

Review

Numerical Simulation of Die Forging Processes: A Review of Finite Element Modelling Approaches, Material Models and Process Parameters

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Abstract

Die forging is a widely used production method for manufacturing high-strength components with high accuracy and good mechanical properties. Since the die forging process involves many complicated thermo-mechanical coupled field physical problems, such as large plastic deformation, high temperature, friction, and heat transfer, etc., experimental studies are difficult and expensive to perform. The numerical simulation method has become the main method of study and optimal design for the die forging process. This paper reviews the published papers on numerical simulation of the die forging process from 2016 to 2026, in a structured literature review of computational simulations dealing with die forging processes. The literature search was conducted using the Scopus and Web of Science databases. After screening and full-text assessment, 24 relevant journal articles were selected for this paper. The articles studied were analyzed in terms of finite element modelling strategies, constitutive and material models used, friction and thermal boundary conditions considered, and process parameters. Typical results obtained from the studies discussed in the paper include stress, strain, temperature, forging load, and metal flow. The current state-of-the-art research has evolved from simple metal-flow predictions to more complex thermo-mechanical models, and even optimization-based models. Most of the current studies are based on experimentally derived constitutive equations, as well as more complex friction and heat-transfer models. Furthermore, studies applying optimization methods (Taguchi methods, design of experiments, machine learning, artificial intelligence) are increasingly common. The growing interest in the digital twin concept and real-time process control is observed. However, experimental validation, thermal contact modelling, and simulation of stress, strain, temperature, and microstructure in one simulation remain key challenges.

Keywords: die forging; closed-die forging; finite element method; numerical simulation; constitutive model; metal flow; friction; heat transfer; temperature distribution; process optimization



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1. Introduction

Forging is a primary shaping process in manufacturing. This technique involves deformation of workpieces taking place between two dies, either by applying impact or a gradual load for deformation [1]. Forging can be described as the technology of shaping the metal piece into the desired shape [2]. While casting involves pouring molten metal into

molds and machining removes material from a larger block, forging achieves its exceptional material properties through the deformation of solid metal. This process refines the metal's grain structure, aligning it with the part's shape and maximizing its performance [3].

The importance of die forging in the industrial sector is a result of the required high strength, reliability, dimensional accuracy, and long service life of the manufactured components [4]. Forged parts are widely used in automotive, aerospace, energy, tooling, and heavy machinery applications. The failures and defects in such components may result in high economic loss or safety risk [5]. In closed-die forging, the quality of the final component depends on the proper design of the billet, preform, die cavity, flash system, lubrication condition, forming temperature, and press parameters. Therefore, modern forging process design must achieve the required final geometry and minimize material waste, forming load, die wear, defects, and production cost [4–6].

Forging can be classified into cold or hot forging based on the temperature [7,8]. Cold forging is carried out below the recrystallization temperature of the metal and its alloys, without initial or intermediate heating of the preform and billet [1]. Hot forging is performed at a temperature that is higher than the recrystallization temperature of the metal to be forged. The recrystallization temperature is defined as the temperature at which new strain-free grains form and grow in the deformed metal. During recrystallization, the strain hardening of the respective metal is prevented using the process of heating at high temperatures. Heating is done on both the workpiece and dies, with the latter being at a few hundred degrees cooler than the former workpiece [1].

Die forging is a complicated process that involves heat and pressure. During shaping, the workpiece is subjected to deformation, severe contact pressure, frictional sliding, heat generation due to plastic work, and heat transfer between the workpiece, dies, and the environment [6]. These coupled effects strongly influence material flow, die filling, flash formation, residual stress, microstructural evolution, and final mechanical properties [5]. For instance, a slight change in the billet temperature can affect the material's flow and lead to variations in the final product's properties. Small changes in process parameters, such as billet temperature, die temperature, friction coefficient, ram speed, or preform geometry, can lead to significant differences in forging load, temperature distribution, and defect formation [9].

Although forging offers excellent mechanical properties and produces parts very close to net shape, the process has complex deformation characteristics and performs at high temperatures and large strains. The process involves friction between the dies and the billet, and a very large amount of material flow, all of which makes experimental investigation extremely difficult, expensive, and time-consuming. Traditionally, the development of any forging process has depended on experience, experimental physical trials, and subsequent modification to the die. However, this approach is costly and consumes time, with physical trials where each trial would require billet preparation, heating, die modification, press runs, and subsequent inspection of the forged product [6]. Moreover, experimental trials can reveal final defects such as underfilling, folds, cracks, or excessive flash, but they do not easily provide complete information about the internal evolution of stress, strain, temperature, damage, and material flow during deformation [10]. Therefore, experiments remain essential for validation, but they are often insufficient on their own for efficient process design and optimization. Thus, numerical simulation has become an essential tool in the analysis and design of forging operations. Among the available numerical methods, the finite element method (FEM) is the most widely used because it can accurately predict metal flow, stress and strain distribution, temperature changes, die filling and forming loads during the forging process. FEM-based simulations also help optimize process parameters

such as billet temperature, die temperature, friction conditions and ram speed before actual manufacturing takes place [11,12].

Several previous reviews have discussed forging simulation, process modelling, die design, and optimization [4,5]. However, earlier studies were either focused on the older literature, general forging simulation, or broad optimization methods rather than providing a focused synthesis of recent FEM-based die forging research [4,5]. In particular, limited attention has been given to comparing recent studies according to constitutive material models, friction and thermal boundary conditions, validation methods, defect prediction approaches, and simulation outputs [5,13]. Since 2016, forging simulation research has increasingly moved toward coupled thermo-mechanical modelling, defect prediction, die-life improvement, design of experiments, machine learning, surrogate modelling, and physics-informed preform design [13–16]. Recent studies also show increasing attention to digital-twin-based quality monitoring, deep-learning-based energy prediction, robotic or automated forging, and data-driven die-degradation prediction in hot die forging processes [17–20]. Therefore, an updated review covering the period 2016–2026 is needed to clarify recent developments, identify current limitations, and define future research directions. The new perspective of this review is that it does not treat die forging simulation only as a general FEM application, but compares recent studies according to modelling inputs, boundary-condition assumptions, validation approaches, predicted outputs, defect-analysis capability, and computational efficiency.

The review period from 2016 to 2026 was selected to focus on recent developments in FEM-based die forging simulation. Although earlier studies established the foundation of forging simulation, the last decade has shown a clear increase in coupled thermo-mechanical modelling, experimentally calibrated friction and heat-transfer conditions, process optimization, machine-learning-assisted simulation, and digital-twin-oriented approaches. Therefore, earlier works are considered as background references, while the detailed review is limited to recent studies in order to provide a focused analysis of current modelling trends and future research directions.

This paper reviews recent works on numerical simulation of die forging between 2016 and 2026. Current finite element methods in the die forging process, commonly used constitutive models for material, thermal, and friction boundary conditions, process parameters, methods for validating numerical results, and simulation results of die forging, such as stress and strain, temperature, metal flow, die filling, forging force, and defect, are reviewed.

The central question addressed by this review is: how have recent FEM-based die forging studies modelled material behavior, friction and thermal boundary conditions, process parameters, validation, and simulation outputs, and what limitations remain for future development?

To reflect this scope, the manuscript is organized according to the main modelling groups identified in the reviewed literature. Section 3 presents the main research directions and a grouped classification of the selected studies. In Section 4 is a discussion of FEM formulation, computational approaches, mesh generation and adaptive remeshing, constitutive material models, rigid and deformable die assumptions, and friction modelling. Analyses of the main process parameters are in Section 5, including billet temperature, die temperature, ram speed, friction coefficient, heat-transfer conditions, and billet/preform geometry. Section 6 compares modelling trends, validation issues, research gaps, and future directions.

2. Literature Review Methodology

A structured literature review methodology was adopted to identify and analyse recent studies related to the numerical simulation of die forging processes. The review focused on peer-reviewed journal articles discussing finite element modelling, constitutive equations, friction, thermal effects, process parameters, and simulation outputs in die forging.

Two scientific databases were used: Scopus and Web of Science. These databases were selected because they provide broad coverage of high-quality engineering and manufacturing journals.

The search was conducted in March 2026. In Scopus, the search was performed under “Article title, Abstract, Keywords”. In Web of Science, the search was performed in the field “Topic”. The following search string was used:

(“die forging” OR “closed die forging” OR “impression die forging”) AND (“finite element method” OR FEM OR “numerical simulation” OR “finite element modelling”) AND (“material model” OR “constitutive model” OR friction OR temperature OR “boundary condition” OR “metal flow” OR stress OR strain’).

The search was limited to the publication years between 2016 and 2026, English-language publications, and peer-reviewed journal articles only. The period between 2016 and 2026 was chosen to best represent the last decade of development in a numerical simulation of die forging. Many recent papers include coupled thermo-mechanical models, improved boundary conditions, optimization methods, AI, and digital-twin concepts. However, the earlier papers were not ignored; instead, they were used for background information and the historical development of forging simulation.

