Sakarya University Journal of Science

ISSN : 2147-835X
Publisher : Sakarya University

Vol. 28, No. 6, 1315-1325, 2024
DOI: https://doi.org/10.16984/saufenbilder.1527971

Research Article

Fracture Surface Morphology of the Impact-Loaded Tempered Spring Steels

Gülcan Toktaş[1*], Adem Biçer[2]

[1] Balıkesir University, Faculty of Engineering, Department of Mechanical Engineering, Balıkesir, Türkiye, gzeytin@balikesir.edu.tr
[2] Dosemenler Factory, Altıeylul, Balıkesir, Türkiye, adem.bicer93@gmail.com
[*]Corresponding Author

ARTICLE INFO

Keywords:
Impact energy
Quasi-cleavage fracture
Tempering temperature
Testing temperature

Article History:
Received: 04.08.2024
Accepted: 20.12.2024
Online Available: 28.12.2024

ABSTRACT

The objective of this study is to evaluate the surface morphology of 51CrV4 and 55Cr3 spring steels after undergoing tempering and testing at various temperatures, with a focus on dynamic fracture behavior. For this purpose, 51CrV4 and 55Cr3 spring steel samples were normalized at 870°C for 30 minutes for the same initial microstructure. Then, samples were austenitized at 870°C for 30 minutes and rapidly quenched in oil following tempering at 300°C-525°C range for 2 hours. Tensile tests at room temperature were performed to identify tensile properties, especially percent elongation values. Charpy V notched impact tests were carried out at –40, 0, room temperature, and +80°C testing temperatures to examine the fracture surface morphology of steels according to heat treatment procedures and testing (environmental) temperature. The fracture surfaces were examined by micro and macro analysis, respectively achieved by a digital camera and a scanning electron microscope (SEM). Mix mode (ductile and brittle) fracture (quasi-cleavage type) was detected for all quenched and tempered steels. Increasing tempering and testing temperatures resulted in more ductile fractures with many dimple formations and fewer secondary cracks.

1. Introduction

Failure analysis ensures steel parts' safety, reliability, and cost-effectiveness. It identifies and mitigates risks, supports better design and manufacturing practices, and contributes to technological advancement. Micro and macro fracture surface investigations are critical aspects of failure analysis in materials, including steel parts. These investigations provide valuable insights into the nature of the failure and guide improvements in design, manufacturing, and material selection. Macro examination offers a broad view of the fracture surface and helps identify general failure modes, such as brittle fracture, ductile fracture, fatigue failure, or corrosion. Micro examination using techniques like scanning electron microscopy (SEM) reveals detailed features at the microscopic level, such as grain boundaries, inclusion particles, and precipitates. These features can indicate the presence of material defects or weaknesses.

Automotive parts that fail can lead to accidents, which can cause injury or even loss of life. Failure analysis of automotive parts is integral to ensuring safety, performance, reliability, and cost-effectiveness. It supports the design and manufacturing of high-quality components, minimizes the risk of recalls and warranty claims, and fosters innovation and improvement. By systematically analyzing failures, the automotive industry can enhance vehicle safety, performance, and customer satisfaction while maintaining compliance with regulations and industry standards.

In the automotive industry, leaf springs are critical components, which are widely used in vehicle’s suspension systems and are subjected

Cite as: G. Toktaş, A. Biçer (2024). Fracture Surface Morphology of the Impact-Loaded Tempered Spring Steels, *Sakarya University Journal of Science*, 28(6), 1315-1325. https://doi.org/10.16984/saufenbilder.1527971

to fluctuating loads [1]. Leaf springs are designed to absorb shocks and support the vehicle's weight, making their reliable performance crucial for vehicle safety and comfort [2]. The primary function of a vehicle's suspension system is to safeguard the vehicle's structure and its occupants from the impacts and fluctuations caused by the road surface [3]. By examining both macro and micro aspects, assessing operational and design factors, and considering manufacturing processes, one can identify the root causes and implement improvements to enhance the reliability and safety of leaf springs. This process not only helps in resolving the immediate failure but also contributes to long-term improvements in design, materials, and manufacturing practices.

Leaf springs are commonly made from high-carbon steel or alloy steel due to their strength, durability, and ability to be heat-treated for enhanced performance. In specialized applications, stainless steel or composite materials may provide additional benefits such as corrosion resistance or weight reduction. The material choice depends on the specific requirements, including load-bearing capacity, environmental conditions, and cost considerations.

