Asian Journal Science and Engineering
Open Access
Vol. 4, No. 1, June 2025
https://attractivejournal.com/index.php/ajse

Optimizing Flexibility in SUP9 Leaf Springs: The Synergistic Effect of Tempering Temperature and Holding Time

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ARTICLE INFO
Article history:
Received
June 03, 2025
Revised
June 27, 2025
Accepted
June 27, 2025

Abstract

This study investigates the influence of tempering temperature and holding time on the flexibility of SUP9 steel leaf springs, addressing a practical need for enhanced vibration absorption in heavy-duty vehicles operating on irregular terrain. An experimental study was conducted using a full factorial design with three temperature levels (450°C, 550°C, 650°C) and three holding times (15, 20, 25 minutes). Flexibility was quantified by measuring the maximum deflection in a three-point bending test. The results demonstrate a strong, positive correlation between the tempering parameters and flexibility. The optimal flexibility (47.76 mm deflection) was achieved at the highest treatment condition of 650°C with a 25-minute holding time, representing an 83% improvement over the least effective treatment. ANOVA results confirmed that temperature, holding time, and their interaction are all statistically significant factors ($p < 0.05$). These findings provide a practical, data-driven guideline for manufacturing more resilient and comfortable leaf springs by optimizing heat treatment protocols.

Keywords: SUP9 Steel, Leaf Spring, Flexibility, Tempering Process, Heat Treatment, Mechanical Properties

Published by	CV. Creative Tugu Pena
ISSN	2963-6752
Website	https://attractivejournal.com/index.php/ajse

INTRODUCTION

The performance and durability of suspension systems in heavy-duty vehicles are critical not only for ride comfort but also for structural integrity and safety, especially under challenging road conditions and heavy payloads [1]. Among the various components of a suspension system, leaf springs play a vital role in absorbing shocks, maintaining vehicle height, and stabilizing the axle positions. With the increasing demand for efficiency and durability, leaf springs are now being subjected to continuous engineering optimization, including geometric redesign and material enhancement [2], [3]. Although composite materials such as carbon epoxy and glass-fiber laminates have gained attention for their lightweight potential [4], steel—particularly medium-carbon chromium spring steel such as SUP9—remains the dominant material in industrial applications due to its superior toughness, fatigue resistance, and cost-effectiveness [5],[6].

However, the mechanical performance of steel leaf springs is not solely determined by the base material but is critically shaped by the applied heat treatment. Among these, the tempering process—reheating quenched steel below its critical temperature for a specified duration—has a significant impact on mechanical properties such as hardness, ductility, and flexibility [7]. As tempering temperature increases, the decomposition of martensite and coarsening of carbides typically lead to reduced hardness and improved impact resistance, a trade-off that must be carefully managed for performance-critical applications [8]. Moreover, achieving the ideal balance of properties requires precise control over tempering parameters, not only for the bulk material but also to prevent detrimental surface phenomena such as ferrite decarburization, which is highly influenced by alloying elements like Mn and Si in spring steels [9], [10]. Recent advancements have also highlighted the effect of varying holding times on microstructural evolution, yet few studies have comprehensively investigated how temperature and duration interact to influence a specific property like flexibility—an essential parameter for vibration damping in rough terrain conditions [11].

SUP9 spring steel, commonly used in automotive applications, has seen limited local research in the context of combined heat treatment parameter optimization. Existing studies in Indonesia often focus on hardness or tensile strength, leaving flexibility—despite its importance for shock absorption in vehicles operating in agricultural or uneven road environments—largely unexplored [12], [13]. Moreover, studies tend to vary either the tempering temperature or the holding time in isolation, neglecting the potential synergistic effects of both.

Therefore, this study aims to fill this gap by systematically analyzing the influence of tempering temperature (450 °C, 550 °C, and 650 °C) and holding time (15, 20, and 25 minutes) on the flexibility of SUP9 steel leaf springs. The primary objective is to map the relationship between these two parameters and the resulting flexibility performance, allowing for the identification of an optimal heat treatment protocol. Ultimately, the results are expected to contribute to the development of more durable and adaptive leaf springs for real-world conditions—such as sugarcane transport trucks operating on uneven terrain—where vibration absorption is a critical requirement.