The academic databases were searched for the established literature, and this returned 1165 records in total, of which 64 were found in Scopus and 1101 in Web of Science. However, the number of records was then reduced using the pre-specified filters for article type, year of publication, language, and full-text availability, to 62 records for screening. Three of these records were identified as duplicates and therefore removed. The remaining 59 unique articles were read from the titles, keywords, and abstracts to check if they were relevant to the review question.

The inclusion criteria were as follows: studies that focus on die forging, closed-die forging, or impression-die forging, and apply finite element analysis (FEM) or another numerical modelling technique. In addition, also included were studies that address at least one of the following topics: constitutive models, friction laws, thermal boundary conditions, metal flow behaviour, stresses, strains, temperatures, or loads. The included papers also had to provide sufficient details about the numerical model, modelling assumptions, simulation parameters, and predicted results.

On the other hand, the exclusion criteria were as follows: duplicate records, conference papers, review articles, books, and book chapters. Studies mainly focused on open-die forging, radial forging, extrusion, rolling, swaging, or other forming techniques outside the scope of die forging were also excluded. In addition, papers dedicated entirely to die wear, tooling design, microstructural analysis, or experimental work without computational simulation were excluded.

Following the title, keyword, and abstract screening, 26 articles were identified to be excluded from the study as they did not relate to the proposed scope of the current study. The full texts of 33 papers were assessed in the screening process. From these, 9 articles were excluded due to the majority of the content relating to open-die forging, microstructural evolution without die forging simulation, and other forming processes. A total of 24 articles were selected for the literature review.

The last group of studies that was considered included two categories: 16 primary studies focusing on closed- or impression-die forging process simulation, and 8 additional papers concerning subjects such as friction modelling, thermal aspects, die lifetime, and residual stresses.

In addition to the selected articles several very recent supporting publications were also considered to enrich the state-of-the-art discussion, particularly in relation to digital-twin-based monitoring, deep-learning-based prediction, die degradation, tool durability, robotic forging, recent process-parameter optimization, near-net die design, industrial process analysis, and high-temperature constitutive modelling.

The complete selection procedure is illustrated in Figure 1 using a PRISMA-style flow diagram.

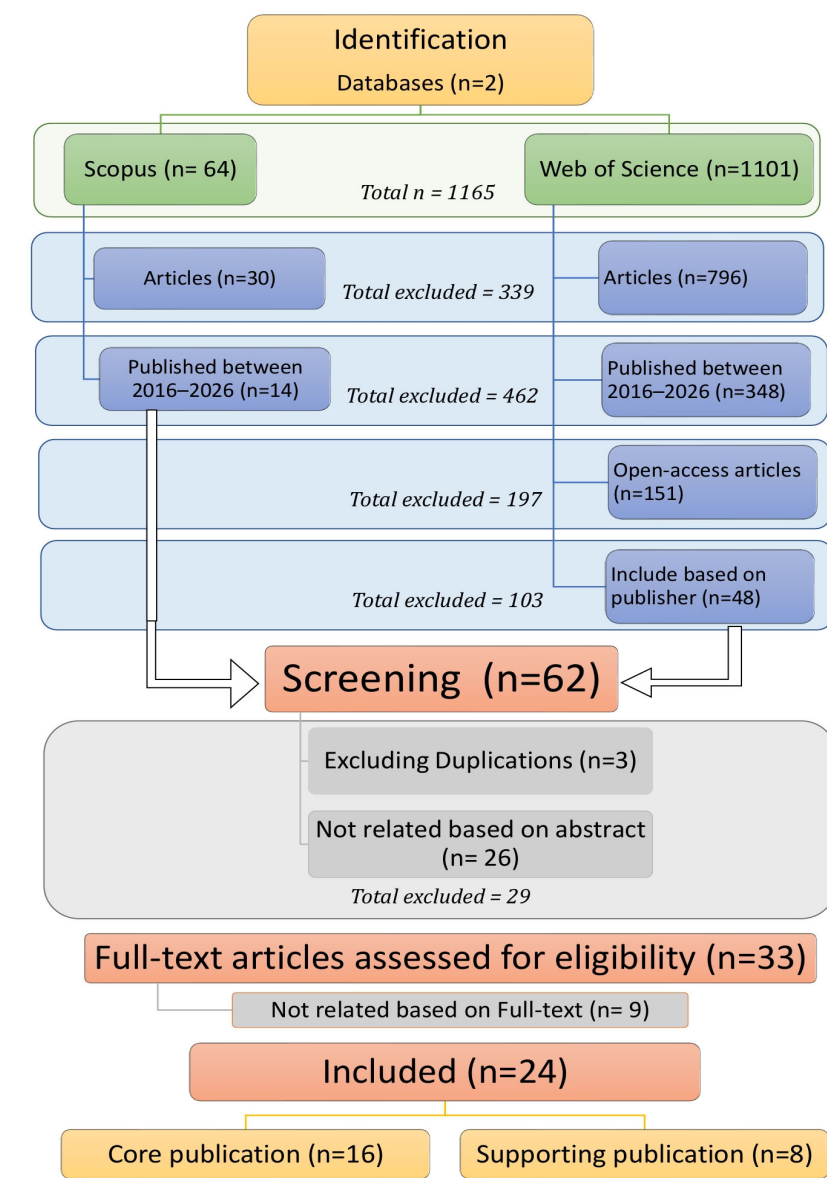


Figure 1. PRISMA-style flow diagram illustrating the identification, screening, eligibility assessment and final selection of journal articles for the literature review on numerical simulation of die forging processes.

Figure 2 shows the keyword co-occurrence network of the reviewed studies. The dominant terms are related to finite element modelling, numerical simulation, forging, hot forging, cold forging, preform design, and microstructure. This indicates that recent

die forging simulation research is mainly concentrated on FEM-based process prediction, forming-parameter optimization, preform design, and microstructural analysis. The presence of optimization-related terms such as Taguchi method, design of experiments, and response surface methodology also confirms the increasing use of statistical and data-driven methods in forging simulation research.

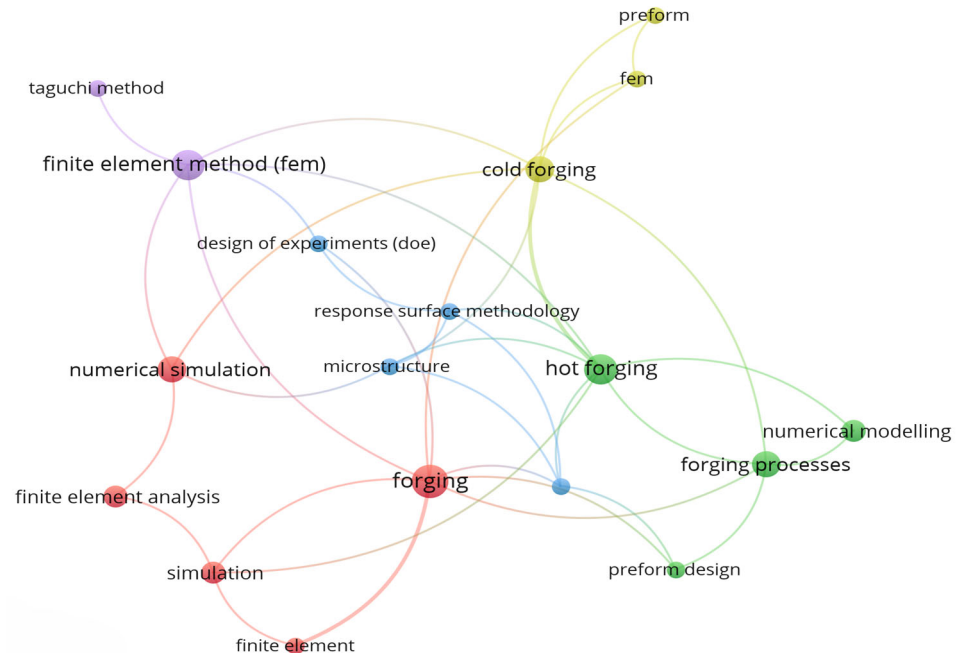


Figure 2. Keyword co-occurrence network of the reviewed forging simulation studies (VOSviewer 1.6.20.0).

3. Main Research Directions in Die Forging Simulation

The reviewed literature shows that numerical simulation of die forging has developed from simple deformation analysis toward integrated thermo-mechanical and optimisation-based modelling. The earliest studies primarily focused on predicting metal flow and die filling, whereas more recent work additionally considers thermal behaviour, constitutive modelling, residual stress, microstructure, and process optimization [21–24].

Table 1 provides a direct comparison of the reviewed studies according to process type, material, FEM software, modelling inputs, and main outputs.