51CrV4 and 55Cr3 are specific grades of alloy steels used in various applications, including automotive components like leaf springs. Both steels are characterized by their unique compositions and properties. The mechanical properties of leaf spring steel are designed to ensure that the springs can withstand the dynamic loads and stresses experienced in vehicle suspension systems. Key properties like tensile strength, yield strength, hardness, fatigue strength, and toughness are carefully balanced to have reliable performance. The specific values can vary depending on the steel grade and the heat treatment applied. Especially, quenching and tempering heat treatment is applied in the production of leaf springs.

Much research has been performed on leaf spring steels in the manner of heat treatment [4-6], microstructure [7, 8], and dynamic/static mechanical [9-12] and corrosion properties [13], so far. Also, some studies [14-16] were conducted on impact behavior, especially ductile-brittle transition temperature (DBTT). DBTT is crucial for leaf springs because it determines the temperature range over which the material remains ductile and capable of absorbing stresses without failing. A low DBTT ensures that leaf springs maintain their toughness and reliability in colder temperatures, preventing sudden and dangerous failures. Proper material selection and heat treatment are essential to achieving a suitable DBTT for the leaf springs' safe and effective performance in various operating conditions. Service temperature affects not only the mechanical properties but also the fracture modes of spring steel. Both directly influence the quality of leaf springs. However, limited studies have investigated the dynamic fracture behavior of spring steels under low and high testing and tempering temperatures.

The Charpy V-notched impact energy, which quantifies the absorbed energy during high strain rate fracture of a material, serves as a measure of the material's resistance to brittle fracture and is often utilized as an indicator of fracture toughness. Nonetheless, it fails to adequately represent the crack propagation process and lacks fracture mechanics-based toughness. [17]. Asghari et al. [18] introduced a novel correlation that uses Charpy V notched energy and yield strength data to forecast K_{JC} (crack initiation resistance, defined by the J-integral) in gas pipeline steel evaluations. Choupani et al. [17] investigated the DBTT of seam weld, girth weld, and base metal of API X65 steel within the temperature range of −80°C to 20°C. The reported DBTT values were −52, −15, and −13°C for seam weld, girth weld, and base metal, respectively, indicating significant insights into the severity of the relevant environment.

At temperatures below the DBTT, a material may exhibit brittle fracture despite possessing high toughness, absorbing minimal energy during Charpy V-notch testing. Not all metals exhibit distinct DBTT values. In this situation, it is crucial to analyze the fracture modes of metals at different low temperatures to anticipate the fracture type: brittle, ductile, or a combination of both. By inspecting a fractured part surface and determining the fracture type, for instance, in a broken leaf spring in service, a failure analysis expert can predict the reason for the failure and take necessary precautions correctly and easily.

The objective of this study was to investigate the fracture modes observed on the fracture surfaces of 51CrV4 and 55Cr3 spring steel when subjected to dynamic (impact) loading. To achieve this objective, the fracture surfaces resulting from the Charpy V impact tests conducted at temperatures of –40°C and +80°C were analyzed from both the microstructure and macrostructure viewpoints.

2. General Methods

The chemical compositions of the hot-rolled 51CrV4 and 55Cr3 spring steels are given in Table 1. The tensile and Charpy V-notched samples were prepared per the concerned standards, parallel and perpendicular to the hot rolling direction, respectively. Firstly, all samples were normalized by preheating at 600°C for 10 minutes, following austenitization at 870°C for 30 minutes and air cooling to eliminate the detrimental microstructural effects produced via the hot rolling process. A group of samples were left normalized as the reference condition. The quenching was applied by preheating at 600°C for 10 minutes, following austenitization at 870°C for 30 minutes and room temperature oil (ISORAPID 277 HM) cooling. Then, the samples were tempered at 300°C, 375°C, 450°C, and 525°C for 2 hours and followed by air cooling.

