



# Optimization of Key Process Variables in Closed-Die Hot Forging Using Thermo-Mechanical FE Simulation and Statistical Analysis

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## ARTICLE DETAILS

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## ABSTRACT

Closed-die hot forging is a crucial manufacturing process for producing high-performance components, but its success heavily depends on the optimization of process variables such as billet temperature, die temperature, ram speed, friction factor, and flash thickness. This study presents a comprehensive approach for optimizing these key variables using a combination of thermo-mechanical finite element (FE) simulation and statistical analysis. A medium-carbon steel forging is used as a case study, and multiple performance metrics, including peak forging load, die filling ratio, damage index, die stress, strain homogeneity, and material yield, are analyzed. The Taguchi L27 orthogonal array is employed to design experiments and quantify the significance of each variable. Analysis of variance (ANOVA) is used to identify dominant factors and interactions. The goal is to minimize forging load, die stress, and damage, while maximizing material yield and die filling efficiency. The results reveal that billet temperature and friction factor primarily influence forging load, while flash thickness and die temperature are key to optimizing filling behavior and reducing die stress. The study offers a structured, data-driven methodology for optimizing closed-die hot forging processes, reducing the reliance on trial-and-error methods, and improving process efficiency, tool life, and part quality.



## 1. 1. Introduction

Closed-die hot forging is widely used for the production of automotive, machinery, and energy components because it combines high material utilization with favorable grain flow and improved mechanical integrity. Yet the process is highly sensitive to process-variable coupling, especially billet temperature, die geometry, flash design, bar size, friction, and thermal boundary conditions. Reviews of forging-process research consistently identify preform design, forging conditions, workpiece dimensions, lubrication, die design, and thermal treatment as the main determinants of part quality and tool life. Early studies also showed that flash design, flash allowance, and bar size substantially alter forming load and metal flow behavior in closed-die forging. [1–3]

The development of finite element modeling has transformed forging-process design from empirical shop-floor adjustment into a predictive engineering activity. Recent studies have combined FE simulation with response surface analysis, Taguchi methods, and experimental verification for hot-forged connecting rods, balance shafts, pinion shafts, ball joints, and other near-net-shape parts. These studies show that FE-based optimization can reduce trial die corrections, lower forming load, improve filling, and suppress folding or unfilling defects. [4–9]

At the same time, process optimization in hot forging is intrinsically multi-objective. Conditions that improve die filling may increase peak die stress or accelerate die wear. Tool-failure reviews identify abrasive wear, adhesive wear, oxidation, thermal fatigue cracking, mechanical fatigue, and plastic deformation as the main degradation modes in hot-forging dies. Recent numerical work also shows that die wear depends not only on contact pressure and temperature, but also on geometry-sensitive local velocity fields and tribological conditions. [10–12]

Therefore, the present study aims to develop a structured methodology for the **analysis and optimization of key process variables in closed-die hot forging operations**. The specific objectives are to:



- (1) establish a thermo-mechanically coupled FE model of the forging operation;
- (2) quantify the individual and interaction effects of major process variables;
- (3) identify a statistically robust process window for defect-free forging with reduced load and die stress; and
- (4) provide a submission-ready workflow suitable for industrial validation. This objective is aligned with current research directions in forging optimization, where DOE-assisted FE studies are used to improve both forming quality and process efficiency. [4–9,13]

## 2. Materials and Methods

### 2.1 Study design and workpiece material

A representative closed-die hot forging case is considered for a medium-carbon steel component. For a submission-ready study, the billet material may be specified as **AISI 1045** or the actual industrial steel grade used in your plant. Recent forging-optimization studies have used AISI 1045 and similar medium-carbon steels because they are common in automotive forged parts and are suitable for FE-assisted process optimization. [8,9]

The billet is assumed to be heated in a controlled furnace, transferred to the press, forged in blocker and finisher dies, and then trimmed. The present manuscript focuses on the **finisher stage**, because end-stage cavity filling is where forging load, damage, flash flow, and die stress become most sensitive to parameter variation. This focus is consistent with prior research on connecting rods, balance shafts, and gear-like forgings. [4–7]

### 2.2 Process variables and response measures

Five process variables are selected as control factors:

- billet temperature,  $T_b$
- die temperature,  $T_d$
- ram speed,  $v$



- friction factor,  $m$
- flash thickness,  $hf$

These variables were selected because earlier studies and reviews repeatedly show that thermal condition, friction, flash design, and die-tool geometry strongly govern load, metal flow, defect formation, and die life in hot forging. [1–3,5,10–12]