Table 1. Comparative summary of FEM-based forging simulation studies reviewed in this paper.

Ref.	Process	Material	FEM/Method	Key Modelling Inputs	Main Outputs
[14]	Hot forging/die-life optimization	32CrMoV12 die steel	QForm-3D (version NR) + DOE	Contact/wear-based model; complete forging cycle	Die stress, die wear, fracture prevention, die-life improvement
[15]	Flashless/near-flashless 3D forging	Cross-joint; three-lobe drive hub	DEFORM 3D 13.1 + SpaceClaim/ANSYS 2022 R2 + Python 3.11 + material-point backtracking	Physics-informed material-flow model; friction variability; thermal gradients	Preform geometry, flash reduction, material flow, and defect-free forming
[21]	Closed-die hot forging/preforming design	AISI-5120; JIS-SKD61 dies	DEFORM-3D (version NR) + Taguchi + GRA	Fixed shear friction 0.2–0.4; billet 900–1000 °C; dies 200 °C	Folding reduction, filling degree, die tensile stress, optimal preforming parameters

Table 1. Cont.

Ref.	Process	Material	FEM/Method	Key Modelling Inputs	Main Outputs
[22]	Large open-die ring forging	S355NL; 5CrNiMo dies	DEFORM (version NR) + BP-NN + FLIR T460 thermal imaging	Arrhenius model; COF = 0.7; measured contact HTC; convection/radiation	Temperature field, stress/strain, optimal die speeds, online temperature prediction
[24]	Hammer forging	708M40 steel	DEFORM (version NR) + uncertainty quantification	Hyperbolic-sine model; lubricated/unlubricated conditions; elevated temperature	Flow-stress uncertainty, final height, flow lines, post-forging geometry
[25]	Connecting-rod forging/preform design	NR	Abaqus CEL (version NR)	CEL formulation; other inputs NR	Preform geometry, flash reduction, forging load, die filling; 42% force reduction and 64% flash-volume reduction
[26]	Hot precision forging on a hydraulic hammer	Window fitting forgings	Forge 3.0 NxT + high-speed camera	Tribological conditions; tool/forging temperature distribution	Material flow, die filling, defects, forging force, tool displacement, and dimensional precision
[27]	Cold forging/compression test	AISI 1045 steel	ANSYS (version NR)	COF = 0.05; isothermal cold condition	Barreling, stress distribution, microhardness, and deformation accuracy
[28]	Hot forging of the conjunction gear	42CrMo steel	DEFORM-3D (version NR) + Pro/ENGINEER + RSM	Hyperbolic-sine constitutive model; thermo-mechanical microstructure model	Temperature, stress, strain, recrystallization fraction, grain size
[29]	Hot closed-die forging with AI control	NR	Abaqus/Standard (version NR) + MATLAB (version NR) + DeepForge ML + MPC	ML microstructure surrogate; die interaction; surface-temperature control	Microstructure prediction, grain-size control, inter-stroke waiting-time optimization
[30]	Precision hot die forging/multi-impression process	AISI 304 stainless steel	Forge NxT 3.0 + industrial trials	Thermal imaging + FEM thermal analysis; other inputs NR	Material flow, die filling, temperature, stress/strain, force, productivity, energy
[31]	Cold forging of the V8 camshaft	AISI 8620; AISI-H-26 dies	DEFORM-3D (version NR) + AutoCAD (version NR)	Cold forging condition; other inputs NR	Metal flow, volumetric analysis, die stress, flash, underfilling, and preform optimization
[32]	Isothermal forging of a multi-rib component	TA15 titanium alloy	DEFORM-3D (version NR) + MATLAB (version NR) + IAPF + RSM/NSGA-II	Rigid-plastic model; friction as uncertainty; temperature transfer neglected	Rib-groove filling, strain homogeneity, material flow, robust billet optimization
[33]	Closed-die hot forging of valve cover	CuZn40Pb2 brass	DEFORM-3D v10.2 + ZW3D CAD + experiments	Lubrication-dependent COF; billet 700 °C; die 350 °C	Defect formation, filling sequence, forging force, stress/strain
[34]	Die forging structural parts/residual stress	Aircraft structural forgings	DEFORM (version NR) + Bayesian inference + monitoring-data fusion	Forging/heat-treatment simulation prior; other inputs NR	Global residual stress field, deformation force, RSF distribution
[35]	Hot forging optimization of the connecting rod	DIN 42CrMo4 steel	DEFORM-3D (version NR) + MINITAB 22 + Taguchi + ANOVA	Arrhenius model; COF as process factor; Fourier heat balance	Maximum stress/strain, tensile stress, damage, optimal parameters
[36]	Cryogenic cyclic closed-die forging	Copper	DEFORM 3D™ (version NR) + experiments	Cryogenic and room-temperature conditions; other inputs NR	Hardness distribution, strain maps, stress distribution, microstructural stability
[37]	Hydraulic hammer forging	NR	DEFORM3D v13 + sequential approximate optimization / RBF network	Energy-based hammer forging model	Total energy, forging load, underfill constraint, optimal energy distribution

Table 1. Cont.

Ref.	Process	Material	FEM/Method	Key Modelling Inputs	Main Outputs
[38]	Hot forging of Ti-6242 alloy	Ti-6242	DEFORM ver. 11.0 / DEFORM-2D + DNN	JMAK + flow-instability model; graphite plate; 750–950 °C	Grain size, flow instability, microstructural risk index, optimized parameters
[39]	Cold upset forging/buckling prediction	Al, stainless steel, Cu	ANSYS 2023R1 + nonlinear regression	Hollomon law; COF = 0.12–0.35; cold condition	Buckling stress, stress distribution, billet deflection, geometry/friction effects
[40]	Multi-stage hot forging/die thermal management	38MnVS5; H13 dies	FORGE NxT 3.2 + COMSOL Multiphysics (version NR) + thermal imaging	Hansel–Spittel; Coulomb friction; full-cycle thermal model; spray/lubrication cooling	Die thermal field, thermal-cycle evolution, contact/spray cooling, validation
[41]	Thermo-mechanical drop forging/ring compression	BS970:708M40 steel	DEFORM v11.3 + 2D axisymmetric thermo-mechanical FE model + experiments	Tabular flow stress; shear friction 0.08–0.7; coupled thermo-mechanical model	Deformation, ring shape, friction calibration, temperature, lubricant effect, damage

NR: not reported; COF: coefficient of friction; HTC: heat-transfer coefficient; DOE: design of experiments; RSM: response surface methodology; GRA: grey relational analysis; DNN: deep neural network; MPC: model predictive control.

Table 1 indicates that the reviewed studies differ considerably in the level of modelling detail reported. Some studies clearly specify the constitutive model, friction model, thermal assumptions, and validation method, whereas others provide only partial information. This variation highlights the need for more complete reporting of simulation inputs and boundary conditions in future die forging FEM studies to improve reproducibility and comparison between results.

To address the broad range of modelling variables considered in the reviewed literature, the studies were grouped according to their dominant modelling focus rather than being discussed only paper by paper. This structure allows the review to compare FEM formulation, constitutive material modelling, friction and thermal boundary conditions, process parameters, validation approaches, simulation outputs, and optimization methods as separate but connected modelling groups. The grouping also shows that most recent studies combine more than one modelling aspect; for example, thermo-mechanical models often include temperature-dependent material behaviour, friction assumptions, heat-transfer coefficients, and process-parameter optimization within the same FEM framework.

Table 2 shows that recent FEM-based die forging studies can be divided into several modelling groups rather than being considered only as individual papers. Studies focused on FEM formulation and computational approaches mainly support the selection of software, rigid-plastic or viscoplastic formulations, coupled Eulerian–Lagrangian formulations, rigid/deformable die assumptions, and thermo-mechanical coupling. Constitutive and material-model studies are mainly important for predicting temperature- and strain-rate-dependent flow stress, forming load, strain distribution, and microstructural response. Friction and thermal boundary-condition studies improve the reliability of temperature, metal flow, and die contact predictions. Process-parameter studies are useful for understanding the effects of billet temperature, die temperature, ram speed, friction coefficient, and billet/preform geometry on die filling, flash formation, and defect development. Output, defect, and validation studies provide the link between simulation results and industrial quality indicators, while optimization and AI-assisted studies show the recent trend toward data-driven parameter selection, surrogate modelling, and digital-twin-oriented process control.

Table 2. Grouped classification of the reviewed FEM-based die forging studies according to their dominant modelling focus, considered modelling aspects, and related references.

