, the response volume achieved is 12,828 cm^3, and the forming force is 104 kNm, resulting in an overall satisfaction rate as high as 96.96%.

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