Table 1. Chemical compositions of 51CrV4 and 55Cr3 steels (wt.%, Fe balanced))

51CrV4		**55Cr3**	
C:0.49	Cr:0.99	C:0.54	Cr:0.82
Si:0.26	Mo:0.02	Si:0.23	Mo:0.03
Mn:0.87	V:0.124	Mn:0.83	V:---
P:0.008	Ni:0.08:	P:0.004	Ni:0.09
S:0.012	Cu:0.10	S:0.006	Cu:0.08

The microstructural observation was made to identify the normalized structure via an optical microscope (OLYMPUS BX51M) by preparing the samples using standard metallographic techniques and etching with 3% Nital solution. Tensile tests were performed by a SCHIMADZU testing device with a 1000 kN capacity, at 5 mm/min crosshead speed under room temperature (25°C) per TS EN ISO 6892-1 standard. The gauge width, thickness, and length of tensile test specimens were 25, 10, and 115 mm, respectively. Three tensile samples were used for each heat-treating condition to establish the repeatability of the test results. To determine the characteristics of fractures at both low and high temperatures, impact tests were conducted using a Mohr and Federhaff pendulum device with a capacity of 300 J. The tests were performed within a temperature range of –40°C to +80°C, following the guidelines outlined in the TS EN ISO 148-1 standard.

Standard Charpy V notched specimens of 10×10×55 mm, having 2 mm deep 45° V notches, were utilized, and testing was conducted three times for each condition, with results averaged. A high testing temperature (+80°C) was achieved by holding the samples in a BINDER drying oven for 30 minutes. Low testing temperatures (0°C and –40°C) were obtained by holding samples in a PMT TAMSON TLC40 cooling circulator full of ethyl alcohol for 30 minutes. The sample's temperature measurements were made with the Testo 925 immersion thermometer.

The macro examination of the fracture surfaces of impact samples was conducted via a digital camera. The microfracture investigation was performed using a Hitachi TM 1000 scanning electron microscope (SEM).

3. Results and Discussion

The normalized (initial) microstructures of steels are given in Figure 1. The microstructures of both steels consist of mostly pearlite (lamellar structure of ferrite and cementite) phase with minimal ferrite phase areas.

Table 2 provides the tensile characteristics including 0.2 yield strength, ultimate tensile strength (UTS), and percent elongation for both steels at different tempering temperatures. The quenching and tempering process provided two between three times higher 0.2 yield strength than the reference, normalized condition. The yield strength increase of 51CrV4 is between

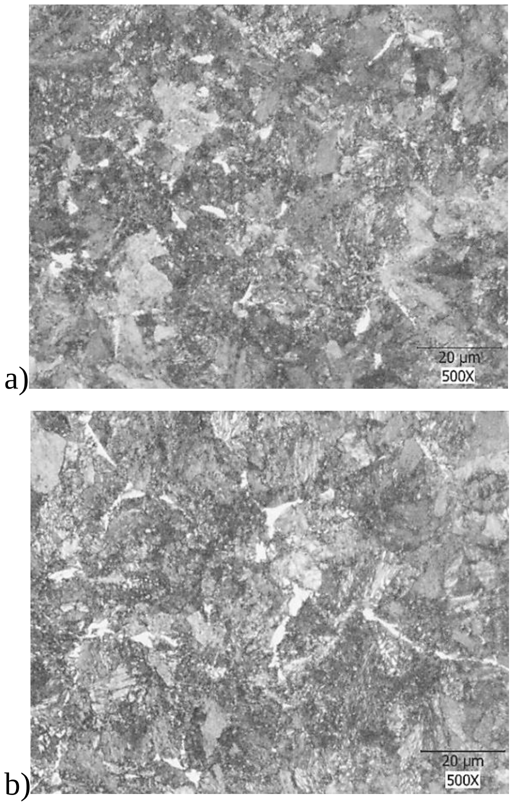

Figure 1. Microstructures of normalized a)51CrV4 and b)55Cr3 steels

2.32 and 3.22 times, while 55Cr3 steel ranges from 1.8 to 3 times. Increases in UTS by the quenching and tempering process according to the normalized condition have been achieved slightly less. 51CrV4 has a maximum of 2.15 times with a minimum of 1.5 while 55Cr3 has an increase of 1.28 and 2.08 times. Parallel with the literature [19], rising tempering temperatures led to a decrease in 0.2 yields and UTS strengths, an increase in percent elongation, and a signal of ductility. Tempering causes the decomposition of a portion of the martensite into ferrite and carbide particles. Increasing the tempering temperatures results in a greater transformation of martensite, which in turn decreases the tensile strength of the steel. With a rise in tempering temperature, the carbides undergo coarsening and enlargement, resulting in a decrease in both dislocation density and internal stresses inside the steel. As a result, the tensile strength decreases while the ductility increases due to the presence of coarsened carbide particles, and low dislocation density in the microstructure.

