SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V13I7P111

Volume 13 Issue 7, 132-144, July 2026
© 2026 Seventh Sense Research Group®

Original Article

Investigation of Deformation Characteristics in Forging through Mathematical Modelling and Microstructure Evolution Analysis

Sayali Kulkarni[1], D.N. Raut[2], Rahul Warghane[3], Atul Jade[4]

[1,2]*VJTI, Matunga, Mumbai, Maharashtra, India.*
[3,4]*PHCET, Rasayni, Raigargh, Maharashtra, India.*

[1]*Corresponding Author : sayalikulkarni@mes.ac.in*

Received: 08 April 2026 Revised: 10 June 2026 Accepted: 13 July 2026 Published: 30 July 2026

Abstract *- Forging is a complex manufacturing process in which materials undergo continuous and non-uniform deformation. The deformation pattern varies across different sections of a forged component. This variation occurs due to geometry-dependent material flow. As a result, it becomes difficult to define a single deformation pattern or failure mode for complex forgings. These limitations have constrained advancements, leading forging process design to remain primarily dependent on experimental trial-and-error approaches. Existing experimental design approaches face challenges, including arbitrary outcomes, elevated costs, artificial conditions, and the lack of standardized design parameters, necessitating further development. To address the limitations of this methodology, a material failure mode–based design formulation has been developed. Critical performance parameters in the forging process are identified through operational studies and micromechanical analysis of material flow. Individual mathematical models are formulated for each performance parameter, and their functional relationships are established using statistical computing techniques. The statistical analysis includes the evaluation of process parameters, stress distribution, and material failure behaviour. The hidden hierarchical relationships within experimental data are identified using an advanced soft computing tool (cftool). Since forging is a sequential process, parameter selection is carried out with the primary objective of minimizing forging force. Mathematical modelling based on material failure theories and MATLAB curve-fitting results is employed to derive functional relationships among dependent parameters. A standardized design template is developed in MATLAB to determine optimal process parameters. The parameters obtained from the design calculator are validated by comparison with experimental data reported in the literature. A correlation-based evaluation approach is adopted to assess the effectiveness of the proposed methodology, achieving a 93% correlation between experimental results and model predictions. The validated design methodology is further evaluated through experimental trials on a developed forged component. Microstructural analysis of the forged component is conducted and compared with the base material to examine grain evolution during forging. The microstructural, morphological, and metallographic analyses confirm that the material behaviour and property development closely align with the predictions made during the design formulation stage.*

Keywords *- Cup-shaped forging, Design Experimentation, MATLAB Calculator, Forging design simulation, Micro-structure study.*

1. Introduction

Design formulation of the forging process is very challenging as the material properties and its strength constantly varies with temperature [1]. Over the years, researchers have investigated to formulate the standard design process for forging. Although the forging design is still based on an experimental test-trial design approach. The experimental test trial design approach follows the principle of selection of design parameters based on experimental test trial results, characteristic graphs, set thumb rules or based on past process experience. The selection of process design parameters based on an experimental design approach incurs uncertainty in results, overhead cost in experimentation and limitations for the selection of set parameters available in research. Several approaches, such as reverse finite element simulation, experimental data analysis, and curve-fitting-based predictive techniques, have been investigated for forging design; nevertheless, a comprehensive and validated design methodology is still awaited [2]. The existing method focuses on optimization of parameters rather than an integrated intelligent design framework. To overcome this, the ill-effect in experimental design approach, an intensive literature review is carried out, and a critical study on process simulation is done [3]. An attempts are made to formulate the forging design process based on the material failure mode analysis method.

The literature review reveals that Analytical and parametric methodologies have demonstrated greater reliability in cost estimation compared with empirical approaches, with material selection and geometric characteristics identified as the primary contributors to forging design cost. [4]. Although simulation-based optimization and Design of Experiments (DOE) methodologies have been adopted to enhance forging process design, these approaches have not yet provided a sufficiently robust and generalized framework for process standardization. [5].

The proposed technique in the current research, namely material failure mode–based forging design, represents an advanced engineering approach for forging process development. It utilizes constitutive material behaviour, damage evolution models, and numerical simulation to predict failure mechanisms during metal deformation. The methodology further enables optimization of process parameters prior to physical production.

Despite of significant advancements in forging technology, several limitations and challenges are still existed, which justify the need for systematic research. With the due advantage of development of material properties in forging, over other manufacturing process the failure of the component can be eliminated. Even though, while in Industry exploration at a petrochemical plant, it has been evident that the end cap of high-pressure headers made by casting are get failed due to excessive pressure and hammering forces. The failure of such an end cap leads to Average 2500 fatal accidents recorded every year in India [6]. The sectional failure of the end cap made by casting is given in Figure 1.

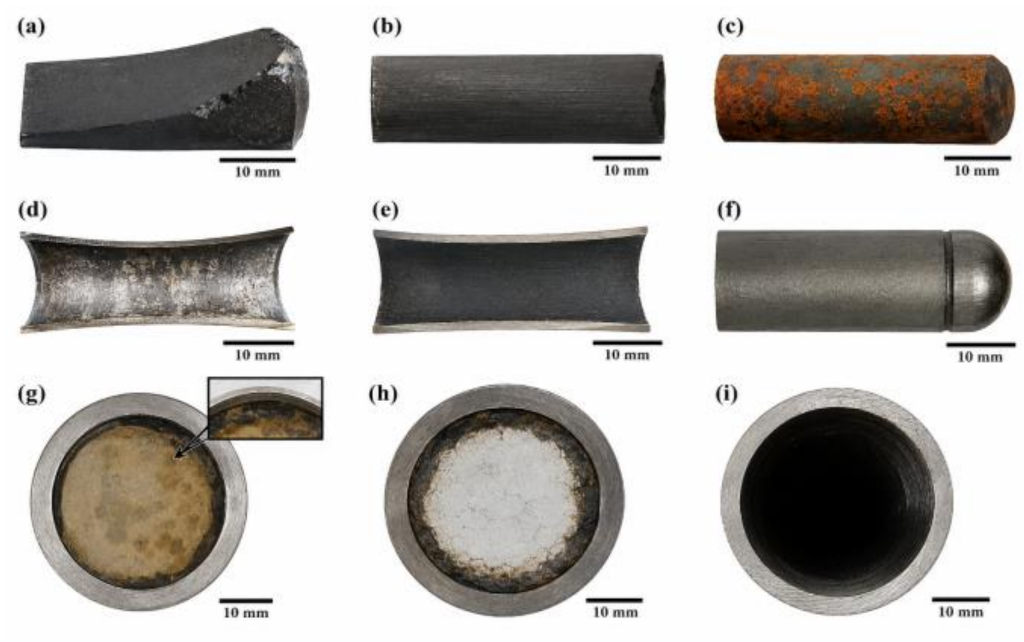

Fig. 1 Failure Mode End-cap

The controlled material deformation commits uniform material strength and prevents failure of the forged component. The material failure mode analysis and the grain flow study in the forging process guides for the formulation of the concept model. The conventional experimental trial-and-error design methodology is substituted by a systematic mechanical design framework driven by failure mode analysis. The process study and the material flow microstructure study show that the material deformation in forging comprises of sequential material deformation modes. The intense localized plastic deformation induced by the forging tool generates significant heat through plastic deformation, resulting in thermal softening of the material within the contact zone beneath the tool. [7]. The further implication of force on thermo-soft material is responsible for grain recrystallization. The grain recrystallization is results into improvement of the material strength [8]. The further extension of force on the billet material causes the material to get slip on its side walls and thereby causes the required material deformation.