Review Group	Main Aspects Considered	Related Studies
FEM formulation and computational approach	Software, rigid-plastic/viscoplastic formulation, CEL formulation, thermo-mechanical coupling	[25–27,30–33,41]
Constitutive and material models	Arrhenius-type models, hyperbolic-sine equations, tabulated flow-stress data, temperature- and strain-rate-dependent material behaviour	[22,24,28,35,38,41]
Friction and thermal boundary conditions	Coulomb/shear friction, lubrication effects, contact heat-transfer coefficient, pressure/temperature-dependent thermal contact	[22,33,40,41]
Process-parameter studies	Billet temperature, die temperature, ram speed, friction coefficient, billet/preform geometry	[15,21,25,32,33,35]
Output, defect, and validation studies	Metal flow, die filling, folding, flash, forging load, stress/strain, temperature, damage, residual stress, hardness, experimental comparison.	[14,21,25,26,31,34,36,40]
Optimization and AI-assisted studies	Taguchi, DOE, RSM, NSGA-II, neural networks, machine learning, surrogate models, digital-twin-oriented control	[14,21,29,32,35,38]

Table 3 shows that the selection of a modelling approach depends strongly on the intended simulation outcome. Rigid-plastic and rigid-viscoplastic models are efficient for general deformation, metal-flow, die-filling, and forming-load prediction. Thermo-mechanical and thermo-viscoplastic models provide better accuracy for hot forging cases where temperature, strain rate, heat generation, and heat transfer strongly affect material behavior. CEL and advanced material-flow models are more suitable for severe deformation, preform design, underfilling, and flash prediction, although they require higher computational effort. Friction/thermal calibrated models improve contact and defect prediction but depend on experimental calibration, while damage, residual stress, and AI-assisted models provide more advanced quality or optimization outputs but require more data and validation.

Overall, the reviewed studies show that the value of FEM-based die forging simulation depends on matching the modelling approach to the intended output. CEL-based and advanced material-flow models are more suitable for severe deformation, preform design, underfilling, and flash prediction, while calibrated friction and heat-transfer models improve contact and temperature prediction in hot forging cases. Constitutive models directly influence predicted flow stress, forming load, strain distribution, and final geometry, whereas optimization and AI-assisted approaches support faster parameter selection and reduce the trial-and-error process design.

Table 3. Comparative evaluation of modelling approaches according to predicted outcomes, suitability for defect/deformation analysis, and computational efficiency.

Model Group	Main Predicted Outcomes	Efficiency
Rigid-plastic/rigid-viscoplastic models	Fast prediction of deformation, metal flow, die filling, forming load	High computational efficiency
Thermo-mechanical/thermo-viscoplastic models	Temperature, flow stress, thermal gradients, hot forging accuracy	More accurate but higher computational cost
CEL/advanced material-flow models	Severe deformation, material redistribution, underfilling, flash	Accurate for flow problems but computationally heavier
Friction/thermal calibrated models	Interface temperature, friction-sensitive defects, contact accuracy	More reliable but requires experimental calibration
Damage/residual-stress models	Cracking, damage, residual stress, quality prediction	High value but needs more data and validation
AI/surrogate/optimization models	Fast parameter optimization, process control, trend prediction	Efficient after training but depends on data quality

One of the main research directions is the prediction of metal flow and die filling during closed-die forging. Improper die filling may lead to underfilling, folds, laps, and excessive flash [21,25,33]. Consequently, many researchers have investigated the optimization of billet and preform geometry [15,25,31]. Ramírez et al. [25] demonstrated in their connecting-rod study based on a coupled Eulerian–Lagrangian formulation in Abaqus that modifying the initial billet geometry significantly improved metal flow and eliminated underfilling defects. Similar conclusions were reported for automobile transmission parts [21] and mining drill-bit preforms [42], where FEM was used to optimize the shape of the preform before forging.

Rajendran et al. also used DEFORM-3D to optimize the hot forging die design for an 18CrNiMo7-6 steel pinion shaft. Their study showed that revised die geometries improved die-cavity filling, grain-flow orientation, material utilization, and near-net forming accuracy, while the FEM model was validated by comparing predicted metal-flow lines with metallographic observations [43].

Improper material flow and incomplete die filling are among the main defects identified in die forging simulations. Figure 3 illustrates a folding defect associated with improper die filling, while Figure 4 shows an example of an unfilled die cavity and the corresponding pressure profile. These examples demonstrate how FEM results can be used to identify local material-flow problems before physical trials are performed.

Another important research direction is the modelling of thermo-mechanical material behavior. Because forging involves high temperatures and large plastic deformation, the flow stress depends strongly on strain, strain rate, and temperature. Therefore, most studies employ temperature-dependent constitutive equations, particularly Arrhenius-type models [22] and experimentally derived flow-stress relationships [32,33,40]. The study of hammer forging uncertainty further showed that relatively small changes in the constitutive parameters may significantly influence the predicted material flow and forging load [24].

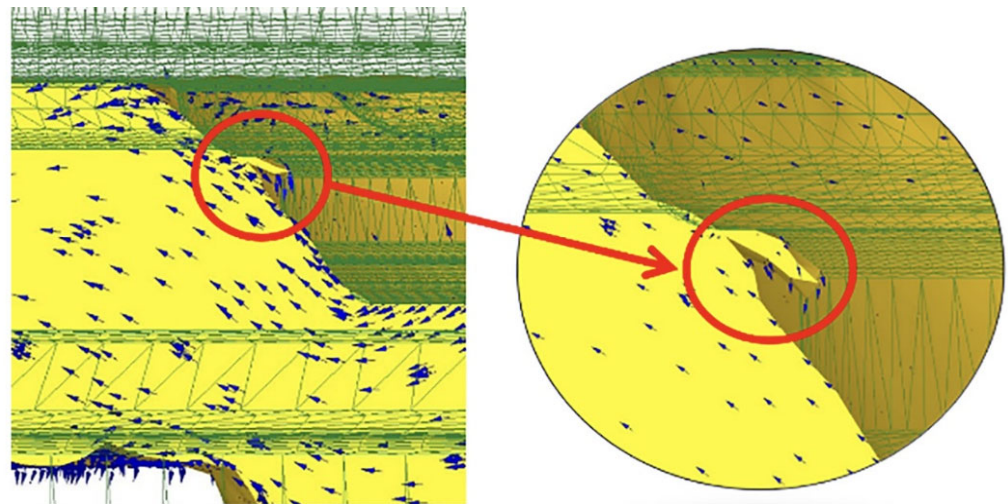


Figure 3. Folding defect due to improper die filling. The blue arrows show the simulated flow-field vectors in the DEFORM-3D result, while the red circles highlight the local folding-defect region. (Source: The optimization design of pre-forming for forging automobile parts using Taguchi method based grey relational analysis, <https://journals.sagepub.com/doi/10.1177/16878132231183531>) (accessed on 10 April 2026) [21].

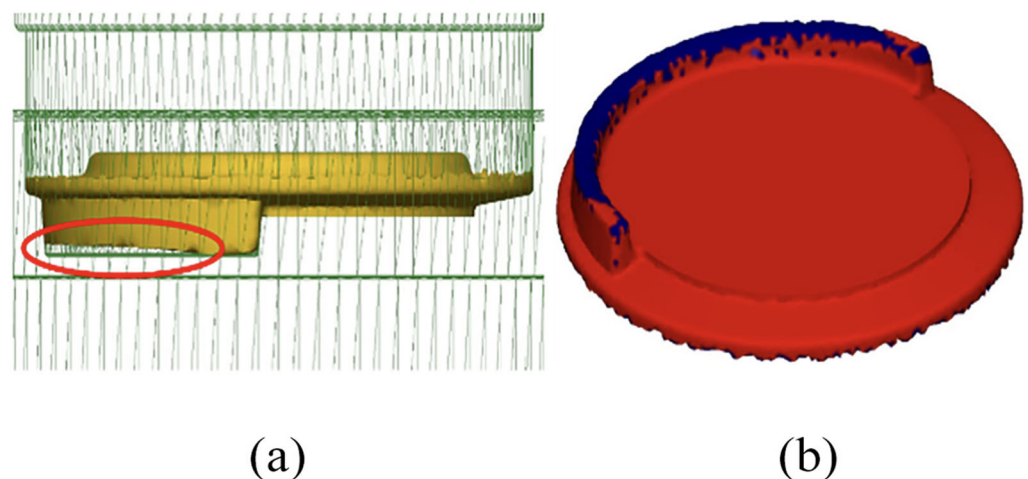


Figure 4. Example of incomplete die filling and pressure distribution: (a) unfilled die cavity, where the red circle highlights the region in which the preform material did not fill the die cavity smoothly; (b) pressure profile (Source: The optimization design of pre-forming for forging automobile parts using Taguchi method based grey relational analysis, <https://journals.sagepub.com/doi/10.1177/16878132231183531>) (accessed on 10 April 2026) [21].

Friction and thermal boundary conditions also form an important part of current research. Earlier studies generally assumed constant values of the friction coefficient and the heat transfer coefficient. However, recent publications demonstrated that these parameters vary with contact pressure, temperature, and lubrication conditions. The large S355NL steel flange study done by Chen et al. [22] and the multi-stage hot forging thermal study done by Veiga-Piñeiro et al. [40] both reported that experimentally determined heat-transfer coefficients result in significantly more accurate temperature predictions than constant values.