Table 2. Tensile properties of steels

	51CrV4			**55Cr3**		
Tempering condition	0.2 yield strength (MPa)	UTS (MPa)	Elongation (%)	0.2 yield strength (MPa)	UTS (MPa)	Elongation (%)
Normalized	510	832.97	19.61	580	929.78	17.75
300°C	---	1789.50	2.12	1790	1937.06	6.12
375°C	1643.33	1713.82	7.19	1616.6	1728.19	6.99
450°C	1420	1486.88	10.41	1351.6	1449.37	9.16
525°C	1185	1253.66	12.20	1096.6	1191.36	12.83

Figures 2 and 3 illustrate the macro fractured surfaces of tempered and normalized 51CrV4 and 55Cr3 impact samples, broken between −40°C and +80°C testing temperatures. At the same time, the impact energies are also given at the bottom of each macrostructure. When examined in terms of impact energies, tempering temperature gave rise to impact energies due to providing more ductility as proven by Table 2 for both steels. While the minimum impact energy was recorded as 3.27 J at −40°C testing temperature for 300°C tempered condition, the maximum value was 21.58 J for the normalized state of 51CrV4 steel. The impact energies of both steels at low-tempering temperatures (300°C and 375°C) were found to be similar, ranging from 3 J to 12 J. At a high tempering temperature of 525°C, the impact energies of 55Cr3 steel were much higher, about twice as much, compared to those of 51CrV4 steel.

On the other hand, increasing the testing temperature gives rise to impact energies. The elevated testing temperature may promote the activation of additional slip systems and enhance the mobility of dislocations, hence facilitating significant deformation and enabling greater absorption of energy. Zhang et al. [20] published findings consistent with the current investigation, indicating that elevated tempering temperatures reduced the strength and increased the impact energy of low-carbon low-alloyed steel due to the merging and coarsening of martensitic laths, as well as the recovery and reduction of dislocation density.