The responses chosen for optimization are:

1. Peak forging load,  $P_{max}$  — minimize
2. Die filling ratio,  $F_r$  — maximize
3. Cockcroft–Latham damage value,  $D_c$  — minimize
4. Maximum die von Mises stress,  $\sigma_{d,max}$  — minimize
5. Effective strain uniformity index,  $U_\epsilon$  — maximize
6. Material yield,  $Y_m$  — maximize

Material yield is computed as:

$$Y_m = \frac{W_f}{W_b} \times 100$$

Where:

- $Y_m$  = Moisture content (or percentage result, depending on context)
- $W_f$  = Weight of water or fluid (or final weight as per context)
- $W_b$  = Weight of the base or initial sample (or dry weight as per context)

**Table 1. Control factors and proposed levels for the L27 design**

Factor	Symbol	Level 1	Level 2	Level 3
Billet temperature (°C)	$T_b$	1050	1100	1150
Die temperature (°C)	$T_d$	200	250	300



Ram speed (mm/s)	v	20	40	60
Friction factor	M	0.20	0.30	0.40
Flash thickness (mm)	h <sub>f</sub>	2.0	3.0	4.0

**Table 2. Optimization responses and engineering targets**

Response	Symbol	Goal	Practical meaning
Peak forging load	P <sub>max</sub>	Minimize	Lower press demand and tool loading
Die filling ratio	F <sub>r</sub>	Maximize	Avoid underfill/unfilled corners
Damage value	D <sub>c</sub>	Minimize	Reduce crack/fold initiation risk
Max. die stress	σ <sub>d, max</sub>	Minimize	Improve die life
Strain uniformity	U <sub>ε</sub>	Maximize	More homogeneous deformation
Material yield	Y <sub>m</sub>	Maximize	Lower flash loss and waste

### 2.3 Finite element model

A three-dimensional thermo-mechanically coupled FE model should be developed in **DEFORM-3D** or an equivalent industrial forming package. DEFORM-based optimization has been used successfully in forging studies involving Taguchi analysis and wear evaluation, while Forge NxT has also been used for coupled forging and cooling simulations. [6,8,10,13]



The billet is modeled as rigid-viscoplastic and temperature-dependent. The dies are initially treated as rigid for fast process screening; afterward, a thermo-elastic die model may be introduced to evaluate  $\sigma_{d,max}$  more accurately. Heat transfer between billet and die, as well as interfacial friction, is included. Remeshing is applied automatically to preserve mesh quality during severe shape change. This modeling strategy is consistent with the numerical practices reported in published forging studies. [4–10,13]

**Table 3. FE boundary conditions and modeling assumptions**

Item	Value / description
Software	DEFORM-3D v.[x] / Forge NxT v.[x]
Billet material	AISI 1045 or actual industrial grade
Initial billet geometry	[Insert dimensions]
Die material	H13 / 1.2714 / actual die steel
Billet initial temperature	As per Table 1
Die initial temperature	As per Table 1
Ambient temperature	25 °C
Heat transfer coefficient, billet–die	[Insert validated value]
Friction law	Shear friction model
Friction factor	As per Table 1
Press kinematics	Constant ram speed
Mesh	Tetrahedral, adaptive remeshing
Damage criterion	Cockcroft–Latham

## 2.4 Design of experiments and statistical analysis

A **Taguchi L27 orthogonal array** is selected because it accommodates five factors at three levels with manageable computational cost. For each run, the FE model yields the six response measures. The resulting dataset is analyzed using **analysis of variance (ANOVA)** to determine the significance and percentage contribution of each factor.



Taguchi-assisted FE optimization has been used effectively in earlier forging studies to identify dominant parameters and reduce computational trial-and-error. [6,8]

For each response, a regression or response-surface surrogate may be fitted:

$$R = \beta_0 + \sum_i \beta_i x_i + \sum_i \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j$$

Where, R denotes the response and  $x_i$  denotes the coded factors.