The complete material deformation model in the forging process is thus mathematically expressed in three stages. The material deformation model consists of sinking phase deformation (thermal softening phase), forging phase deformation (grain recrystallization) and sizing phase deformation (grain slip [9]. The review on the process parameter required for the complete mathematical modelling of the forging process identifies the governing parameters of forging process as are τ- Shear stress, m- Friction coefficient (Constant friction model), σ - Yield stress, F- Forging Force, R - Tool radius, δ - Reduction rate, μ - Friction coefficient (General friction model Model) and L - Length in the chamber [10].

The literature review guides for the selection of the X-shaped material deformation model to formulate the mathematical model [11]. The X-shaped deformation model shows that the stress area under the tool surface increases longitudinally, whereas the stress area reduces laterally. Material deformation during forging is governed by the high compressive impact exerted by the forging tool on the billet. The associated accumulation of deformation energy follows the strain energy principle, which provides the theoretical basis for describing the plastic flow behaviour of the material. [12]. The process study states that the forging force is the only parameter responsible for imparting the material deformation and development of material property in forging process [13]. A statistical framework of the forging process is developed to predict the evolution of forging force as a function of material properties, process variables, and deformation characteristics. The three-phase deformation model is shown in Figure 2.

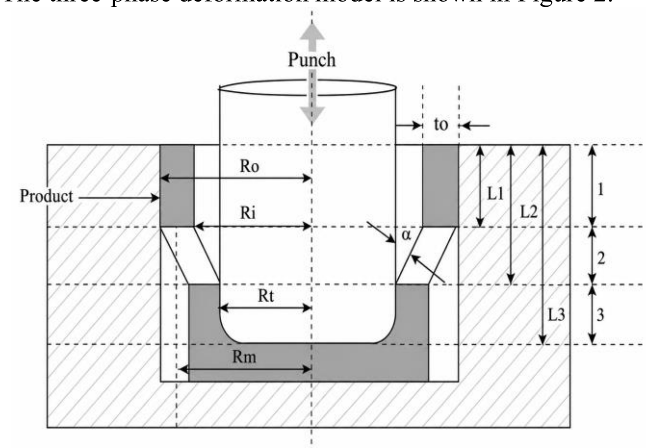

Fig. 2 Forging process concept diagram with step deformation

The fundamental strain energy equation in the form of force is given as,

$$F = \frac{\sigma^2 \, x \, V}{\varepsilon} \tag{1}$$

The strain energy formulation is applied to each incremental stage of material deformation to establish the mathematical framework governing the forging process. The corresponding stepwise deformation model is expressed as follows,

1.1. Sinking Phase Deformation Model

The sinking phase deformation is the phase of thermal softening in which the longitudinal and lateral stresses are acting on the material geometry [14].

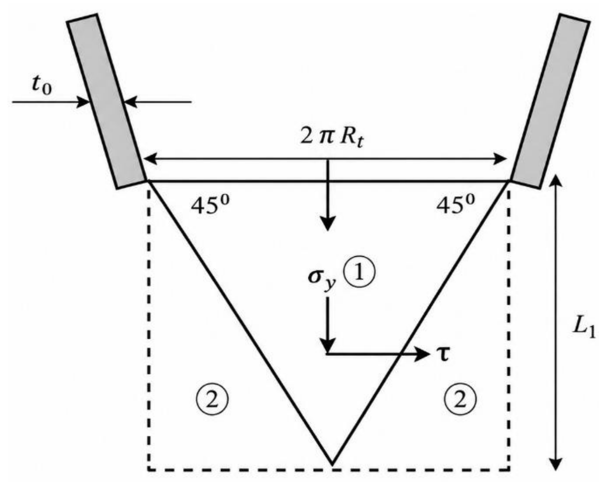

Fig. 3 Sinking phase deformation model

The localized area under the deforming face of forging tool offers the shrinking of the stress distribution line on the longitudinal plane, whereas the incremental volume is experienced in the lateral plane. In multistage forging, the unit step deformation is considered for analysis in a single stage. The total deformation is effective for the entire deformation length of the component. The longitudinal stress incurred a decrement area and thereby the derivative function. Whereas the lateral deformation incurred an incremental area and thereby the integral function [11]. In the actual loading trial, the deformation force is given as,

$$F_S = \frac{\sigma^2 \, \frac{d}{d_{l_1}} \, \Pi \frac{1}{3} r^2 \, {l_1}^2}{\varepsilon} + \frac{\tau^2 \, \frac{2}{3} \int_0^{l_1} \Pi \, r^2 \frac{dl_1}{3}}{\varepsilon} \tag{2}$$

Where, σ & τ are the material stress in yielding and shear, l_1= Unit step deformation, ε = strain rate (Forging ratio), F_S = Forging force in the Sinking phase. The material properties are the design input parameters of the billet material. The step deformation is selected based on the forging ratio.

1.2. Forging Phase Deformation Model

The forging phase is the phase of grain recrystallization in which the material incurs the flow stress due to excessive loading on the material. The constitutive flow stress relationship for ferrous materials is expressed as follows [15],

$$\sigma = K \, \varepsilon^n \tag{3}$$

Here, ε - Strain.

The strength coefficient (K) and strain-hardening exponent (n) are functions of the evolving grain size, with the strain-hardening exponent defined as,

$$n = \frac{5}{(10 + \sqrt{d})} \tag{4}$$

Here, d – Grain size.

The strength parameter '*K*' is given as

$$K = 645 + 14\sqrt{d} \qquad (5)$$

The effective stress required to sustain plastic deformation beyond yielding is represented by the difference between the applied stress and the yield stress, accounting for the contribution of strain hardening. Accordingly, the additional forging stress acting within the deformation zone is expressed as:

$$\nabla_\sigma = \sigma_h - \sigma_y = \left(14\sqrt{d_h} - 14\sqrt{d_y}\right)\left[\varepsilon^{\left(\frac{\left(5\left(10\sqrt{d_y}\right) - 5\left(10\sqrt{d_h}\right)\right)}{\left(10\sqrt{d_h}\right) - \left(10\sqrt{d_y}\right)}\right)}\right] \qquad (6)$$

d_y – denotes the average grain diameter at the onset of yielding, d_h – represents the grain diameter corresponding to the strain-hardening stage. The grain diameter before and after forging as selected based on the material strength tobe developed in the billet material. It is evident that with the 50 % reduction in grain size, the material strength is improved by two times that of billet material [16].