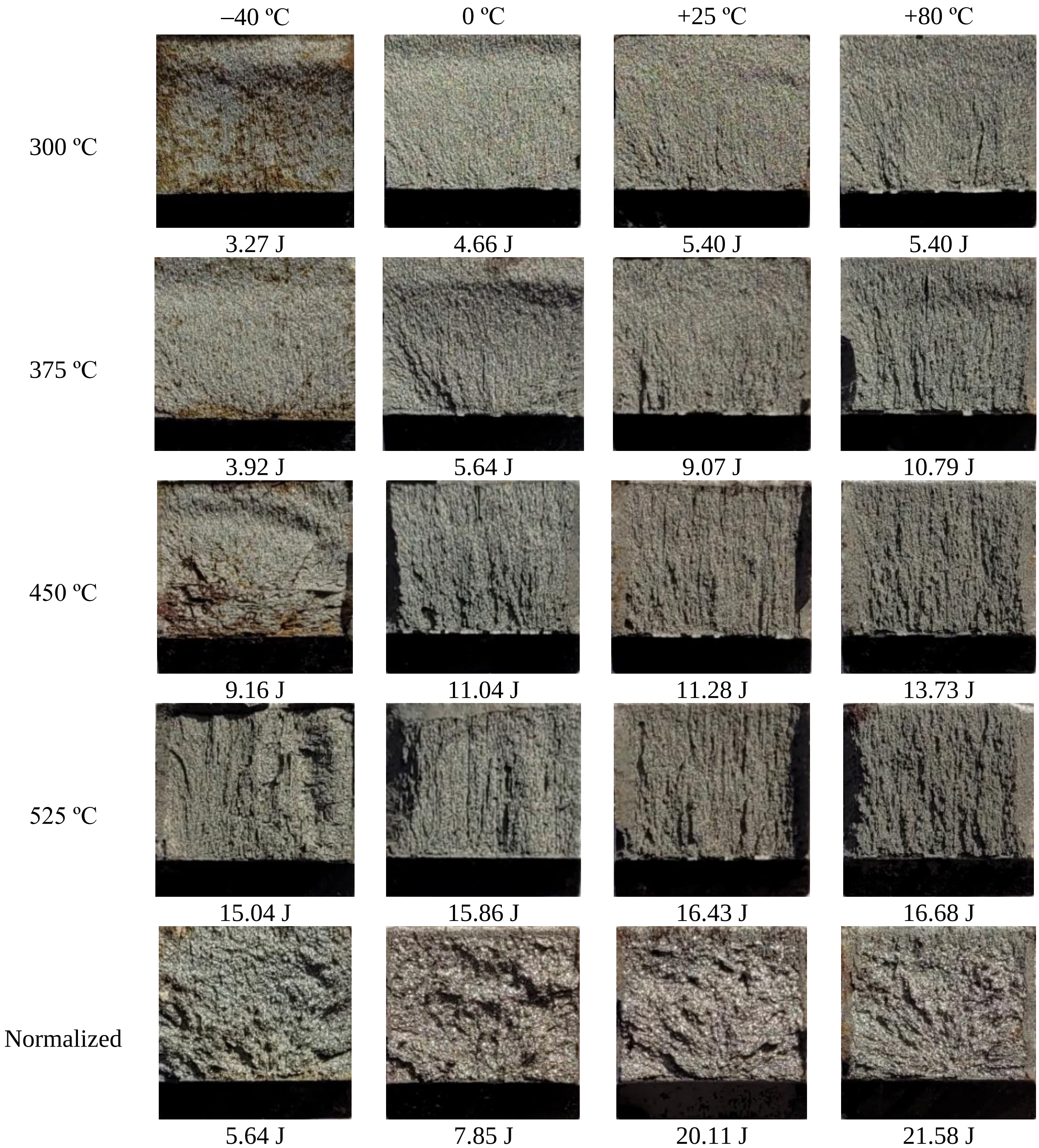

Figure 2. Macrostructures of fractured surfaces and impact energies of 51CrV4 steel tempered between 300°C–525°C and impact tested between –40°C and +80°C

By evaluating the macro structures of fracture surfaces in Figures 2 and 3, 300°C tempering showed the most brittle fracture with a crystalline (granular) view. Above 300°C tempering temperatures, radial fracture marks perpendicular to the notch root base are seen. These radial marks indicate the crack growth direction. As the tempering and testing temperatures increase, it is seen that these marks get coarser and deeper. This result is consistent with the literature that reports tempering to lower strengths results in coarser radial marks [21]. Increasing the tempering temperature from 300°C to 525°C and testing temperature –40°C to +80°C, lateral shear lip formation is observed, especially in 525°C tempered and +80°C tested 55Cr3 steel. The lateral shear lip is an indication of plastic deformation occurrence before rupture. This shear lip formation is consistent with the high impact energy (32.38 J) value of the tempered-tested condition of this steel. In normalized conditions of both steels, the macrostructures differed from those of the tempered conditions. Instead of radial marks perpendicular to the base of the notch root, secondary cracks and crack growth in different directions were observed in normalized steels. As in tempered conditions, increasing testing temperature formed lateral shear zones in normalized macrostructures. However, despite the high impact energies (21.58 J for 51CrV4 and 40.55 J for 55Cr3) in normalized samples compared to 525°C tempered and +80 tested ones, the plastic deformation (shear zone) areas are smaller than the tempered ones.