The reviewed literature further indicates a growing trend toward process optimization and artificial intelligence. Numerical simulation is increasingly combined with the design of experiments, Taguchi methods, grey relational analysis, neural networks, and machine learning to improve die filling, reduce forging load, and increase die life [14,21,34,38].

Recent studies, such as DeepForge, have extended FEM-based analysis toward intelligent process control and digital-twin concepts [29].

4. Modelling Approaches in Numerical Simulation

Finite element modelling in die forging is mainly performed using thermo-mechanically coupled three-dimensional models. The most frequently used software packages are DEFORM-3D [28,31–33,41,42], Abaqus [25], Forge NxT [26,30,40], ANSYS [27], and QForm [14]; the corresponding software versions reported in the reviewed studies are summarized in Table 1. In most cases, the billet is modelled as rigid-viscoplastic or thermo-viscoplastic, whereas the dies are assumed to be rigid. More advanced studies additionally include elastic die deformation and residual stress prediction [14,34].

4.1. Mesh Generation, Adaptive Remeshing and Mesh Convergence

Mesh generation and remeshing strategies are important in die forging simulation because large plastic deformation can affect mesh quality and numerical accuracy. Excessive element distortion during large deformation may reduce simulation stability and introduce numerical error; therefore, remeshing or adaptive mesh refinement is often required to maintain element quality and improve solution reliability [44,45]. In forging simulations, complex three-dimensional material flow, die contact, thermal gradients, underfilling, and flash formation require suitable mesh density and refinement strategy [15,25]. Coupled Eulerian–Lagrangian formulations can also reduce the need for remeshing operations normally required in traditional Lagrangian approaches, which is useful for severe material-flow problems such as preform design, die filling, underfilling, and flash prediction [25]. Some reviewed studies reported detailed mesh and solver information, including tetrahedral mesh size, refined mesh regions, global remeshing, relative interference depth, direct iteration methods, and conjugate-gradient solvers [33,35]. Koval et al. [24] also showed that mesh size influences strain-distribution prediction and used a mesh-refinement study to identify an appropriate element number. In addition, Veiga-Piñeiro et al. [40] included convergence checking, time-step advancement, and remeshing analysis in the thermo-mechanical coupling procedure. Some of the reviewed studies, however, do not provide sufficient information regarding the mesh used, the mesh refinement, the number of remeshes, the solver used, the time step, the criteria for convergence, as well as the processing time. Thus, future FEM-based studies on forging should explicitly describe the mesh generation strategy, the remeshing criteria, the solver used, and the related processing time to improve reproducibility and practical comparison.

4.2. Material Models, Die Assumptions and Contact Modelling

Rigid-viscoplastic modelling assumes that the elastic deformation of the billet is negligible compared with the large plastic deformation occurring during forging [46,47]. In the rigid-viscoplastic formulation, deviatoric stress is related to the strain rate through a nonlinear viscosity coefficient, which is defined by the flow stress and the equivalent strain rate [46]. This approach is commonly used for predicting metal flow, die filling, strain distribution, and forming load, especially in bulk metal-forming processes where permanent deformation dominates. Thermo-viscoplastic modelling extends this approach by including the effect of temperature on the material response. This is particularly important in hot forging, where flow stress changes significantly with temperature, strain, and strain rate. Therefore, thermo-viscoplastic models are more suitable for coupled thermal-mechanical simulations involving heat generation, heat transfer, and temperature-dependent material behaviour [48].

The assumption of rigid dies is commonly used to reduce computational cost and simplify the contact analysis between the billet and the tools. This simplification is acceptable when the main objective is to analyze workpiece deformation, filling behavior, forming load, or defect formation. However, when the objective includes die stress, die wear, die life, elastic tool deflection, or post-forging residual stress, the dies may be modelled as deformable elastic or thermo-elastic bodies. These advanced models provide more information about tool loading and residual stress development, but they require more detailed material data and higher computational effort.

Recent die-focused studies further show that FEM can be used not only for workpiece deformation analysis, but also for evaluating die stress distribution, wear resistance, degradation mechanisms, and tool durability, including hybrid or hardfaced die designs and ANN-assisted die-life prediction [20,49].

Most studies employ temperature-dependent constitutive equations to describe the relationship between flow stress, strain, strain rate, and temperature. Arrhenius-type and hyperbolic-sine constitutive equations are commonly used to describe temperature- and strain-rate-dependent flow stress in hot forging simulations [22,24,28,35], whereas in cold forging simulations, experimentally derived or tabulated flow-stress data are commonly used to represent the material response, while upsetting or compression tests are often used to obtain the required flow-stress curves [23,27,41].

A commonly used form is the hyperbolic-sine Arrhenius equation:

$$\dot{\epsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where $\dot{\epsilon}$ is the strain rate, σ is the flow stress, T is the absolute deformation temperature, R is the gas constant, Q is the activation energy for deformation, and A , α , and n are material constants. This formulation is suitable for hot forging because it captures the reduction in flow stress at higher temperatures and the increase in flow stress at higher strain rates. In FEM-based forging simulations, Arrhenius-type models are usually calibrated using hot compression or upsetting tests and then implemented as material input data to predict metal flow, forming load, stress distribution, strain distribution, and temperature-dependent deformation behavior. However, when the objective includes microstructure evolution, dynamic recrystallization, grain-size prediction, or flow softening, the basic Arrhenius form may need to be coupled with additional microstructure or recrystallization models [22,28,35].

Recent work by Yuan et al. further illustrates the importance of accurate constitutive modelling in forging simulation [50]. They established a strain-compensated Arrhenius constitutive model for a novel Cr-Mo-V hot-work die steel using hot-compression data, and combined hot-processing maps with FEM simulation and trial production to guide the forging process of large die-steel components [50].

The contact between the billet and die is generally represented by Coulomb or constant shear friction models. Earlier studies assumed constant friction and heat-transfer coefficients [21,27], while more recent work uses experimentally determined or pressure-dependent values to improve the prediction of temperature and metal flow [22,40].

Figure 5 shows the evolution of preform geometry obtained using the FEM/CEL approach. This example highlights how numerical simulation can be used to redistribute material, reduce flash volume, lower forging load, and improve die filling before the final forging stage.

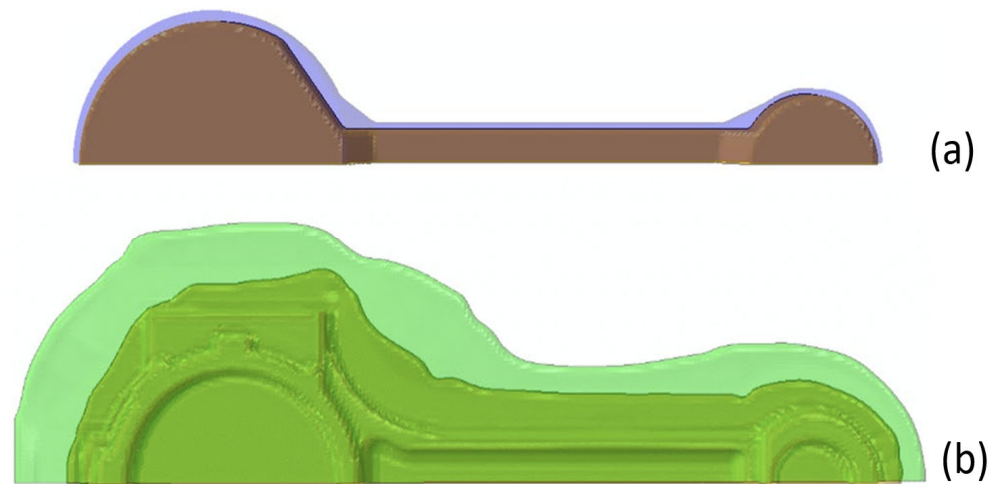


Figure 5. Preform geometry evolution using the FEM/CEL approach for connecting-rod forging: (a) superimposed preform geometries before forging, where blue represents the initial preform design and orange represents the optimized preform design; (b) final forged geometries after forging, where green represents the initial design result and orange represents the optimized design result. (Source: Preform geometry determination for a connecting rod forging by CEL model in Abaqus™, <https://link.springer.com/article/10.1007/s00170-023-11865-5> (accessed on 10 April 2026) [25].

5. Key Parameters in Die Forging FEM Studies

The most important process parameters in die forging simulations are billet temperature, die temperature, ram speed, friction coefficient, and billet geometry. These parameters strongly influence metal flow, forging load, and die filling [21,22,25].

Zeng et al. recently combined numerical simulation, hot forging experiments, and response surface methodology for a high-Mn steel turnout core, showing that forging temperature, forging speed, and friction conditions strongly affect die load, billet damage, temperature field, forming quality, and final mechanical properties [51].

