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MULTI-CRITERIA DECISION-MAKING FOR FORGING 38MNSIVS5 STEEL USING TOPSIS APPROACH

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Abstract

This study investigates the optimisation of forging parameters for 38MnSiVS5 micro-alloyed steel to optimise mechanical properties, specifically impact strength and hardness. Hot forging experiments were conducted using open-die forging to evaluate the effects of forging temperature, percentage deformation, and cooling rates on these properties. A full factorial design of experiments was employed, and the resulting samples were assessed for impact strength, hardness and microstructural changes. The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) analysis was applied to identify the optimal forging conditions. The results indicated that forging at 900°C with 60% deformation under normal air cooling provided the best balance between impact strength and hardness. TOPSIS effectively identified this condition as optimal, highlighting its utility in decision-making for material processing.

Keywords: *Hot forging, Impact strength, hardness, TOPSIS, Multi-criteria decision-making*

1. Introduction

Forging is one of the oldest and most effective metalworking processes, involving the plastic deformation of materials to achieve desired shapes and improve mechanical properties. By subjecting metals to compressive forces at elevated temperatures, forging induces grain refinement and enhances key mechanical properties, including strength, toughness, and resistance to wear. These improvements make forged components ideal for high-performance applications in industries such as automotive, aerospace, and heavy machinery [1]. The ability to control forging parameters, such as forging temperature, percentage deformation, strain rate, die geometry, cooling rate, and friction coefficient, is crucial for achieving optimal mechanical properties in the final product. These parameters play a vital role in influencing grain structure, phase transformations, recrystallisation, and overall microstructure, which directly impact the material's strength, toughness, hardness, and ductility [2]. Additionally, factors such as lubrication, forging speed, friction between the die and workpiece, and the type of forging (open die, closed die, isothermal) further contribute to the overall performance of the forged component. Proper control and optimisation of these parameters ensure uniform deformation, reduce defects, and improve the efficiency and quality of the forging process. In recent years, the development of micro-alloyed steels, such as 38MnSiVS5, has garnered significant attention in forging applications. Micro-alloyed steels contain small amounts of alloying elements like vanadium, niobium, and titanium, which precipitate as fine carbides or nitrides during the forging process. Among these, vanadium is often preferred over titanium and niobium due to its ability to form more stable and finely dispersed vanadium carbides (VC), which significantly improve grain refinement. This leads to better control of recrystallisation and phase transformations during forging, resulting in enhanced strength and toughness. Additionally, vanadium provides a more consistent and reliable strengthening effect across a broader range of forging temperatures, making it a versatile choice for hot forging applications [3]. It is also more effective in high-temperature environments, enhancing fatigue resistance and durability. These attributes, combined with cost-effectiveness, make vanadium-alloyed micro-alloyed steels ideal for manufacturing critical structural components such as automotive crankshafts, connecting rods, and suspension parts. However, to fully harness the potential of micro-alloyed steels, optimising key forging parameters, including forging temperature, percentage deformation, cooling rate, friction conditions, and even die design, remains essential. This optimisation ensures the proper balance between different mechanical properties, leading to superior performance across various applications.