METHOD

This research was conducted using a full factorial experimental design to systematically investigate the effects of tempering temperature and holding time on the flexibility of SUP9 steel leaf springs. The material selected for this study was commercial-grade JIS SUP9 steel (also known as 9260 steel), a high-carbon silicon-manganese alloy prized for its high strength, toughness, and fatigue resistance, making it a primary choice for automotive suspension springs [14]. The as-received material was machined into standardized rectangular specimens with dimensions of 200 mm x 20 mm x 7 mm for all subsequent testing.

The heat treatment protocol consisted of two primary stages: hardening and tempering. First, all specimens underwent a uniform hardening process to create a consistent baseline microstructure. This involved austenitizing the specimens in an electric furnace at 850°C, a standard temperature for medium/high-carbon steels to ensure the formation of a fully austenitic structure prior to quenching [15]. Subsequently, the specimens were quenched in oil. Oil was selected as the quenching medium to achieve a sufficiently rapid cooling rate for martensite formation while mitigating the risk of distortion and quench cracking, a critical consideration for high-carbon alloy steels [16].

The core of the experiment was the tempering process, which was performed at three distinct temperature levels: 450°C, 550°C, and 650°C. This range was strategically chosen to cover the typical spectrum for spring steels, where tempering significantly alters the balance between hardness, strength, and toughness by modifying the martensitic structure and promoting carbide precipitation [17]. For each temperature, three holding times were applied: 15, 20, and 25 minutes. This 3x3 factorial design resulted in nine unique treatment conditions, with each condition replicated three times to ensure data reliability and statistical power (total n=27). After the specified holding time, all samples were removed from the furnace and allowed to cool in ambient air [18].

The primary mechanical property of interest, flexibility, was evaluated by measuring the maximum deflection of the specimens under a static load. This was performed using a three-point bending test (Fig. 1), chosen as it effectively simulates the loading conditions of a leaf spring in service [19]. The tests were conducted on a universal testing machine (UTM), and the procedure was guided by the principles of the ASTM E290 standard for bend testing. During each test, a constant load was applied to the center of the specimen, and the resulting vertical deflection was precisely measured. The collected deflection data were then statistically analyzed using Analysis of Variance (ANOVA) with Minitab 19 software to determine the individual and interactive effects of tempering temperature and holding time on the steel's flexibility [New Ref. 7].

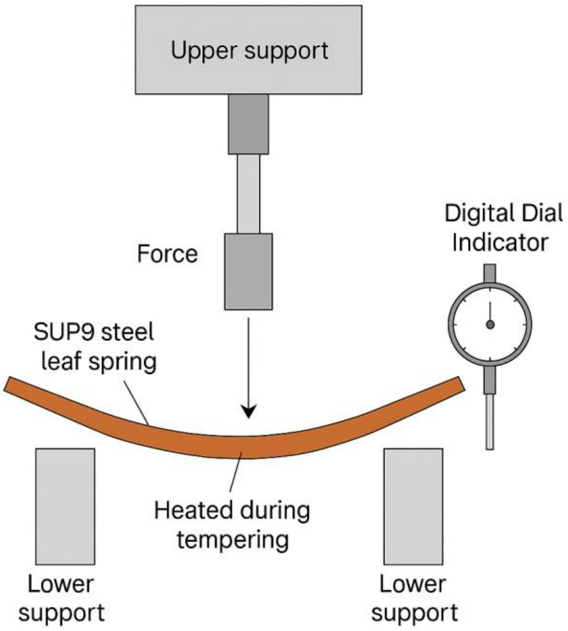

Figure 1 Experimental Setup

RESULT AND DISCUSSION

The experimental results unequivocally demonstrate that both tempering temperature and holding time are significant factors influencing the flexibility of

SUP9 steel leaf springs. that the chosen parameters account for the vast majority of the variability observed in spring flexibility.

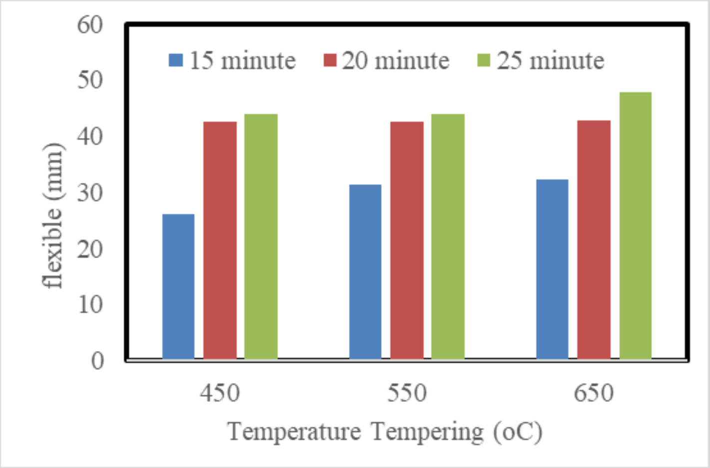

Figure 2. Temperature relationship temperature to flexibility (mm).