Similarly, Chen et al. compared response surface methodology, main effects plot analysis, and Taguchi–grey relational analysis for aluminum crown forging optimization [52]. Their FEM-supported study showed that billet diameter, billet length, and barrier-wall design strongly influence filling rate and material underfill, and the optimized parameters were verified through FEM simulation and actual production validation [52].

Billet temperature is one of the most influential parameters in hot forging simulations because it directly affects the flow stress of the material [22]. A higher billet temperature generally reduces flow stress, improves material flow, decreases forging load, and supports complete die filling [28,29]. However, excessive billet temperature may increase oxidation, grain growth, excessive flash, or microstructural instability [28,33]. In contrast, insufficient billet temperature increases the resistance to deformation. It may lead to higher forming load, incomplete filling, folding, or cracking, especially when combined with unsuitable preform geometry, friction conditions, or die temperature [21,29,33].

The die temperature has a strong influence on the thermal field and deformation behavior in hot forging simulations [35]. Heat dissipation occurs through the workpiece surface and the die–workpiece interface, where the temperature gradient can produce a local chilling effect. This temperature reduction may increase the required deformation load and contribute to non-uniform deformation [35]. In some cases, high strain near the die–workpiece interface may also contribute to cracking. Therefore, accurate modelling and control of die thermal behavior are important for predicting temperature distribution, metal flow, and forming response. However, uncontrolled or excessive die temperature

may contribute to thermal fatigue cracks, plastic deformation, thermal softening, die wear, and premature tool failure [14,40].

Ram speed or die velocity affects the strain rate, contact time, heat generation, and heat loss during forging [35,40]. Higher ram speed reduces the time available for heat transfer from the billet to the dies, which may help maintain billet temperature during deformation. At the same time, a higher strain rate may increase flow stress and forming load depending on the material model. Lower ram speed allows more heat loss during deformation and may increase the risk of local cooling, incomplete material flow, and non-uniform flow. Therefore, ram speed must be selected carefully to balance forming load, die filling, and thermal stability [22,24,38].

The friction coefficient controls the resistance to sliding between the billet and the die surface [33,41]. High friction can restrict material flow, increase forming resistance, and promote non-uniform strain distribution [24,27]. It can also influence forming load, interface heating, and die wear. However, the effect of friction on die filling is process-dependent because friction conditions interact with preform geometry, die design, temperature, lubrication, and contact pressure [15,41]. Therefore, inappropriate friction assumptions may lead to inaccurate predictions of material flow, filling sequence, flash formation, and forging force. Recent studies, therefore, use experimentally calibrated, lubrication-dependent, or process-dependent friction conditions instead of relying only on a constant friction value [15,41].

Heat-transfer conditions are particularly important in hot forging because the temperature field strongly affects flow stress and material formability. The contact heat-transfer coefficient between the billet and the dies controls the heat exchange at the billet–die interface and therefore affects the cooling rate at the contact surface [22,40]. If a constant heat-transfer coefficient is assumed, the simulation may not accurately capture local thermal gradients and may indirectly affect the prediction of flow stress and forming force [22]. More advanced models consider the effects of contact pressure, temperature, lubrication, and spray cooling, which improve the reliability of thermal-field prediction and support die-life assessment [40].

Billet and preform geometry determine the initial material distribution before deformation. A well-designed billet or preform supports uniform material flow, complete die filling, reduced flash volume, lower forging load, and fewer defects [25]. Poor preform geometry may cause material shortage in critical regions, leading to underfilling, or excessive material in other regions, leading to high flash volume and unnecessary forming load [25]. For this reason, many recent FEM studies use preform optimization, Taguchi methods, response surface methodology, material-point backtracking, or machine-learning-assisted approaches to improve billet design and forming robustness [15,21,25,32].

The principal outputs predicted by FEM are effective stress, effective strain, temperature distribution, forging load, and metal flow. These outputs are used to identify defects such as underfilling, folding, and excessive flash, and to assess quality-related responses such as residual stress, damage, hardness distribution, and microstructure evolution [15,21,31,34].

6. Comparative Discussion, Research Gaps, and Future Directions

The reviewed articles show a clear evolution in die forging simulation. Earlier studies mainly focused on predicting metal flow, die filling, and forging load using simplified assumptions, particularly constant friction coefficients and constant heat-transfer coefficients [21,27,33]. Despite being computationally simpler, this assumption may impair the accuracy in calculating the temperature distribution and flow behavior in the metal. Modern studies tend to use more experimental data for the determination of material

properties. An illustration is the research on the S355NL flange, where experimentally obtained coefficients of heat transfer were considered to be temperature dependent [22]. The findings from the studies were used to develop a pressure- and lubrication-dependent thermal contact model, which was applied to a multi-stage hot forging simulation, hence improving the accuracy of thermal cycle simulation [40].

An example of an advanced contact heat-transfer model is shown in Figure 6. The figure illustrates the importance of using realistic contact heat-transfer coefficients in forging simulations. Unlike simplified models that assume a constant heat-transfer value, advanced models consider the influence of contact pressure, temperature, and lubrication conditions. This is particularly important in hot forging because inaccurate thermal boundary conditions can lead to errors in predicted temperature distribution, flow stress, metal flow, and forging load.

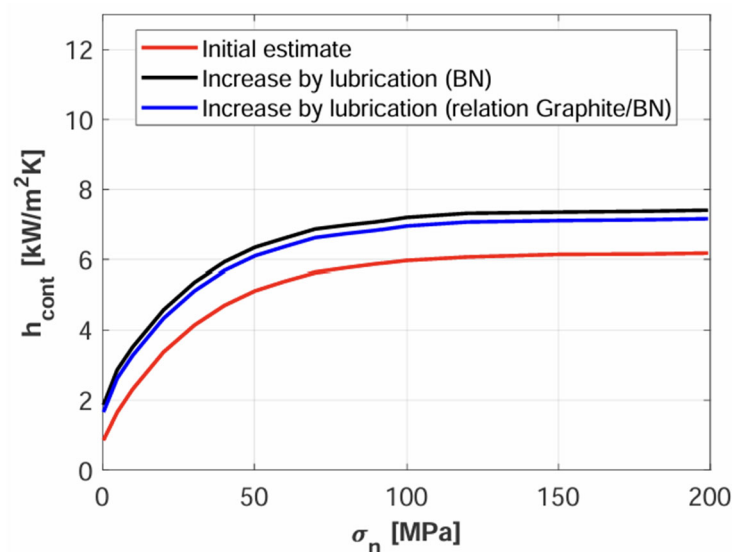


Figure 6. Contact heat-transfer coefficient model (Source: Thermal Management in Multi-Stage Hot Forging: Computational Advances in Contact and Spray-Cooling Modelling, <https://www.mdpi.com/1996-1944/18/14/3318>) (accessed on 12 April 2026) [40].

The reviewed studies also differ in the complexity of the predicted outputs. Some papers focused only on deformation, die filling, and forging load, whereas more recent work additionally predicts hardness, microstructure, residual stress, and damage evolution. For example, the cryogenic closed-die forging study predicted hardness distribution and strain maps [11], while the residual-stress study extended FEM toward post-forging stress prediction [34]. Recent research also shows a strong trend toward optimization and artificial intelligence. FEM is increasingly combined with design of experiments, Taguchi methods, machine learning, and digital-twin concepts in order to reduce forging load, improve die filling, and increase die life [14,29,35,38].

Recent supporting studies confirm that die forging simulation is moving beyond offline FEM analysis toward online prediction, intelligent monitoring, automation, and data-driven process control. Digital-twin systems have been proposed for in-process dimensional prediction and out-of-tolerance alarming [17], while hybrid deep-learning models have been used for energy-consumption prediction in hot die forging production lines [18]. Robotic forging studies also show that automation requires FEM-supported process design, stable process synchronization, and industrial validation [19]. In addition, die-degradation studies demonstrate the growing use of optical scanning, microstructural analysis, FEM, and ANN models for tool-life and failure-mechanism prediction [20].

From an industrial perspective, the reviewed simulation approaches can support several practical applications, including preform design, die filling improvement, forging load reduction, defect prevention, die-life extension, temperature control, and real-time process monitoring. In particular, the integration of FEM with experimentally calibrated boundary conditions, AI-based optimization, and digital-twin concepts can help reduce trial-and-error testing and support more reliable process design in industrial forging production.

An example of industrial application of process simulation is given by Hawryluk et al. [53]. They have developed a thermo-mechanical simulation model of the hub-forging process using FEM and deformable tools. The model was used to evaluate material flow, die-impression filling, temperature distribution, plastic deformation, and defect formation, supporting process correction and improved industrial forging quality [53].