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2. Literature Review

To achieve optimal operating parameters in metal forming, extensive research has focused on medium-carbon micro-alloyed steels. Babakhani et al. [4] studied the effects of hot forging parameters such as deformation temperature, strain, and cooling rate on the microstructure and mechanical properties of vanadium micro-alloyed forging steel. Khameneh et al. [5] highlighted the importance of cooling strategies by investigating their impact on the microstructure and mechanical properties of 30MSV6 micro-alloyed forging steel after hot compression. Sujith Bobba et al. [6] investigated the effects of hot deformation and controlled cooling temperature on the microstructure of medium carbon micro-alloyed steel 38MnSiVS5, aiming to improve impact toughness and hardness. Zhang Yingjian et al. [7] simulated the hot forging process of microalloyed steel for crankshafts using FEM software (ANSYS/LS-DYNA). Gunduz et al. [8] investigated the effect of different microstructures on the fatigue behaviour of medium-carbon vanadium microalloyed steel, finding that cooling rates significantly influenced the microstructure, hardness, and fatigue behaviour at room temperature. R.D.K. Misra et al. [9] examined the effect of cooling rate on mechanical behaviour and microstructural features, revealing that both Nb and V-microalloyed steels showed increased toughness with higher cooling rates. They also observed that Nb-microalloyed steels exhibited greater toughness than their V-microalloyed counterparts under similar processing conditions. Weijun Hui et al. [10] studied the effect of cooling rate on the microstructure and hardness of medium carbon steel micro-alloyed with vanadium (0.15% and 0.28%). Using a Gleeble-3800 thermal simulator for single compression tests, they found that cooling rate significantly influences the microstructure and hardness of the steels, highlighting the importance of cooling strategies in enhancing mechanical properties. H. Mirzadeh et al. [11] investigated the hot deformation behaviour of medium carbon microalloyed steel by analysing hot compression flow curves over a temperature range of 850–1150 °C and strain rates from 0.0001 to 3 s^{-1}. Despite these contributions, there remains limited analysis on determining the optimal levels of forging parameters that yield the best combination of mechanical properties and forging quality. The present work aims to bridge this research gap by identifying the most effective forging parameters to maximise mechanical performance. The relationship between forging temperature, percentage deformation, and cooling rate has a significant impact on the impact strength, hardness, and overall microstructural development of the forged parts. For instance, higher forging temperatures generally promote grain growth, which can reduce strength, while faster cooling rates may enhance hardness but negatively impact toughness. Therefore, a careful optimisation process is required to ensure that the forging parameters are aligned with the desired performance characteristics of the material. Traditional approaches to determining the ideal forging conditions have typically relied on trial and error or intuition, which are time-consuming and resource-intensive. The introduction of systematic approaches, such as Full Factorial Design of Experiments (DOE), enables a more efficient exploration of multiple variables and their interactions. This method enables engineers to assess the combined effects of forging temperature, percentage deformation, and cooling rate on mechanical properties in a structured and statistically rigorous manner. Additionally, Multi-Criteria Decision-Making (MCDM) techniques, such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and WSM (Weighted Sum Model), as well as Grey relational analysis, provide robust frameworks for optimising complex industrial processes where multiple, often conflicting objectives must be balanced. These techniques have proven effective in various manufacturing contexts, offering a comprehensive approach to decision-making when multiple factors influence the desired outcomes. In this study, we aim to optimise the forging parameters for 38MnSiVS5 micro-alloyed steel by employing a Full Factorial Design of Experiments (DOE) and a Multi-Criteria Decision-Making (MCDM) technique, specifically the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Through a series of hot forging experiments, we evaluate the effects of forging temperature, percentage deformation and cooling rates on the impact strength, hardness and microstructure of the forged parts. The results are analysed using TOPSIS to identify the optimal trade-off between mechanical properties. This research contributes to the understanding of how forging parameters affect micro-alloyed steel and offers insights into the most suitable approaches for optimising forging processes in industrial applications.

3. Materials and Methodology

This study investigates the optimisation of forging conditions for 38MnSiVS5 micro-alloyed steel using a systematic approach that includes material selection, forging setup, heating and cooling processes and experimental evaluation methods incorporating Multi-Criteria Decision-Making (MCDM) techniques. The selected material, 38MnSiVS5 micro-alloyed steel, is known for its superior mechanical properties. The chemical composition of as-received steel is listed in Table 1.

Table 1: Chemical Composition of 38MnSiVS5 Steel in (wt. %)

	C	Si	Mn	P	S	Cr	V	Mo	N
38MnSiVS5	0.401	0.198	1.213	0.017	0.024	0.138	0.085	0.046	0.0058

Hot forging experiments were conducted using a 150-ton hydraulic press on cylindrical specimens (60 mm diameter, 90 mm length) with open-die forging. Specimens were heated in an electric furnace at 900°C, 1000°C, and 1100°C for 30 minutes, followed by diameter reductions of 40%, 50%, and 60%. After forging, samples were cooled using normal air, forced air and quenching oil. The forging parameters, along with their corresponding levels, are shown in Table 2.

Table 2: Factors and their levels

Factors	Symbol	Level 1	Level 2	Level 3	Unit
Forging temperature	FT	900	1000	1100	ºC
Percentage Deformation	PD	40	50	60	-
Cooling Rate	CR	NA	FA	OQ	-

A full factorial experimental design was employed to systematically vary forging parameters, such as temperature, deformation, and cooling rate, allowing for a comprehensive evaluation of impact strength and hardness, as presented in Table 3. Mechanical testing involved evaluating impact strength and hardness according to ASTM standards. Specimens were prepared for microstructural analysis to assess changes in microstructure and identify any correlations between processing conditions and mechanical properties. To optimize the forging conditions for 38MnSiVS5 micro-alloyed steel, the Multi-Criteria Decision-Making (MCDM) technique of TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was employed.