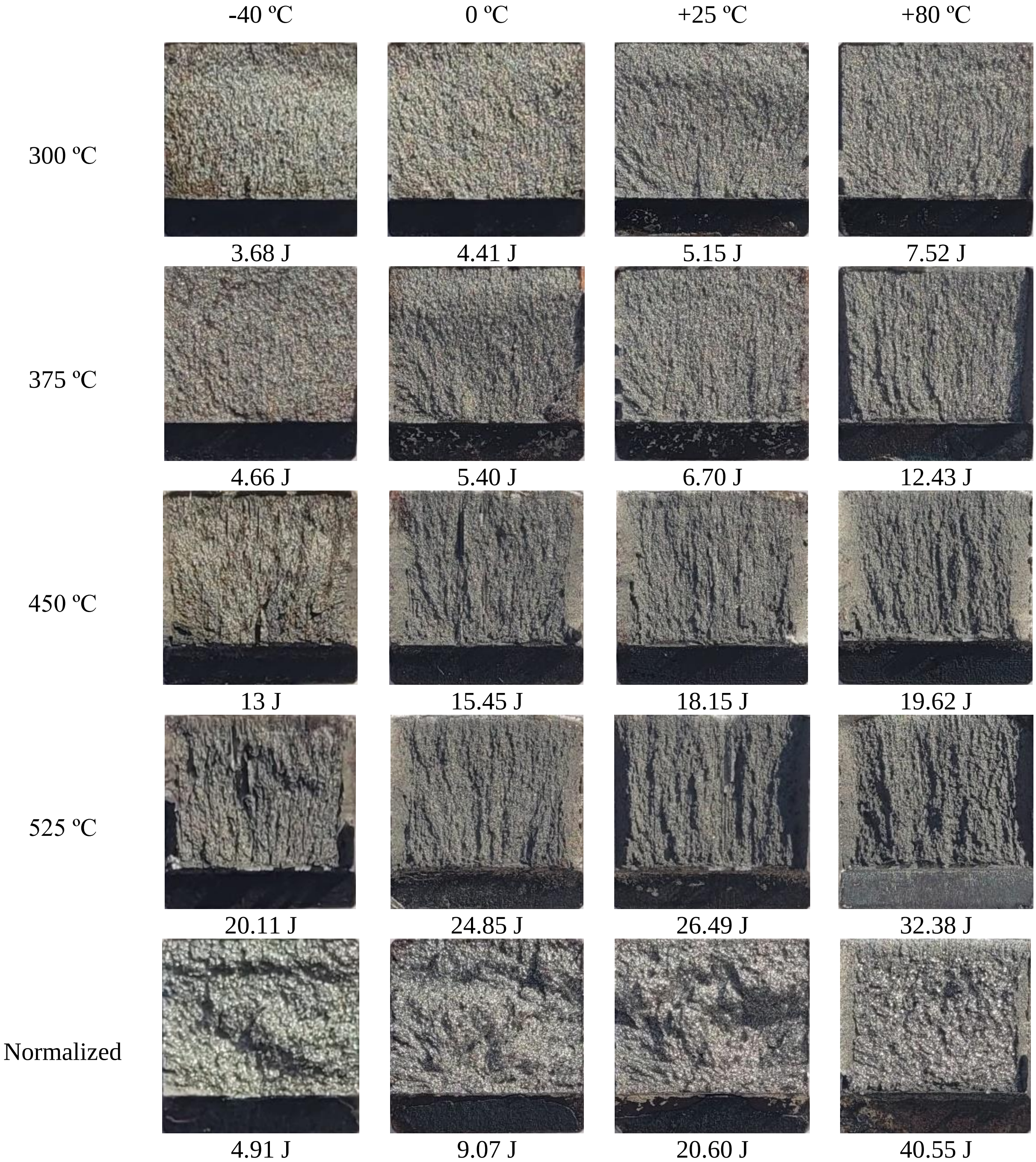

Figure 3. Macrostructures of fractured surfaces and impact energies of 55Cr3 steel tempered between 300°C-525°C and impact tested between -40°C and +80°C

The fracture surfaces of the impact-loaded 51CrV4 and 55Cr3 samples were examined via SEM method. The fracture surfaces of the normalized steels at room temperature are given in Figure 4. The predominant fracture type observed is mostly brittle, characterized by cleavage, along with numerous secondary cracks. The secondary cracks are more evident in 51CrV4 compared to 55Cr3, as it has a lower impact energy of 21.58J, while 55Cr3 has an impact energy of 40.55J. Although normalized steels exhibit large impact energies compared to tempered ones, their brittle fracture behavior has mostly been acknowledged (Figures 5 and 6).

This could be attributed to the microstructure of these steels. The microstructure of normalized steels is characterized by the presence of mostly pearlite and little ferrite phases, as well as numerous grain boundaries. Grain boundaries, as commonly known, are heterogeneous regions that facilitate the formation and propagation of cracks more easily. In addition, the lamellar pearlitic structure can also be responsible for brittle fracture with cleavage planes in the interfaces of ferrite and cementite [22].