Despite these advances, several research gaps remain. A large number of papers deals with simplified friction and the thermal boundary conditions. Only a few papers focus on the simulation of the forging process, and are verified by experimental data, especially for stress, strain, and temperature. In addition, most studies analyse only one aspect of the process, such as deformation or temperature, rather than combining stress, strain, temperature, microstructure, and residual stress within a single model. Future research should therefore focus on coupled thermo-mechanical-microstructural models, experimentally determined contact conditions, and AI-assisted real-time FEM systems capable of supporting digital twins for industrial forging processes.

7. Conclusions

The reviewed literature confirms that the FEM technique is predominantly used for the simulation of die forging operations. Finite element modelling can effectively predict behavior in terms of material flow, stresses, strains, temperature distribution, and forging load.

The simulation accuracy is dependent on the constitutive model, the friction model, and the thermal boundary conditions. However, recent work has successfully used experimentally determined material and thermal properties. The literature also shows an increasing number of reports on process optimization using techniques of process design, machine learning, and artificial intelligence. Future research will aim at developing intelligent and real-time simulation systems for hot forging processes.

Based on the reviewed papers, three research gaps regarding the accuracy and completeness of modeling assumptions for numerical simulation of die forging were identified. In many models, simple friction models, constant heat transfer coefficients, rigid die, and limited experimental validation are used. Such simplifications are introduced to reduce computational efforts. However, they might introduce considerable errors in the calculation of the temperature field, material flow, forging force, residual stress, die wear, and possible defects. Future work should concentrate on the experimental verification of friction and thermal contact models, on a better coupling of the applied thermo-mechanical models with the corresponding microstructural models. A more systematic experimental validation of the modeling results by industrial forging processes is also needed. Finally, a more accurate description of the inputs and boundary conditions of the models has to be given. In addition to these research paths, promising approaches for future work in die forging simulation, such as the application of artificial intelligence, surrogate models, and digital twins for real-time simulation, process optimization, and intelligent control of die forging processes, are outlined. Nevertheless, these methods still require reliable training data, physical interpretability, and validation under industrial conditions before they can be widely applied.

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References

- Sharma, S.; Sharma, M.; Gupta, V.; Singh, J. A Systematic Review of Factors Affecting the Process Parameters and Various Measurement Techniques in Forging Processes. *Steel Res. Int.* **2023**, *94*, 2200529. [CrossRef]
- Bhoyar, V.; Umredkar, S. Manufacturing Processes Part II: A Brief Review on Forging. *Int. J. Innov. Eng. Sci.* **2020**, *5*, 26–32. [CrossRef]
- Karkhana. A Comprehensive Guide to Forging Processes: Choosing the Right Method for Your Application—2024. Available online: <https://karkhana.io/a-comprehensive-guide-to-forging-processes-choosing-the-right-method-for-your-application/> (accessed on 12 May 2026).
- Kumar, D.; Mondal, S. A Review on Modelling, Design and Optimization of Forging Process. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1126*, 012001. [CrossRef]
- Hartley, P.; Pillinger, I. Numerical Simulation of the Forging Process. *Comput. Methods Appl. Mech. Eng.* **2006**, *195*, 6676–6690. [CrossRef]
- Schaeffer, L.; Brito, A.M.G.; Geier, M. Numerical Simulation Using Finite Elements to Develop and Optimize Forging Processes. *Steel Res. Int.* **2005**, *76*, 199–204. [CrossRef]
- Huang, H.-S.; Hsia, S.-Y. New Design of Process for Cold Forging to Improve Multi-Stage Gas Fitting. *Adv. Mech. Eng.* **2016**, *8*, 1687814016641571. [CrossRef]
- Forging: Processes, Types & Benefits | IQS Directory. Available online: <https://www.iqsdirectory.com/articles/forging/what-is-forging.html> (accessed on 12 May 2026).
- Pandya, V.A.; George, P.M. Effect of Preform Design on Forging Load and Effective Stress during Closed Die Hot Forging Process of Pin. *Mater. Today Proc.* **2021**, *44*, 106–112. [CrossRef]
- Berti, G.A.; Monti, M. Thermo-Mechanical Fatigue Life Assessment of Hot Forging Die Steel. *Fatigue Fract. Eng. Mater. Struct.* **2005**, *28*, 1025–1034. [CrossRef]
- Tomov, B.I.; Gagov, V.I.; Radev, R.H. Numerical Simulations of Hot Die Forging Processes Using Finite Element Method. *J. Mater. Process. Technol.* **2004**, *153–154*, 352–358. [CrossRef]
- Reddy a Review on Finite Element Simulations in Metal Forming | Semantic Scholar. Available online: <https://www.semanticscholar.org/paper/A-Review-on-Finite-Element-Simulations-in-Metal-Reddy-Reddy/9bf2037296624ff4f5ed4c616d8e40986965861a> (accessed on 31 March 2026).
- Zhang, H.; Tu, H.; Yuan, C.; Li, Y.; Chen, X.; Wang, H. Predicting Forging Defects Using FEM: A Brief Review. *Int. J. Adv. Manuf. Technol.* **2025**, *141*, 1143–1157. [CrossRef]
- Alessio, A.; Antonelli, D.; Doglione, R.; Genta, G. Application of Design of Experiments to Forging Simulations to Increase Die Life Expectancy. *Int. J. Interact. Des. Manuf.* **2023**, *17*, 1351–1361. [CrossRef]
- Ngaile, G.; Kumaran, K. Physics-Informed Preform Design for Flashless 3D Forging via Material Point Backtracking and Finite Element Simulations. *J. Manuf. Mater. Process.* **2025**, *9*, 202. [CrossRef]
- Connolly, D.; Sivaswamy, G.; Rahimi, S.; Vorontsov, V. Miniaturised Experimental Simulation of Open-Die Forging. *J. Mater. Res. Technol.* **2023**, *26*, 3146–3161. [CrossRef]
- Hu, Z.; Mao, Y.; Pang, Q.; Hua, L. Digital Twin-Driven Dimensional Prediction and Quality Monitoring System for Aluminum Alloy Die Forging Process. *J. Manuf. Process.* **2026**, *168*, 675–691. [CrossRef]
- Wang, Z.; Wang, H.; Yuan, C.; Du, W.; Liu, Y. A Hybrid Deep Learning Model for Energy Consumption Prediction in Hot Die Forging Production Lines. *Eng. Appl. Artif. Intell.* **2026**, *177*, 114964. [CrossRef]
- Hawryluk, M.; Dudkiewicz, Ł.; Polak, S. Robotic and Manual Hot Die Forging of Connecting Rods—Efficiency, Forging Quality and Automation Potential. *J. Mater. Res. Technol.* **2025**, *39*, 2897–2910. [CrossRef]
- Emamverdian, A.; Pruncu, C.; Liu, H.; Rahimzadeh, A.; Lamberti, L. Prediction of the Main Degradation Mechanisms in a Hot Forging Steel Die: Optical Scanning, Simulation, Microstructural Evolution, and Neural Network Modeling. *J. Mater. Res. Technol.* **2025**, *37*, 432–443. [CrossRef]