The methodology involved the following steps:

Data Collection: All the quantitative data are gathered for the alternatives based on performance indicators (like impact strength and hardness).

Table 3: Full factorial design of experiments

Exp. No.	FT	PD	CR	IS (kJ/m^2)	Hardness (HV)
1	900	40	NA	900	267
2	900	40	FA	710	281
3	900	40	OQ	330	333
4	900	50	NA	1050	249
5	900	50	FA	850	277
6	900	50	OQ	400	318
7	900	60	NA	1120	244
8	900	60	FA	890	268
9	900	60	OQ	620	295
10	1000	40	NA	930	266
11	1000	40	FA	690	285
12	1000	40	OQ	290	350
13	1000	50	NA	940	263
14	1000	50	FA	840	279
15	1000	50	OQ	520	305
16	1000	60	NA	1040	251
17	1000	60	FA	870	275
18	1000	60	OQ	610	298
19	1100	40	NA	960	255
20	1100	40	FA	680	289
21	1100	40	OQ	250	373
22	1100	50	NA	980	253
23	1100	50	FA	790	280
24	1100	50	OQ	420	315
25	1100	60	NA	1060	246
26	1100	60	FA	980	272
27	1100	60	OQ	570	304

Normalisation of Data: The output responses were normalised to a common scale of 0 to 1, in accordance with Eq. (1), which is essential for enabling accurate comparisons within the TOPSIS framework.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}} \quad (1)$$

Where i = 1, 2, 3,…..,m, and j = 1, 2, 3,…….,n.

Weight Assignment: Here, a weight is assigned to each criterion to reflect its importance following Eq. (2). The sum of weights should equal 1:

$$\sum_{j=1}^{n} W_j = 1 \quad (2)$$

Identification of Ideal and Anti-Ideal Solutions: The ideal (best) and anti-ideal (worst) solutions were established from the normalized data in accordance with Eq. (3) and Eq. (4)

Ideal solution A+ = {max (rij) | j ∈ beneficial criteria} U {min (rij) | j ∈ non-beneficial criteria}
(3)

Anti-ideal solution A- = {min (rij) | j ∈ beneficial criteria} U {max (rij) | j ∈ non-beneficial criteria}
(4)

Distance Calculation: The distance of each alternative from both the ideal and anti-ideal solutions was computed using Eq. (5) and Eq. (6) Distance from ideal solution:

$$\text{Si+} = \sqrt{\sum_{j=1}^{n}\left(r_{ij} - A_j^{+}\right)2} \quad (5)$$

Distance from anti-ideal solution:

$$\text{Si+} = \sqrt{\sum_{j=1}^{n}\left(r_{ij} - A_j^{-}\right)2} \quad (6)$$

Calculation of Relative Closeness: Compute the relative closeness of each alternative to the ideal solution using Eq. (7)

Ci = Si- / (Si+- Si-) (7)

where Ci ranges from 0 to 1, with values closer to 1 indicating better performance.

Ranking of Alternatives: Rank the alternatives based on their Ci values, with higher values indicating superior performance in achieving the desired outcomes [12].

4. Results and Discussion

To investigate the effect of forging parameters, namely Forging Temperature (FT), Percentage Deformation (PD) and Cooling Rate (CR), on the output responses, impact strength and hardness during the hot forging of 38MnSiVS5 micro-alloyed steel, experiments were conducted using the Full Factorial Design of Experiment (FFDE) methodology. The output responses were measured using impact and hardness test specimens prepared from the forged bars. Table 3 presents the experimental results obtained from the hot forging trials as per the selected FFDE. Analysis of Variance (ANOVA) at a 95% confidence level was applied to assess the relative influence of the forging parameters on the output responses.

ANOVA results corresponding to each studied response is presented in Tables 4 and 5. In these tables, SS corresponds to sum of square, MS corresponds to mean sum of square, and DOF corresponds to degree of freedom.

Table 4. ANOVA results for Impact Strength

Source	DF	Seq SS	Adj MS	F	P
FT	2	1985	993	0.37	0.696
PD	2	226807	113404	42.1	0
CR	2	1420274	710137	263.63	0
Error	20	53874	2694		
Total	26	1702941			
R^2 = 96.84% R^2 (adj) = 95.89%					

Table 5. ANOVA results for Hardness

Source	DF	Seq SS	Adj MS	F	P
FT	2	179.6	89.8	0.65	0.532
PD	2	3463.4	1731.7	12.57	0
CR	2	20354.7	10177.4	73.87	0
Error	20	2755.6	137.8		
Total	26	26753.4			
R^2 = 89.70% R^2 (adj) = 86.61%					

Adequacy of regression and significance of each term are determined using the F value given in the ANOVA table [13]. The probability of the F value being greater than the calculated F value due to noise is indicated by the p-value. If the p-value is less than 0.05, the corresponding term is considered to be significant or vice versa. ANOVA results show that PD and CR are significant for both responses.