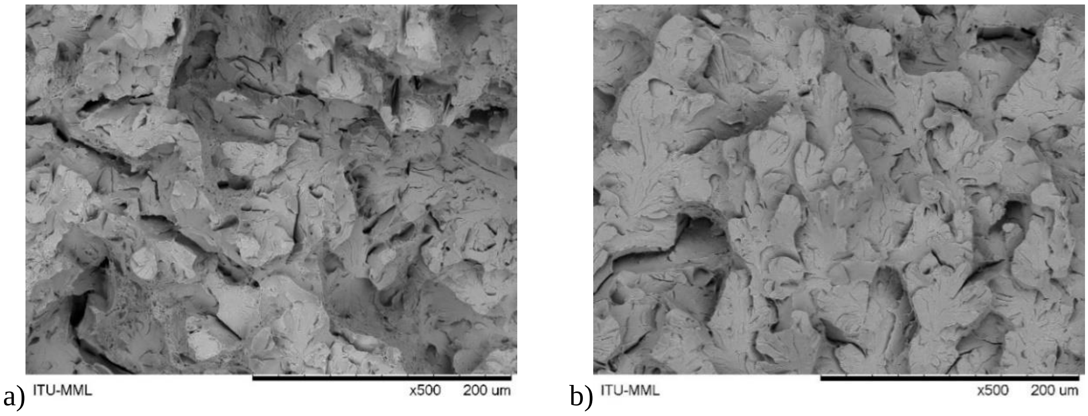

Figure 4. Fracture surfaces of the normalized a)51CrV4 and b)55Cr3 steels at room temperature

Figure 5 illustrates the fracture surfaces of 51CrV4 samples tempered at low (300°C) and high (525°C) tempering temperatures and at low (–40°C) and high (+80°C) testing temperatures. Typical quasi-cleavage fracture mode (ductile and brittle) is observed in Figure 5. This type of fracture is most prevalent in tempered steel, as evidenced by a prior investigation [22]. Additionally, earlier research revealed a transcrystalline brittle impact fracture characterized by cleavage planes, quasi-cleavage facets, and a limited presence of shallow dimples in a quenched and tempered commercial spring steel (tempered at 300°C for 90 minutes) [23].

The microstructure exhibits higher granularity and roughness under low-temperature tempering and testing conditions (300°C and –40°C, as shown in Figure 5a). Visible voids or cavities are present, suggesting that the material may be brittle or prone to cracking at low temperatures. In Figure 5b, the micrograph exhibits a less rough appearance in contrast to the testing temperature of –40°C. The material appears denser, with a reduced number of visible voids, indicating enhanced plasticity at this higher temperature. Under the conditions of tempering at 525°C and testing at -40°C (Figure 5c), the presence of larger voids, a reduced number of secondary cracks, and potential microstructural coarsening have been observed. The observed outcome can be attributed to the elevated tempering temperature of 525°C, which facilitates the development of a coarser microstructure and the formation of larger carbides due to increased diffusion.

The presence of large voids shown in Figure 5c is likely attributed to the presence of large carbides inside the tempered microstructure, resulting in the formation of prominent tracks. Figure 5d demonstrates additional alterations in the microstructure at a tempering temperature of 525°C and testing temperature of +80°C, characterized by an increased occurrence of dimple formation, indicating a mostly ductile fracture pattern. The structure exhibits greater deformation with elongated regions. Upon entire inspection, it was seen that in Figures 5a to 5d, the rise of tempering and testing temperatures resulted in a deterioration of the number of secondary cracks and the occurrence of cleavage-type brittle fracture.

Figure 6 depicts the SEM micrographs of 55Cr3 samples impact-loaded at low(–40°C) and high (+80°C) testing temperatures for 300°C and 525°C tempered conditions. Figure 6a displays an intergranular fracture characterized by significant voids and numerous secondary cracks of substantial depth and width, particularly