The forging force required to overcome material flow and strain hardening within the deformation layer is determined as follows,

$$F_F = \frac{\nabla_\sigma{}^2 \; x \; \Pi(R_O - R_I)^2 \; x \frac{L_2}{\sin\alpha}}{\varepsilon} \qquad (7)$$

Here, R_0 - Billet radius after deformation, R_t – Tool radius.

Here, F_F = Force in the Forging phase. The parameters d_y & d_h are design input parameters. The grain diameter before yielding is available from the material properties. Whereas grain diameter after forging is given as a design input parameter based on the material strength required to produce a forged component. The grain size and material strength follows the inverse proportionality.

1.3. Sizing Phase Deformation Model

The recrystallized material in the forging phase acquired the required strength due to recrystallization. With the further application of the force on the material, the grain particles get slip over and get deformed into the required shape. The slip of the material offers the frictional resistance for the material slip. The total friction in the sizing phase is the friction component in the normal plane and the lateral plane. The friction components can be calculated by the normal friction model and constant friction model [14, 17]. The frictional resistance on the normal plane is mapped with the sinking phase deformation force, as the material slip is at the normal plane to the deformation force. The analytical expression governing the forging force during the sizing phase is given by,

$$F_Z = m\,\frac{\tau^2 \; x \int_0^{l_1} \frac{2}{3}\Pi R_t{}^2 l_1}{\varepsilon} + \mu\,\frac{\sigma^2 \; x \; \frac{d}{d_{l_1}}\frac{2}{3}\Pi R_0{}^2 \, l_1{}^2}{\varepsilon} \qquad (8)$$

Where, F_z = Force in the Forging phase. R_t = Tool diameter, R_0 = Dia diameter, m_1 & m_2 = Friction coefficient between billet-tool- Die

As discussed, the only controlling parameter in the forging process is forging force. The other governing parameters are selected based on the geometrical constraints and material constraints in the forging process. The selection approach for the governing parameters in the forging process is given in research published by Kitayama. [3]. The complete mathematical model of the forging process representing the total step deformation is given in (9).

$$F_T = \left(\frac{\sigma^2 \, x \frac{\Pi R_t{}^2}{3}\left[\frac{l_1}{2}\right]_0^{l_1}}{\varepsilon} + \frac{\tau^2 \, x \frac{2}{3}\Pi R_t{}^2 l_1}{\varepsilon}\right) + \left(\frac{\left(14\sqrt{d_h} - 14\sqrt{d_y}\right)\left[\varepsilon^{\left(\frac{\left(5\left(10\sqrt{d_y}\right) - 5\left(10\sqrt{d_h}\right)\right)}{\left(10\sqrt{d_h}\right) - \left(10\sqrt{d_y}\right)}\right)}\right]^2 x \; \Pi(R_O - R_I)^2 \, x \frac{L_2}{\sin\alpha}}{\varepsilon}\right) + \left(\left[m_1\left\{\frac{\sigma^2 \, x \frac{\Pi R_t{}^2}{3}\left[\frac{l_1}{2}\right]_0^{l_1}}{\varepsilon}\right\}\right] + m_2\left\{\left(\frac{\tau^2 \, x \frac{2}{3}\Pi R_t{}^2 l_1}{\varepsilon}\right)\right\}\right) \qquad (9)$$

2. Analytical Solution

To validate the mathematical model, the analytical solution is traced by considering the practical product scenario in the forging industry. The model specification required is given in Figure 4.

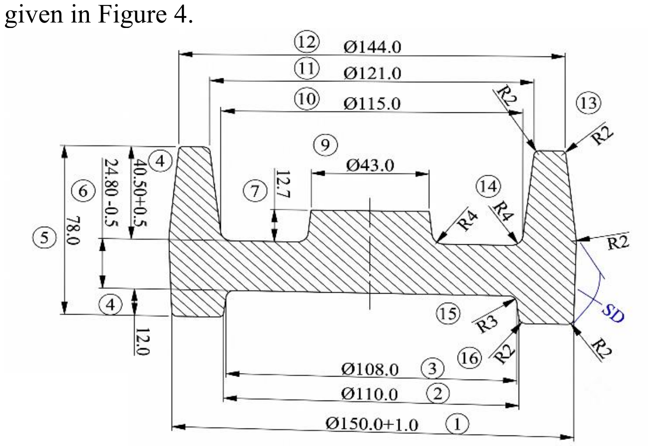

Fig. 4 Experimental model specification

The product specification and the design input requirements are given in Table 1.

Table 1. Design input parameters

Design Parameter	X *	Y*	Z*	% Diff.
Yield Stress	σ_y	sig_y	560	8.75
Billet height	h	h	80	21.13
Single deformation	L1	l	4	1.81
Yield grain dia.	d_y	dgy	70	3.05
Hardened grain dia.	d_h	dgh	30	6.81
Tool friction factor	m_1	m1	0.15	4.42
Billet friction factor	m_2	m2	0.2	13.03
Tool deformation	α	ta	10	8.75
Forging ratio	ε	eps	8	21.13

X * - Representation in design calculation
Y* - Representation in MATLAB design calculator
Z* - Design input parameter

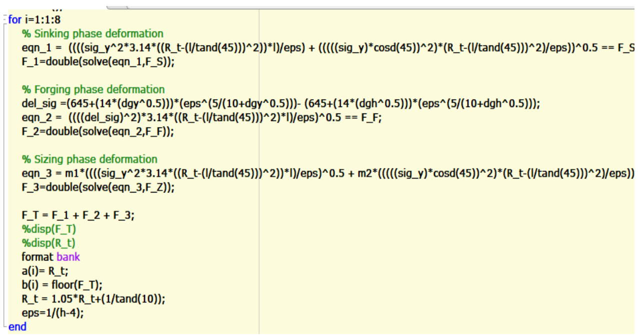

Fig. 5 MATLAB design calculator script

The product specification requirement leads to the selection of a multistage forging process. The MATLAB design calculator is developed to perform the computation of forging force in each stage. The MATLAB design calculator architecture and user interface are given in Figure 5.