5. Optimisation using TOPSIS

This study utilised the TOPSIS multi-criteria decision-making (MCDM) method to rank 27 forging process alternatives based on two key performance indicators: impact strength and hardness. The objective was to identify the optimal combination of forging temperature, deformation percentage, and cooling rate that achieves the best balance between these criteria. The results of the TOPSIS analysis are presented in Table 6, showcasing the rankings of the alternatives.

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The results of the TOPSIS analysis provide critical insights into the optimisation of forging parameters for 38MnSiVS5 micro-alloyed steel, specifically focusing on impact strength and hardness. The alternatives are ranked, as shown in Fig. 1, based on their Ci values, which reflect their proximity to the ideal solution. The highest-ranking alternative, A1, with a Ci value of 0.752, demonstrates a strong capability to optimise both impact strength and hardness. This suggests that the specific combination of forging temperature, percentage deformation, and cooling rate associated with A1 is particularly effective in enhancing these mechanical properties.

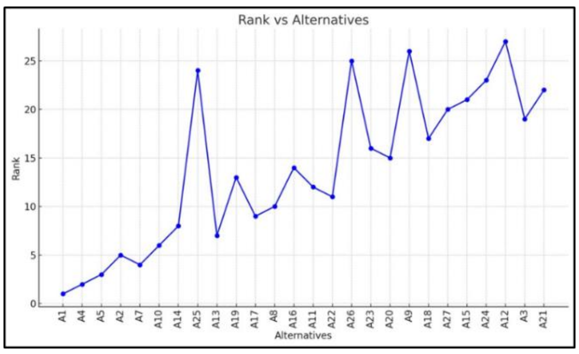

Fig. 1. Graph of Rank vs. Alternatives

The favourable conditions identified warrant further investigation, as they could significantly improve the performance of components manufactured from this steel. In contrast, the lowest-ranking alternative, A12, with a Ci value of 0.444, indicates a less effective combination of parameters. This finding emphasises the importance of careful selection in forging conditions, as suboptimal parameters may not only fail to optimise desired properties but could potentially degrade the material's overall performance. The observed rankings clearly illustrate how variations in forging temperature, percentage deformation, and cooling rate directly impact the mechanical properties of 38MnSiVS5 steel. These results underscore the necessity of a systematic approach to parameter optimisation, moving away from traditional trial-and-error methods. By employing TOPSIS, this study provides a robust framework for decision-making in material processing, offering a pathway to improve the manufacturing processes used in industry.

6. Microstructural Analysis

The microstructure of 38MnSiVS5 steel was investigated for both pre- and post-forging conditions at various temperatures and cooling rates, including normal air cooling (NA), forced air cooling (FA), and oil quenching (OQ). It is observed that, depending on the different thermo-mechanical conditions, a variety of microstructures may be obtained. The variation in mechanical properties in 38MnSiVS5 steel can be explained in terms of the microstructure obtained after forging, followed by different cooling rates.

Fig. 2 depicts the microstructural evolution of 38MnSiVS5 micro-alloyed steel samples subjected to different cooling conditions after forging. The as-received material primarily consists of a ferrite-pearlite microstructure, characterised by soft ferrite grains interspersed with lamellar pearlite colonies. This microstructure is largely retained in samples cooled under Normal Air (NA) and Forced Air (FA) conditions, where relatively slow cooling rates allow sufficient time for diffusional transformations, resulting in coarse pearlite and ferrite phases that enhance ductility and impact toughness. In contrast, oil-quenched (OQ) samples experience rapid cooling, which suppresses the formation of equilibrium phases and promotes bainitic transformation. These OQ samples exhibit a microstructure comprising bainite, alloyed cementite, and finely dispersed vanadium-rich carbides and carbo-nitrides. The fine and uniform distribution of these precipitates, coupled with a refined prior austenite grain size and the redistribution of alloyed cementite, acts as an effective barrier to dislocation movement, thereby significantly increasing hardness and strength.