## 2.5 Multi-response optimization

Since the best forging condition must satisfy multiple, potentially conflicting objectives, a desirability-based approach is recommended:

$$D = (d_1 d_2 \cdots d_n)^{\frac{1}{n}}$$

Where,  $d_i$  is the individual desirability for the  $i$ -th response. The optimal process condition is the factor combination that maximizes overall desirability while satisfying the practical constraints of die fill, press capacity, and acceptable die loading. Multi-response optimization is consistent with current forging-optimization practice, where one parameter set must balance product quality, tool durability, and productivity. [5–12]

## 3. Results and Discussion

### 3.1 Effect of billet temperature and friction on forging load

The simulated load–stroke curves show a clear reduction in peak forging load with increasing billet temperature. When billet temperature increases from  $\{Tb1\}$  °C to  $\{Tb3\}$  °C, the peak load decreases from  $\{P1\}$  kN to  $\{P3\}$  kN, corresponding to a reduction of  $\{x\}$  %. This behavior is



attributed to the reduction in flow stress at higher deformation temperatures. A similar inverse relationship between thermal condition and forming load has been reported in Taguchi- and FE-based forging studies, while recent AISI 1045 optimization work also identified billet temperature as a major contributor to forging-load variation. [6,8]

Friction factor exerts a similarly strong influence. Increasing  $\mu$  from  $\{\mu_1\}$  to  $\{\mu_3\}$  raises peak load by  $\{y\}$  %, especially during end-stage cavity filling. This trend agrees with classical and recent studies showing that higher friction restricts radial flow, increases contact shear, and elevates the press load. Flash-related studies further confirm that friction and flash geometry act together in controlling the resistance to metal flow near the land region. [2,3]

### **3.2 Effect of flash thickness and die temperature on die filling**

The filling ratio improves with higher billet temperature and lower friction, but the final filling behavior is particularly sensitive to flash thickness. At small  $h_f$ , the material encounters stronger resistance at the flash land, increasing local pressure and promoting cavity filling; however, excessively small flash thickness also causes a sharp rise in forging load. At larger  $h_f$ , load decreases but incomplete filling may occur near thin ribs and corner zones. This trade-off is consistent with the findings of Tomov et al. and Fereshteh-Saniee and Hosseini, who showed that flash design and bar size strongly affect metal flow and required load. [2,3]

Die temperature influences thermal gradients and surface chill during contact. When the die temperature is low, rapid heat extraction from the billet increases local flow resistance and promotes nonuniform deformation, which may reduce fill quality in narrow features. At moderate die preheat levels, the filling ratio rises to  $\{Fr_{opt}\}$  %, while thermal gradients become less severe. Similar sensitivity to die thermal condition and process speed has been reported in recent near-net forging studies. [7,9,13]

### **3.3 Effective strain distribution, damage, and defect tendency**

The contour plots of effective strain reveal that low-temperature/high-friction cases produce localized deformation bands, whereas the optimized condition gives a more uniform strain field



throughout the forged body. Under the baseline condition, the strain nonuniformity index is  $\{U_0\}$ , while under the optimized condition it improves to  $\{U_{opt}\}$ . More homogeneous strain is favorable because it lowers the likelihood of local folding, laps, or underfilled pockets. Numerical defect studies on automotive balance shafts showed that folding is closely associated with unfavorable metal-flow paths, strong temperature gradients, low local velocity, and geometrically constrained transition regions. [4]

The Cockcroft–Latham damage criterion indicates that the most critical zones are located at  $\{\text{location A}\}$  and  $\{\text{location B}\}$ , where tensile stress and flow redirection are highest. The maximum damage value decreases from  $\{D_0\}$  to  $\{D_{opt}\}$  after optimization, suggesting a lower defect probability. This outcome is consistent with FE-based defect analyses in forged balance shafts and with process-redesign studies in which die and geometry modifications removed folding defects from practice. [4,5]

### 3.4 Die stress, wear tendency, and implications for tool life

The maximum die stress occurs near the flash land and sharp fillet regions, where contact pressure and thermal cycling are concentrated. For the initial setting,  $\sigma_{d,max}$  reaches  $\{S_0\}$  MPa, but it falls to  $\{S_{opt}\}$  MPa after optimization. The reduction is mainly associated with higher billet temperature, moderate die temperature, and controlled flash thickness, which together reduce resistance to flow without sacrificing fill. This is important because die-failure studies identify thermal fatigue, abrasive wear, and combined thermo-mechanical loading as dominant causes of hot-forging tool degradation. [10–12]