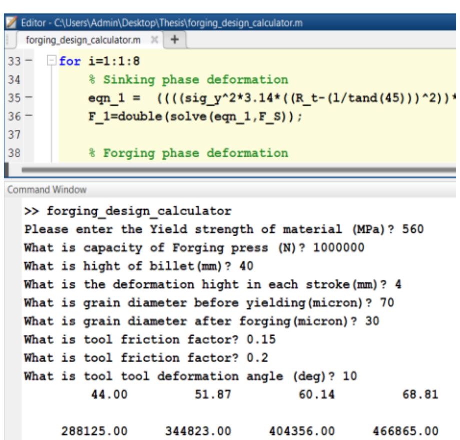

Fig. 6 Design calculator console interface

The MATLAB calculator is run for the product specification and design requirements as stated in table 01. As per the design formulation, the design requirements lead to the calculation related to the incremental tool diameter and forging force in each step. The design calculation results obtained from the MATLAB model run is given in Figure 6.

The design calculation results are applied on the billet material, and the product development is done on the forging press. The product obtained on the forging press is given in Figure 7.

Fig. 7 Forged product developed

3. Software design validation for End Cup

In the analytical method, the design calculations are done as per the material failure mode, and the software analysis can be used for design validation [18]. The forging force is used as an analysis output, and design input parameters are given as analysis constraints. The software validation of the proposed design is done on ANSYS Workbench. The simulation mode run for analysis is given in Figure 8.

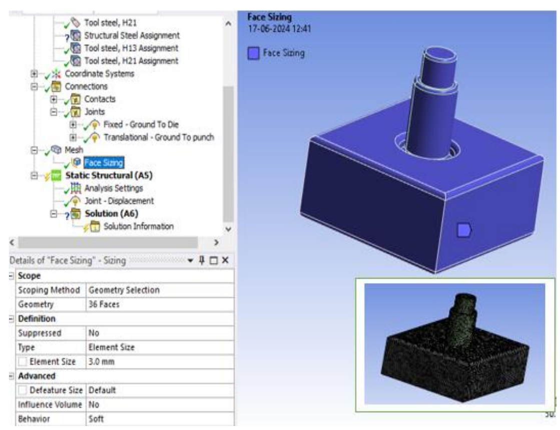

Fig. 8 ANSYS simulation model

Model (A4) > Transient (A5) > Solution (A6) > Force Applied

Time [s]	Minimum [N]	Maximum [N]	Total [N]
1.25e-003	-4.4129e+005	4.1707e+005	1.1753e+007
2.5e-003	-7.1737e+005	8.2114e+005	2.2366e+007
3.75e-003	-4.5346e+005	1.2318e+006	3.4812e+007
5.e-003	-1.923e+005	1.6423e+006	4.7207e+007
6.25e-003	-1.3612e+005	2.053e+006	5.9659e+007
7.5e-003	-1.6341e+005	2.4635e+006	7.2041e+007
8.75e-003	-1.9057e+005	2.8741e+006	8.4504e+007

Fig. 9 Reaction force analysis ANSYS

The simulation model is run with a view to trace the for reaction force as an analysis output. The step deformation as per the design calculation is provided in the analysis.

The analysis result gives the reaction force, which can be mapped with the forging force required for deformation. The reaction force results for the simulation run on ANSYS are given in Figure 9.

The MATLAB design calculator gives the forging force required based on the material failure approach of design; also, the ANSYS analysis gives the reaction force (deformation force required). The forging force and reaction force are mapped to evaluate the effectiveness of the proposed design. The parametric correlation is calculated by comparing the step deformation results in the analytical method (MATLAB calculator results) and software analysis (Ansys results). The parametric correlation results are given in Table 2.

Table 2. Software design validation comparative result

Deformation step	Statistical forging force	Ansys Reaction force	% Diff.	Avg. % diff.
1	457	417	8.75	
2	1041	821	21.13	
3	1209	1231	1.81	
4	1569	1521	3.05	8.42
5	1762	1642	6.81	
6	1966	2053	4.42	
7	2179	2463	13.03	

The correlation analysis gives the maximum variance of 8.42 % between analytical and software results.

4. Experimental Design and Validation for End Cup

The forging process is implemented to develop the material properties in the forged component. The design constraints are laid down based on the literature review and process requirements. As per the design formulation, the forging force is correlated with grain recrystallization. The grain recrystallization is imparted to double the material strength. The course grain impart weak material bond as compared with fine grain, as the surface area in contact is more in fine grain.

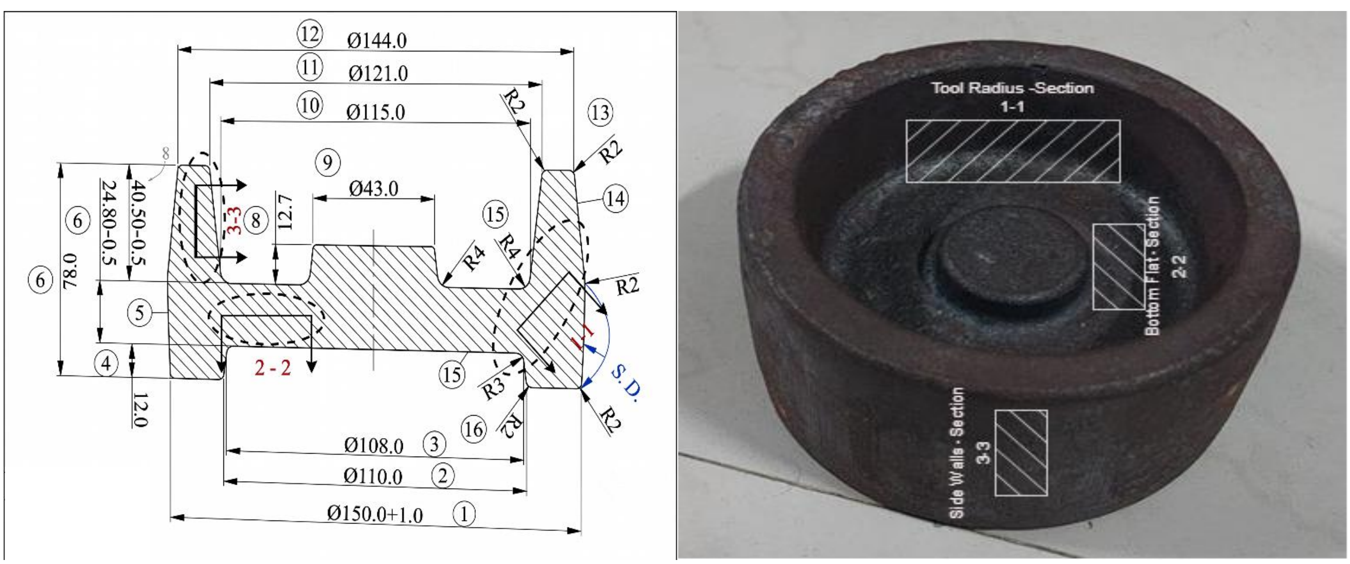

Fig. 10 Critical section model

To validate the design constraints framed in the design stage, the experimental analysis is done on the developed forged component. The stress analysis in ANSYS gives the location of the maximum stress induced. The sample sectioning is done based on the critical failure section identified in the software analysis. The sample section model is given in Figure 10.