Figure 2 presents the results of testing the flexibility of the material that has gone through a tempeh process in temperature variations (450 ° C, 550 ° C, and 650 ° C) and detention time (15 minutes, 20 minutes, and 25 minutes). From this rod graph, it is clear that the temperature and time of temperature collectively affect the nature of the material flexibility. In general, this graph shows that an increase in temperature of temperature tends to increase the value of material flexibility, and at the same temperature, longer detention time also generally produces higher flexibility. The most striking trend is that the temperature treatment at 650 ° C with a 25-minute detention time (the rightmost green stem) produces the highest flexibility value, reaching around 47-48 mm.

The phenomenon of increased flexibility in line with the increase in temperature and temperature time can be explained through microstructure changes that occur in the material. Tempering process is the heat treatment carried out after quenching (rapid cooling) to reduce the fragility and increase the tenacity and flexibility of the material. After quenching, the material structure tends to be a hard and brittle martensite. When the material is re-heated at temperatures, carbon atoms trapped in the martensite grid begins to diffuse out, forming more stable carbide deposits and spread evenly. The higher the temperature and the longer the temperature time, the more carbon atoms diffuse, and the carbide particles that are formed also tend to grow to be larger and spread further. The formation and coagulation of this carbide converts the structure of martensit to tempeing martensite or even ferrite and cementite, which is far more resilient and elastic than martensite as-quenched. This more resilient structure allows material to undergo greater plastic deformation before broken, thereby increasing the value of flexibility.

At low temperatures (450 ° C), although there is an increase in flexibility over time of detention, its flexibility is still relatively low (around 26-32 mm). This shows that at this temperature, carbon diffusion and carbide formation have not been ongoing optimally; Martensit still dominates the structure, so the material remains relatively brittle. When the temperature is increased to 550 ° C, there is a significant increase in flexibility (around 42-43 mm) for all detention times, indicating the start of a more substantial microstructure transformation towards a more resilient condition. The peak of flexibility is seen at 650 ° C, where the material shows the maximum deformation ability, especially at the time of detention 25 minutes. At this high temperature, martensit transformation into a more stable and tenacious structure has reached an excellent level, producing material with an optimal combination of strength and flexibility for applications that require resistance to plastic deformation. However, it should be noted that although flexibility increases, the nature of violence may be reduced, a trade-off that often occurs in heat treatment.

This trend aligns with established metallurgical principles where the heat treatment relieves internal stresses and facilitates the extensive decomposition of the hard, brittle as-quenched martensite into a more ductile and tougher microstructure composed of ferrite and spheroidized carbides [20]. At 650°C, this transformation is more complete, leading to a significant restoration of ductility, which manifests as higher flexibility. These findings are consistent with research on similar Cr-alloyed spring steels. For instance, Toktaş and Biçer [21] reported significant improvements in toughness and ductility for 51CrV4 and 55Cr3 steels when tempered above 600°C, and a similar conclusion was reached by Fadare et al. [22] in their study on 51CrV4 steel.

CONCLUSION

1. The experimental findings definitively show that both tempering temperature and holding time significantly impact the flexibility of SUP9 steel leaf springs. A clear trend emerged where increased temperature and longer holding times led to enhanced flexibility. Optimal flexibility, reaching around 47-48 mm, was achieved at 650°C for 25 minutes. This improvement stems from microstructural changes, as higher temperatures and prolonged heating promote greater carbon diffusion and the formation of ductile carbide precipitates, transforming brittle martensite into a more flexible structure.
2. Lower tempering temperatures yielded limited flexibility gains, while 650°C allowed for near-maximal ductility. These results are consistent with metallurgical principles, confirming that precise control of tempering parameters is crucial for optimizing the mechanical properties, specifically flexibility, of SUP9 steel.d.

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