21. Chiang, M.-Y.; Hu, J.-W.; Hsiao, T.-C.; Tsai, M.-C.; Huang, S.-C. The Optimization Design of Pre-Forming for Forging Automobile Parts Using Taguchi Method Based Grey Relational Analysis. *Adv. Mech. Eng.* **2023**, *15*, 16878132231183531. [\[CrossRef\]](#)
22. Chen, Y.; Zhao, J.; Kong, L.; Zhang, J.; Huang, Z.; Li, D.; Wang, Y. Temperature Prediction for Forging a Large S355NL Steel Flange for Offshore Wind Turbines Using Neural Network and Numerical Simulation. *Results Eng.* **2025**, *27*, 106108. [\[CrossRef\]](#)
23. Nakeenopakun, N.; Olarnrithinun, S.; Aue-u-lan, Y. Method for Approximating the Flow Stress Curves of Upsetting Test under Sticking Condition. *Int. J. Adv. Manuf. Technol.* **2026**, *143*, 1933–1944. [\[CrossRef\]](#)
24. Koval, O.; Das, A.; Paramatmuni, C.; Pickering, E.; Cogswell, D. Evaluation of Uncertainty in Material Flow Predictions in Hammer Forging of Steel through Constitutive Modelling. *J. Manuf. Process.* **2025**, *133*, 1207–1221. [\[CrossRef\]](#)
25. Ramírez, E.I.; Ruiz, O.; Reyes-Ruiz, C.; Ortiz, A. Preform Geometry Determination for a Connecting Rod Forging by CEL Model in AbaqusTM. *Int. J. Adv. Manuf. Technol.* **2023**, *127*, 5569–5576. [\[CrossRef\]](#)
26. Dudkieiwcz, Ł.; Hawryluk, M.; Polak, S.; Kaczyński, P.; Suliga, M.; Ziemba, J. Analysis and Improvement of the Hot Precision Forging Technology for Forgings with a Transverse Protrusion Produced in Multiple Systems. *Int. J. Adv. Manuf. Technol.* **2025**, *138*, 1945–1963. [\[CrossRef\]](#)
27. Lorenzo-Galindo, I.; Landa-Castro, M.; Flores-Sanchez, D. Cold Forging in Medium Carbon Steel: AISI 1045 Characterization via Experimental and Numerical Techniques. *Model. Simul. Eng.* **2026**, *2026*, 6921477. [\[CrossRef\]](#)
28. Huang, X.; Zang, Y.; Ji, H.; Wang, B.; Duan, H. Combination Gear Hot Forging Process and Microstructure Optimization. *J. Mater. Res. Technol.* **2022**, *19*, 1242–1259. [\[CrossRef\]](#)
29. Petrik, J.; Bambach, M. DeepForge: Leveraging AI for Microstructural Control in Metal Forming via Model Predictive Control. *J. Manuf. Process.* **2024**, *121*, 193–204. [\[CrossRef\]](#)
30. Dudkieiwcz, Ł.; Hawryluk, M.; Polak, S.; Trusz, A. Development of a New and High-Performance Precision Forging Technology. *Int. J. Adv. Manuf. Technol.* **2025**, *141*, 3829–3845. [\[CrossRef\]](#)
31. Saquib, A.N.; Khaleed, H.M.T.; Badruddin, I.A.; Algahtani, A.; Addas, M.F.; Abdullah, A.B.; Athani, A.; Kamangar, S.; Khan, T.M.Y. Development of Preform for Simulation of Cold Forging Process of A V8 Engine Camshaft Free from Flash & Under-Filling. *Mathematics* **2019**, *7*, 1026. [\[CrossRef\]](#)
32. Ding, T.; Wei, K.; Hou, Y.; Dong, X.; Huang, L.; Lee, M.-G. Enhancing the Robustness of Rib-Groove Filling and Strain Homogeneity in the Isothermal Forging of Titanium Alloy Multi-Rib Components. *Chin. J. Mech. Eng.* **2024**, *37*, 98. [\[CrossRef\]](#)
33. Ceviz, M.; Cetintav, I. Finite Element Simulation and Experimental Study on Defects in CuZn40Pb2 Brass Alloy Water Valve Covers during Hot Forging. *Proc. Est. Acad. Sci.* **2025**, *74*, 82–89. [\[CrossRef\]](#)
34. Chen, S.; Li, Y.; Liu, C.; Zhao, Z.; Chen, Z.; Liu, X. Global Residual Stress Field Inference Method for Die-Forging Structural Parts Based on Fusion of Monitoring Data and Distribution Prior. *Vis. Comput. Ind. Biomed. Art* **2025**, *8*, 4. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Obiko, J.; Mxolisi, B.; Malatji, N. Integrated Numerical and Taguchi-Based Optimisation of Forging Parameters for DIN 42CrMo4 Engine Connecting Rod Steel. *Eng. Rep.* **2025**, *7*, e70339. [\[CrossRef\]](#)
36. Magalhães, D.C.C.; Pratti, A.L.; Kliauga, A.M.; Rubert, J.B.; Ferrante, M.; Sordi, V.L. Numerical Simulation of Cryogenic Cyclic Closed-Die Forging of Cu: Hardness Distribution, Strain Maps and Microstructural Stability. *J. Mater. Res. Technol.* **2019**, *8*, 333–343. [\[CrossRef\]](#)
37. Kitayama, S.; Sugita, R.; Amano, M.; Miyoshi, K.; Kondo, S.; Aono, E. Optimal Energy Distribution in Hydraulic Hammer Forging for Minimizing Total Energy and Forging Load. *Int. J. Adv. Manuf. Technol.* **2024**, *133*, 4967–4980. [\[CrossRef\]](#)
38. Kim, Y.; Jeong, H.Y.; Park, J.; Kim, K.; Kwon, H.; Ju, G.; Kim, N. Optimizing Process Parameters for Hot Forging of Ti-6242 Alloy: A Machine Learning and FEM Simulation Approach. *J. Mater. Res. Technol.* **2023**, *27*, 8228–8243. [\[CrossRef\]](#)
39. Lagat, D.; Munawar, H.; Akhusama, E.; Alugongo, A.; Rutto, H. Predictive Numerical Modeling of Inelastic Buckling for Process Optimization in Cold Forging of Aluminum, Stainless Steel, and Copper. *Processes* **2025**, *13*, 3177. [\[CrossRef\]](#)
40. Veiga-Piñeiro, G.; Martín-Ortega, E.; Pérez-Betanzos, S. Thermal Management in Multi-Stage Hot Forging: Computational Advances in Contact and Spray-Cooling Modelling. *Materials* **2025**, *18*, 3318. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Hill, S.; P. Turner, R. Thermo-Mechanical Forging of 708M40 Steel Ring Samples: Experiments and Modelling. *Int. J. Adv. Manuf. Technol.* **2021**, *116*, 2577–2590. [\[CrossRef\]](#)
42. Yurgel, C.C.; Rockwell, N.M.; Misiolek, W.Z.; Lora, F.A.; de Sousa, R.A. Hot Forging-Based Development of Mining Drill Bit Preforms: Experimental and Numerical Analysis. *Int. J. Mater. Form.* **2026**, *19*, 8. [\[CrossRef\]](#)
43. Rajendran, N.; Yurgel, C.C.; Misiolek, W.Z.; Sousa, R.A. de Hot Forging Die Design Optimization Using FEM Analysis for Near-Net Forming of 18CrNiMo7-6 Steel Pinion Shaft. *Metals* **2023**, *13*, 815. [\[CrossRef\]](#)
44. Crawshaw, J.R.; Flegg, J.A.; Osborne, J.M. A Simple History-Dependent Remeshing Technique to Increase Finite Element Model Stability in Elastic Surface Deformations. *J. Comput. Appl. Math.* **2022**, *405*, 113876. [\[CrossRef\]](#)
45. Bespalov, A.; Haberl, A.; Praetorius, D. Adaptive FEM with Coarse Initial Mesh Guarantees Optimal Convergence Rates for Compactly Perturbed Elliptic Problems. *Comput. Methods Appl. Mech. Eng.* **2017**, *317*, 318–340. [\[CrossRef\]](#)
46. Kang, Z.; Luo, Y. Sensitivity Analysis of Viscoplastic Deformation Process with Application to Metal Preform Design Optimization. *Eng. Optim.* **2012**, *44*, 1511–1523. [\[CrossRef\]](#)

47. Jackson, J.E.; Ramesh, M.S. The Rigid-Plastic Finite-Element Method for Simulation of Deformation Processing. In *Numerical Modelling of Material Deformation Processes: Research, Development and Applications*; Hartley, P., Pillinger, I., Sturgess, C., Eds.; Springer: London, UK, 1992; pp. 148–178.
48. Grzywiński, M.; Służalec, A. Rigid-Thermo-Viscoplasticity in Metal Forming Process Described by Stochastic Finite Elements. In *Proceedings of the European Congress on Computational Methods in Applied Sciences and Engineering*, Barcelona, Spain, 11–14 September 2000.
49. Turek, J.; Bajda, S. Performance of Hybrid Forging Dies: Unveiling the Role of Hardfaced Coatings in Stress Distribution and Wear Resistance. *Eng. Fail. Anal.* **2026**, *195*, 111052. [[CrossRef](#)]
50. Yuan, Y.; Lin, Y.; Wang, W.; Zhang, B.; Shi, R.; Zhang, Y.; Xie, J.; Wu, C.; Mao, F. Study on High-Temperature Constitutive Model and Plasticity of the Novel Cr-Mo-V Hot-Work Die Steel Forging. *Materials* **2024**, *17*, 6071. [[CrossRef](#)] [[PubMed](#)]
51. Zeng, Y.; Ji, H.; Song, C.; Wang, M.; Li, J. Numerical Simulation and Experiment on Hot Forging of High-Mn Steel Turnout Core. *Mater. Today Commun.* **2024**, *40*, 109588. [[CrossRef](#)]
52. Chen, C.-P.; Su, H.-Z.; Shih, J.-K.; Huang, C.-F.; Ku, H.-Y.; Chan, C.-W.; Li, T.-T.; Fuh, Y.-K. A Comparison and Analysis of Three Methods of Aluminum Crown Forgings in Processing Optimization. *Materials* **2022**, *15*, 8400. [[CrossRef](#)] [[PubMed](#)]
53. Hawryluk, M.; Rychlik, M.; Więclaw, M.; Jabłoński, P. Analysis of the Industrial Process of Producing a Hub Forging Used in Motorcar Power Transmission Systems—A Case Study. *J. Manuf. Mater. Process.* **2021**, *5*, 32. [[CrossRef](#)]

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