4.1. Tensile test on specimen (End Cup)

As per the tensile test for the sectional area of 24 mm^2, the maximum load sustained by the component is 18.95 kN.

The tensile test analysis gives the ultimate stress of the material as 699 MPa.

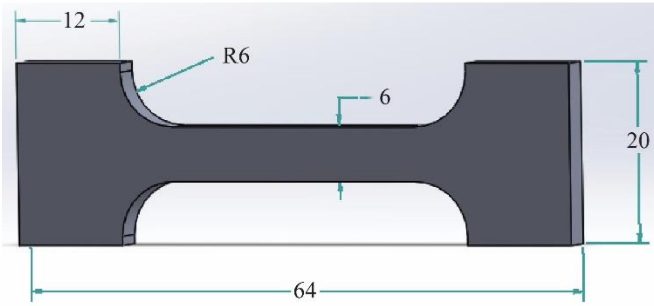

Fig. 11 IS-Standard test specimen-Tensile testing

Fig. 12 Section failure model-Tensile testing

4.2. Shear Test on Specimen (End Cup)

The section material is also tested for the shear strength of the material. The section sample is prepared as per IS 5242-1979 standard. The shear test of the material gives the material strength of 502.48 MPa. The shear test analysis results recorded by the testing agency are provided in Figure 13.

Parameter	Result
Gauge Dia(mm)	9.35
Initial (mm^2)	68.66
Shear Load in (kN)	69.00
Shear Strength in (MPa)	502.48

Fig. 13 Shear test analysis result

4.3. Bending Test on specimen (End Cup)

The bending strength of the material is done as per IS-1599:1985 standard. The normal 3-t bending test is done on the test specimen.The bending test analysis results recorded by the testing agency are provided in Figure 14.

Fig. 14 3-Point bending test analysis result

The structural orientation and maximum load of 4.8KN, 3t bending test gives the bending stress of the material of the End Cup is 1422 MPa.

4.4. Microstructural Analysis of End Cup

The mathematical formulation of the forging process is established based on the underlying material deformation and failure mechanisms governing plastic flow. The grain restructuring is the main reason for improving the material strength [19]. The microstructural analysis is done to compare the grain size before and after the forging process. The Planimetric method of grain size estimation is used. The sample sectioning is done based on the critical section identified in the software analysis. The Planimetric analysis gives the average grain size for the specimen as 28 microns. The microstructural analysis shows the grain elongation in the direction of the forging force. The elongated grain causes the stress distribution on a longer plane as compared to the round grain.

The section sample is treated, and the microstructure is recorded at 100 X zoom. The sample image with the grain count image is given in Figure 15.

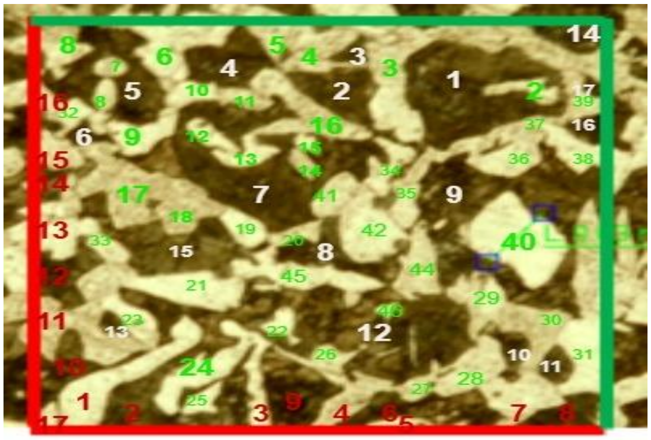

Fig. 15 Microstructure-100 X for end cup

5. Experimental Design and Validation for Cup Cone

The cup cone is also a cone cup, a shaped object having a similar deformation pattern as of cup shaped component. The radial forging is followed for material deformation as per the deformation sequence proposed by the design calculator. The Cup-cone objected is given in Figure 16.

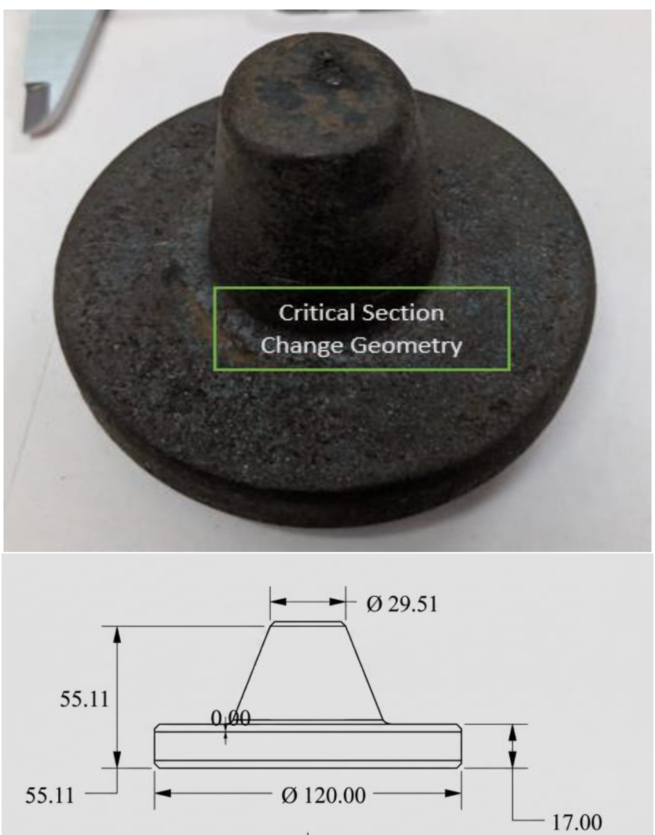

Fig. 16 Actual experimental test sample-cup cone

The experimental analysis involves morphological analysis and metallurgical study. The morphological analysis includes tensile test and bending test analysis.

5.1. Tensile Test on specimen (Cup Cone)

The tensile test is performed as per ISO 6892-1 norms. The section failure and maximum load readings are given in Figure 17. The tensile testing gives the material failure in the cup-cone for the load of 26.4 kN. The section thickness of the material is 38.43 sq. mm. The tensile test analysis gives the ultimate stress of the material as 686.93 MPa.

Fig. 17 Section failure model-Tensile testing-cup cone

5.2. Bending Test on specimen (Cup Cone)

The bending test on the developed cup cone is also done as per IS-1599:1985 standard. The bending test is performed for the 3-t bending test. The three-roll bending test is performed with 45^0 bending test. The loading is offered till 45-degree bend is obtained at the mandrel. The specimen loading and test reading is depicted in Figure 18.