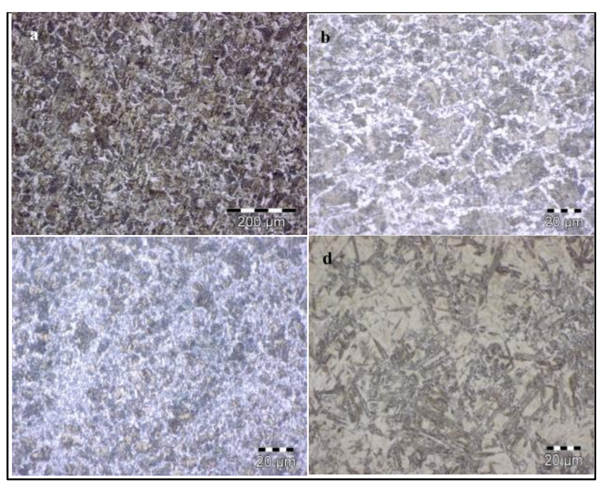

Fig. 2. Microstructures of 38MnSiVS5 steel under conditions of (a) As-Received (b) NA (c) FA and (d) OQ.

The Vickers hardness measurements substantiate this, showing markedly higher hardness values in OQ specimens compared to NA and FA samples. The rapid cooling rate in OQ samples facilitates a fine dispersion of alloy carbides, which impede plastic deformation mechanisms. However, this increased hardness comes with a trade-off: the higher volume fraction of upper bainite and hard precipitates reduces the material's ductility and impact toughness due to restricted grain boundary mobility and limited atomic diffusion during transformation.

Overall, the microstructural differences governed by cooling rates illustrate the fundamental balance between strength and toughness in micro-alloyed steels. While slower cooling favours tougher, more ductile microstructures dominated by ferrite and pearlite, faster cooling yields stronger but more brittle bainitic structures reinforced by fine carbide precipitates. Understanding this interplay is crucial for tailoring forging parameters to achieve the desired mechanical performance.

7. Conclusions

This study investigated the influence of forging parameters, Forging Temperature, Percentage Deformation, and Cooling Rate, on the mechanical properties of 38MnSiVS5 micro-alloyed steel.

- A Full Factorial Design of Experiments (FFDE) was used along with TOPSIS analysis for evaluation.
- ANOVA results showed that Percentage Deformation and Cooling Rate have significant effects on impact strength and hardness.

Table 6: Results of TOPSIS

Rank	Alternative	Normalized Impact Strength	Normalized Hardness	Si^+	Si^-	Ci
1	A1	0.649	0.288	0.155	0.47	0.752
2	A4	0.759	0.268	0.218	0.474	0.685
3	A5	0.613	0.299	0.222	0.465	0.676
5	A2	0.512	0.303	0.243	0.464	0.656
4	A7	0.807	0.263	0.247	0.464	0.652
6	A10	0.671	0.287	0.269	0.466	0.634
8	A14	0.607	0.3	0.266	0.463	0.634
24	A25	0.765	0.265	0.276	0.468	0.629
7	A13	0.678	0.284	0.276	0.465	0.627
13	A19	0.693	0.275	0.279	0.467	0.626
9	A17	0.629	0.296	0.274	0.456	0.625
10	A8	0.641	0.289	0.272	0.454	0.625
14	A16	0.75	0.271	0.285	0.465	0.62
12	A11	0.498	0.307	0.283	0.443	0.61
11	A22	0.707	0.273	0.297	0.464	0.609
25	A26	0.707	0.293	0.3	0.462	0.605
16	A23	0.57	0.302	0.292	0.444	0.604
15	A20	0.49	0.311	0.305	0.444	0.592
26	A9	0.448	0.318	0.347	0.418	0.546
17	A18	0.44	0.321	0.353	0.417	0.541
20	A27	0.411	0.328	0.363	0.415	0.533
18	A6	0.288	0.343	0.382	0.424	0.526
21	A15	0.375	0.329	0.451	0.394	0.466
23	A24	0.303	0.34	0.474	0.396	0.454
27	A12	0.209	0.377	0.516	0.412	0.444
19	A3	0.238	0.359	0.569	0.432	0.431
22	A21	0.181	0.402	0.585	0.396	0.403

- TOPSIS analysis identified alternative A1 as the optimal condition, with a closeness coefficient (Ci) value of 0.752, indicating superior mechanical property enhancement.
- Microstructural analysis found that oil-quenched samples exhibited higher hardness due to the formation of bainite and fine vanadium carbides.
- However, increased hardness in oil-quenched samples was accompanied by decreased ductility and impact strength.
- This highlights the trade-off between hardness and toughness when optimizing forging parameters.

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