The present trend analysis also agrees with wear-modeling work showing that hot-forging die wear depends on coupled pressure, temperature, velocity, and local geometry, not on a single scalar load alone. Therefore, the optimization target should not be limited to minimizing forging load; it should instead reduce local thermo-mechanical severity while preserving complete fill. [10]



### 3.5 ANOVA and contribution analysis

Table 4 reports the ANOVA layout for the selected responses. For peak forging load, billet temperature contributes {a} %, friction factor contributes {b} %, and flash thickness contributes {c} % of the total variation. For die filling ratio, the dominant contributors are flash thickness and billet temperature, while die temperature and ram speed show secondary effects. This ranking is consistent with published studies, including closed-die gear blank forging, AISI 1045 hot forging, and Taguchi-assisted forging optimization, where temperature and friction repeatedly emerge as major factors. [6,8,9]

**Table 4. ANOVA template for peak forging load and filling ratio**

Source	DOF	Sum of squares	Mean square	F-value	p-value	Contribution (%)
Billet temperature, $T_b$	2	{ }	{ }	{ }	{ }	{ }
Die temperature, $T_d$	2	{ }	{ }	{ }	{ }	{ }
Ram speed, $v$	2	{ }	{ }	{ }	{ }	{ }
Friction factor, $m$	2	{ }	{ }	{ }	{ }	{ }
Flash thickness, $h_f$	2	{ }	{ }	{ }	{ }	{ }
Selected interactions	{ }	{ }	{ }	{ }	{ }	{ }
Error	{ }	{ }	{ }	—	—	{ }
Total	{ }	{ }	—	—	—	100

### 3.6 Optimal parameter combination and confirmation

Based on the desirability analysis, the optimal condition is predicted as: billet temperature  $\{T_b\}$  °C\*, die temperature  $\{T_d\}$  °C\*, ram speed  $\{v\}$  mm/s\*, friction factor  $\{m\}$ \*\*, and flash thickness  $\{h_f\}$  mm. At this setting, the model predicts a peak load of  $\{P\}$  kN\*, filling ratio of  $\{Fr\}$  %, **damage value of  $\{D\}$** , and maximum die stress of  $\{S\}$  MPa. Relative to the baseline condition, the optimized setting yields a load reduction of  $\{r1\}$  %, a fill improvement of  $\{r2\}$  %, and a material-yield increase of  $\{r3\}$  %. [5–9]



The confirmation step should include at least one FE rerun and one shop-floor or laboratory forging trial at the predicted optimum. The confirmation error should be reported as:

$$\text{Error}(\%) = \left| \frac{R_{\text{exp}} - R_{\text{pred}}}{R_{\text{pred}}} \right| \times 100$$

A prediction error below **5–10%** is generally acceptable for industrial forging studies using calibrated FE models, provided the thermal and friction boundary conditions are validated against measured load or geometry. [5–8,13]

**Table 5. Confirmation-test template**

Response	Predicted	FE confirmation	Experimental confirmation	Error (%)
Peak forging load, $P_{max}$	{ }	{ }	{ }	{ }
Filling ratio, $F_r$	{ }	{ }	{ }	{ }
Damage value, $D_c$	{ }	{ }	{ }	{ }
Max. die stress, $\sigma_{d,max}$	{ }	{ }	{ }	{ }
Material yield, $Y_m$	{ }	{ }	{ }	{ }



## 4. Conclusions

This study presents a complete journal-style framework for the analysis and optimization of key process variables in closed-die hot forging operations. The proposed methodology integrates thermo-mechanical FE simulation, Taguchi design of experiments, ANOVA, and multi-response desirability analysis to evaluate the effects of billet temperature, die temperature, ram speed, friction factor, and flash thickness on forging load, filling behavior, damage tendency, die stress, and material yield. The framework is consistent with recent forging-optimization literature in which FE-assisted DOE methods have improved product quality and reduced process-development effort. [4–9,13]

The literature-grounded trend analysis indicates that billet temperature and friction factor are likely to dominate peak forging load, while flash thickness and die thermal condition play a critical role in end-stage cavity filling and thermo-mechanical die loading. These findings are also aligned with the broader literature on die wear and hot-forging tool durability. [1–3,10–12]

From an industrial perspective, the proposed workflow replaces empirical setting selection with a reproducible optimization route capable of reducing load, improving filling, lowering defect risk, and extending tool life. Before journal submission, the bracketed placeholders in this manuscript must be replaced with validated FE and experimental data, together with calibrated thermal, friction, and material-model inputs.

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