Fig. 18 Bending test-cup-cone

The structural orientation and maximum load of 8.96 KN, 3t bending test gives the bending stress of the material of Cup cone is 2138 MPa.

5.3. Microstructural Analysis of Cup cone

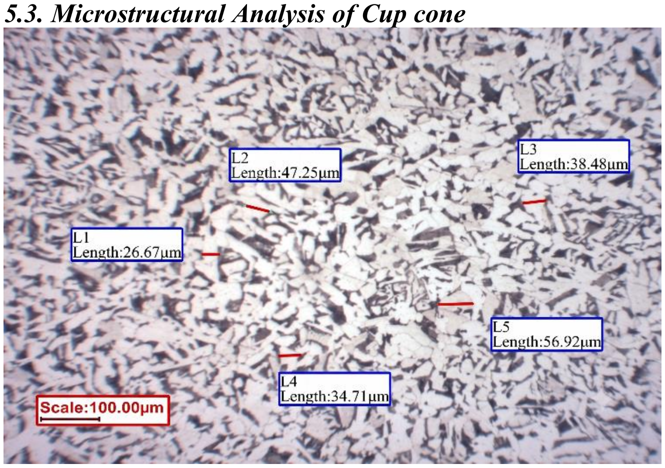

Fig. 19 Grain microstructure-cup cone

The metallographic test is performed at the metallurgical lab, and the grain orientation is studied at 100-X zoom. The grain orientation study involves a grain distribution study and grain size estimation.

The grain grade method is adopted in this stud. The grain orientation obtained on the metallurgical microscope is given in Figure 19. As per the lab report, the grain size number for the given microstructure is 7. The grain diameter for the given sample is 34 microns.

6. Results & Analysis

6.1. Forging Force for End Cup (ANSYS)

The design formulation results are compared with software analysis results. As discussed, the reaction force can be correlated with forging force. The statistical study results are given in Figure 20. The statistical study is done for the same material specification as the software study and experimental analysis.

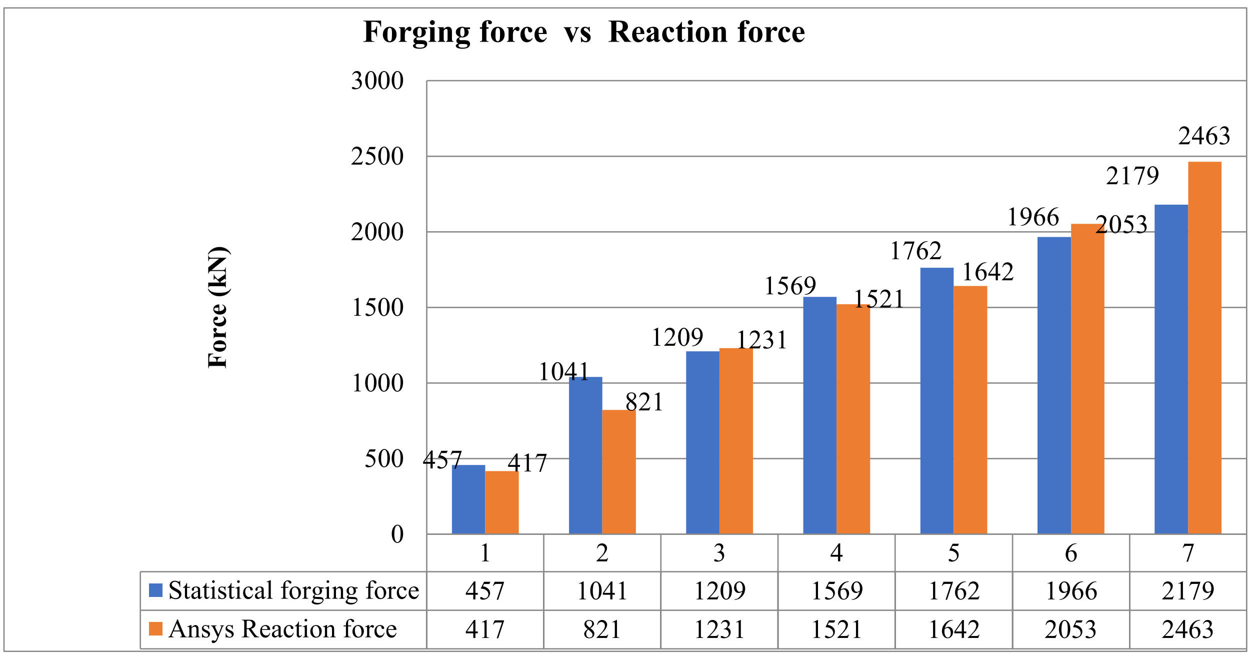

Fig. 20 Ansys reaction force

The mathematical modelling gives the solution to the selection of forging force for step deformation issues in the forging industry. The forging force results are having close approximation with software analysis results. The average difference between the Ansys Forging force (Reaction force) and failure-mode-analysis Force (Statistical forging force) is 3.2 %.

6.2. Material Strength

The tensile and shear test is performed on the standard test specimen as per ISO-1692 standard. The material strength analysis results are given in Table 3.

Table 3. Experimental test results for end cup

Material	Material property	Billet material	Forged material
40 C 8	Tensile strength	250 MPa	699.4 MPa
40 C 8	Shear strength	186 MPa	502 MPa

6.3. Grain Size

The optical microscopic analysis is done to study the microstructural behaviour under the forging process. The analysis results are given in Table 4.

Table 4. Microstructural analysis test results end cup

Analysis method	Material	Grain size billet (Microns)	Grain pattern
Optical Microscopy	40 C_8	70	Spherical
Optical Microscopy	40 C_8	28	Elongated

The grain analysis shows that with decreasing the grain size by 40 %, the material strength gets improved two times as that of the billet material. The grain analysis thus validates the forging phase deformation model.

6.4. Correlation Study Result for End Cup using MATLAB Design Calculator

The mechanical design formulation of Multi stage forging process was validated by performing the analysis of step deformation using Ansys software with a biased weight of experimental study and statistical calculation of MATLAB design calculator. The correlation mapping results are given in Table 5.

Table 5. Correlation evaluation of forging process

Deformation Step	Deformation	Forging Force (N)	Reaction Force (N)	Correlation coefficient
Step - 01	4 mm	1.83×10^7	1.75×10^7	0.95
Step - 02	8 mm	2.42×10^7	2.23×10^7	0.92
Step - 03	12 mm	3.76×10^7	3.48×10^7	0.92
Step - 04	16 mm	4.89×10^7	4.72×10^7	0.96
Step - 05	20 mm	6.13×10^7	5.96×10^7	0.97
Step - 06	24 mm	7.46×10^7	7.20×10^7	0.96
Step - 07	28 mm	8.69×10^7	8.45×10^7	0.97

6.5. Experimental Load Trial Results

The software analysis provides the validation of the proposed design methodology with an average correlation coefficient of 0.95, validated the design methodology with a maximum 5 % of variance. The design validation is further done by performing the actual load trail om developed component. The morphological and metallurgical study of material properties is done, and the analysis results are depicted.

The experimental study shows the true development in material properties after forging. The tensile shear and bend test follows the same material deformation and strength improvement as predicted in the design formulation stage.

6.6. Microstructure Analysis Results

The Image scan analysis and Planimetric grain size estimation method was used for grain size estimation. The optical microscopy analysis results obtained are given in Table 6.

Table 6. Optical microscopy analysis result table

Parameter	Unit	Base Material MS	Forged Component SG5C-548C
Grain size	Microns	70	28
Orientation	-	Spheroidal	Elongated
Tampered layer	mm	-	0.4
Grain count	$No./mm^2$	47	81

The microstructural analysis confirmed that the three-phase deformation pattern predicted during the design formulation stage was accurately reproduced during the experimental load trials. Microstructural characterization demonstrated that grain refinement validates the deformation mechanism occurring during the forging phase.

The elongated grain morphology confirms directional plastic deformation in the sizing phase, whereas tempered layer formation verifies the thermal and deformation effects associated with the sinking phase.

6.7. Comparative Analysis - Mechanical Design and Experimental Trial of End Cup and Cup-Cone

The design methodology formulated based on the material failure approach of design is validated by comparing the design calculation results with experimental load trial results. The sections of parameters for the comparative analysis are governed by material failure mode analysis.

The experimental load trial is done to estimate whether the material properties are developed as per the design formulation or not. Whereas the microstructure study is done to examine the behaviour of the material in an actual load trial. The design formulation approach adopted the principle of stain hardening and development of material strength by restructuring the microstructure. The grain restructuring and strength development is compared with the base material. The strength and microstructure comparative analysis is given in Table 7.

Table 7. Experimental test comparative results

Component		Morphological Parameter		Metallographic parameters	
		Yield Stress MPa	Bending stress MPa	Grain size µm	Orientation
End Cup	Billet	250	690	70	Corse (Spheroidal)
	Sample I	699.4	1422	28	Fine (Elongated)
Cup Cone	Billet	400	700	80	Coarse (Spheroidal)
	Sample I	686.9	2318	34	Fine (Elongated)

7. Comparative Study - Recent Literatures and Practical Implications

The experimental investigation validates the proposed forging design methodology by demonstrating close agreement between the predicted and experimental results for material strength, microstructural evolution, grain size, and forging force, confirming its accuracy in predicting critical forging parameters.

To further assess its robustness, the proposed methodology was compared with previously published experimental forging studies involving similar materials, deformation conditions, and performance parameters.

Lorenzo-Galindo et al. (2026) [20] achieved strength improvement from 450 to 680 MPa, grain refinement from 45 to 18 µm, and forging forces of 900–1600 kN. The proposed methodology produced comparable results with a maximum deviation of approximately 12%, demonstrating good predictive accuracy.

Poungprasert et al. (2025) [21] reported flow stress increasing from 120 to 180 MPa, grain sizes of 9–13 µm, and forging loads of 700–1200 kN. The present methodology showed consistent agreement, confirming its capability to predict material behaviour and grain refinement.

Tekaüt (2023) [22] reported a final material strength of approximately 470 MPa, a forging force of 1250 kN, and an average grain size of 12 µm, which closely agree with the results predicted by the proposed methodology.

Similarly, Anand et al. (2016) [23] reported an increase in material strength from 260 to 320 MPa, grain refinement to 8–15 µm, and forging forces of 800–1400 kN during single-stage hot upsetting. Unlike their approach, the present methodology accurately predicts forging force while optimizing incremental tool geometry. A comparative summary of the present research and previous experimental studies is presented in Table 8.

Table 8. Quantitative comparison with recent studies

Study	Strength Improvement	Grain Size (µm)	Forging Force (kN)
[20]	51.1 %	18	1600
[21]	50.0 % (Flow Stress)	9	1200
[22]	40 %	12	1250
[23]	23.1 %	8	1400
Present Study	58 %	28	869

In addition to the experimental validation, the proposed methodology was compared with recent analytical and simulation-based forging design approaches. Campi et al. (2020) [24] and Favi et al. (2021) [4] improved manufacturing cost prediction using analytical and parametric models but did not incorporate failure mechanisms or material deformation behaviour into the design framework. Kitayama (2024) [3] demonstrated improved cavity filling, load prediction, and process optimization through finite element analysis, while highlighting the need for a generalized and standardized forging design methodology. The proposed approach addresses this gap by integrating material behaviour, deformation mechanisms, and process design within a unified framework.

The comparative evaluation confirms that the proposed methodology accurately predicts material behaviour, deformation characteristics, microstructural evolution, and forging load, with results consistent with previously published studies. Unlike conventional trial-and-error approaches, it integrates material failure mechanisms, deformation analysis, constitutive behaviour, and experimental validation into a unified design framework. This standardized methodology improves design reliability, reduces experimental effort and development cost, and provides a robust framework for systematic forging process design and optimization.

8. Conclusion

Based on the material failure mode study in the forging process, the failure mechanism identifies that the material undergoes step deformation in three phases, which were given as the sinking phase, forging phase and sizing phase. In the sinking phase, the grain restructuring occurs, and the new grain formation takes place due to excessive straining. The restructuring of grains in forging was termed the sinking phase.

The X-shaped deformation model can be applied to formulate the mathematical modelling in the sinking phase. The flow strain at elevated temperature was principle mode of failure. The formulation of the material failure mode was governed by the flow stain principle. The longitudinal travel of the forging tool was responsible for yielding stress, whereas the lateral plane offers the shear stress deformation. The X-shaped deformation model gives the 45^0 orientations among yield and shear plane. The longitudinal travel follows the derivative approach for the material deformation, whereas the shear plane follows the integral approach of material deformation. The forging force equation represents the complete mathematical model of the forging process. The process-dependent parameter and its functional relationship is provided by performing the step-by-step material deformation study. The complete forging cycle is decomposed into three sequential stages: initial sinking, primary forging, and final sizing, each characterized by distinct deformation mechanics and load responses. The material properties development in the forging process is solely dependent on the forging force applied.

The proposed mathematical model is validated by performing a simulation run on the same material configuration model in Ansys. The simulation run gives the reaction force for the material deformation, which is correlated as a forging force required for material deformation. The step deformation analysis gives a percentage error of 8.42 % between the software analysis results and statistical results.

The validated mathematical model is then evaluated for its proof testing by performing the experimental study on the actual forged component developed. The forged component is analysed for material property development. As per the design formulation, the forging force is correlated with the process parameter with a view to double the material strength by inducing the grain restructuring. The tensile test and shear test analysis gives the material strength result almost double the base material strength.

The material property development is due to the grain restricting. The grain restructuring is evaluated by performing the microstructure analysis. The Planimetric microstructure analysis method gives the deformed grain size of 38 microns, which was originally 70 microns. The microstructure analysis validates the basic concept of grain restructuring used in mathematical modelling.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This research is a part of PHD research of the corresponding author.

References

[1] Dhiraj Kumar, and Sharifuddin Mondal, "A Review on Modelling, Design and Optimization of Forging Process," *IOP Conference Series: Materials Science and Engineering*, vol. 1126, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] C. C. Chang, and A. N. Bramley, "Forging Preform Design Using a Reverse Simulation Approach with the Upper Bound Finite Element Procedure," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 214, no. 1, pp. 127-136, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[3] Satoshi Kitayama, "Technical Review on Design Optimization in Forging," *The International Journal of Advanced Manufacturing Technology*, vol. 132, no. 9, pp. 4161-4189, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[4] Claudio Favi et al., "Key Features and Novel Trends for Developing Cost Engineering Methods for Forged Components: A Systematic Literature Review," *The International Journal of Advanced Manufacturing Technology*, vol. 117, no. 1, pp. 2601-2625, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[5] David Uribe et al., "Real-Time Forging Process Control: Integrating Billet-Related Surrogate and Machine Behavior Models," *Journal of Intelligent Manufacturing*, vol. 37, no. 13, pp. 1433-1446, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[6] Michael Hoerner, Case Studies: End Cap Failure, KnightHawk Materials Lab, 2017. [Online]. Available: https://knighthawkmaterialslab.com/end-cap-failure

[7] Jakub Krawczyk, Paweł Widomski, and Marcin Kaszuba, "Advanced Complex Analysis of the Thermal Softening of Nitrided Layers in Tools during Hot Die Forging," *Materials*, vol. 14, no. 2, pp. 349-355, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Kenneth Kanayo Alaneme, and Eloho Anita Okotete, "Recrystallization Mechanisms and Microstructure Development in Emerging Metallic Materials: A Review," *Journal of Science: Advanced Materials and Devices*, vol. 4, no. 1, pp. 19-33, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[9] Zuofa Liu et al., "Deformation Mechanism and Control Strategy of Die Cover in Forging Process," *Materials Today Communications*, vol. 50, no. 2, pp. 629-636, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[10] G. D. Lahoti, and T. Altan, "Analysis of the Radial Forging Process for Manufacturing Rods and Tubes," *Journal of Engineering for Industry*, vol. 98, no. 1, pp. 265-271, 1976. [CrossRef] [Google Scholar] [Publisher Link]

[11] W. Khraisat, N.A. Rawashdeh, and L. Nyborg, "Visualizing Shear Bands in 3-D Using Axisymmetric Sample: An Experimental Study," *Journal of King Saud University, Engineering Sciences*, vol. 29, no. 3, pp. 264-268, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[12] N.T. Switzner, C.J. Van Tyne, and M.C. Mataya, "Effect of Forging Strain Rate and Deformation Temperature on the Mechanical Properties of Warm-Worked 304L Stainless Steel," *Journal of Materials Processing Technology*, vol. 210, no. 8, pp. 998-1007, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[13] Naiyanut Jantepa, Nattarawee Siripath, and Surasak Suranuntchai, "Predictive Modeling and Optimization of Hot Forging Parameters for AISI 1045 Ball Joints Using Taguchi Methodology and Finite Element Analysis," *Metals*, vol. 14, no. 10, pp. 1198-1224,2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Khemraj Sahu et al., "Microstructural Analysis of Forged Al-11Si-2.5Cu-0.6Fe Alloy at Different Processing Conditions," *Materials Today: Proceedings*, vol. 47, no. 19, pp. 6682-6685, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] P. Aghasafari, M. Salimi, and A. Daraei, "Flow Stress Evaluation in Hot Rolling of Steel," *Journal of Materials Engineering and Performance*, vol. 23, no. 1, pp. 2819-2828, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jayanta Kumar Mahato et al., "Effect of Grain Size and Strain Rate on Tensile Work Hardening Behavior of Two Different FCC Metals," *Materials Today: Proceedings*, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[17] Ömer Necati Cora, "*Friction Analysis in Cold Forging*," Thesis, Karadeniz Technical University, pp. 1-19, 2004. [Google Scholar]

[18] Alson E. Hatheway, "Review of Finite Element Analysis Techniques: Capabilities and Limitations," *Proceedings of SPIE - The International Society for Optical Engineering*, pp. 121-127, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[19] Zhizhou Pan et al., "Improving Mechanical Properties of a Forged High-Manganese Alloy by Regulating Carbon Content and Carbide Precipitation," *Metals*, vol. 12, no. 3, pp. 473-481, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Irving Lorenzo-Galindo, Midori Landa-Castro, and Daniel Flores-Sancheez, "Cold Forging in Medium Carbon Steel: AISI 1045 Characterization via Experimental and Numerical Techniques," *Modelling and Simulation in Engineering*, vol. 2026, no. 1, pp. 1-9, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[21] Raschanan Poungprasert et al., "FEM Modeling and Comparative Study of Graphite Lubricants in the Hot Forging of AISI 1045 Medium Carbon Steel," *Journal of Metals, Materials and Minerals*, vol. 35, no. 4, pp. 2315-2325, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[22] İsmail Tekaüt, "Investigation of the Microstructure, Machinability and Hole Quality of AISI 1045 Steel Forged at Different Temperatures," *Proceedings of the Institution of Mechanical Engineers*, *Part E*: *Journal of Process Mechanical Engineering*, vol. 237, no. 5, pp. 261-276 .2023. [CrossRef] [Google Scholar] [Publisher Link]

[23] Aniket Anand et al., Hot Deformation Behaviour Studies on Medium Carbon Steel by Thermo-Mechanical Simulation and Finite Element Method," Proceedings of the 4th International Conference on Thermo-Mechanical Simulation and Processing of Steels, Ranchi, Jharkhand, 2016. [Online]. Available: https://www.researchgate.net/publication/308364285_Hot_Deformation_Behavior_Studies_on_Medium_Carbon_Steel_by_Thermo_Mechanical_Simulation_and_Finite_Element_Method

[24] Federico Campi et al., "An Analytical Cost Estimation Model for the Design of Axisymmetric Components with Open-Die Forging Technology," *The International Journal of Advanced Manufacturing Technology*, vol. 110, no. 7, pp. 1869-1892, 2020. [CrossRef] [Google Scholar] [Publisher Link]