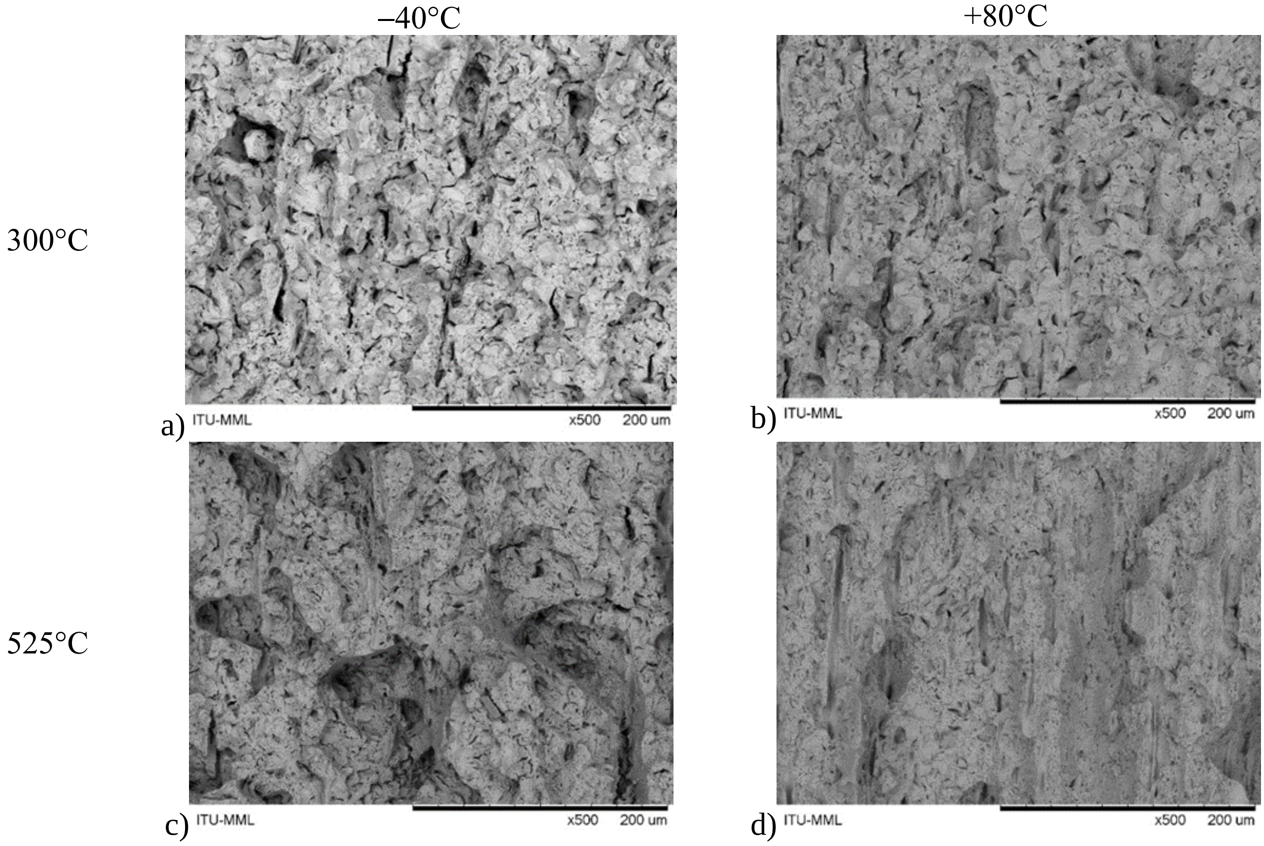

Figure 5. Fracture surfaces of 51CrV4 steel tempered at low and high tempering/testing temperatures, a) 300°C/–40°C, b) 300°C/+80°C, c) 525°C/–40°C and d) 525°C/+80°C

evident at low tempering and testing temperatures. This result aligns with the steel's lowest impact energy (3.68 J) under the specified conditions. Figure 6b exhibits a similar appearance, however, with a slightly more pronounced dimple formation, which suggests that the testing temperature (+80°C) provides more energy absorption. Figures 6c and 6d exhibit a greater presence of dimples and a reduced occurrence of cracks, in comparison to Figures 6a and 6b. The 55Cr3 steel's percent elongation value of 12.83% (Table 2) is the greatest among its tempered conditions, indicating superior ductility.

Additionally, the impact energies for 300°C tempered 55Cr3 steel are limited to a range of 3.68 J and 7.52 J, but for the other case (525°C tempering), they fall between 20.11 J and 32.38 J. Figure 6d demonstrates that increasing the testing temperature to +80°C enhances the occurrence of more ductile-type fracture, resulting in a greater number of dimples formed. This outcome is anticipated because elevated testing temperatures can stimulate more slip systems, facilitating plastic deformation and promoting ductile fracture. In conjunction with Figure 5, it was observed that elevating the tempering and testing temperatures led to a decrease in the occurrence of secondary cracks and an increase in the presence of dimples, indicative of ductile fracture. The fracture behavior is in line with the percentage of elongation and impact energy values for both types of steel.

After conducting a comprehensive analysis of fracture morphologies, impact energies, and static strengths, it was determined that tempering at 525°C is the optimal condition for meeting the leaf spring production requirements of both steels. Normalized steels generally exhibit high impact energies at room temperature, except for 55Cr3 steel tempered at 525°C. However, their 0.2 yield and ultimate tensile strengths are significantly lower, almost half of those observed in tempered steels. Furthermore, the presence of a lamellar pearlitic structure in normalized steel microstructure led to the stress raiser effect, which in turn caused brittle fracture behavior.

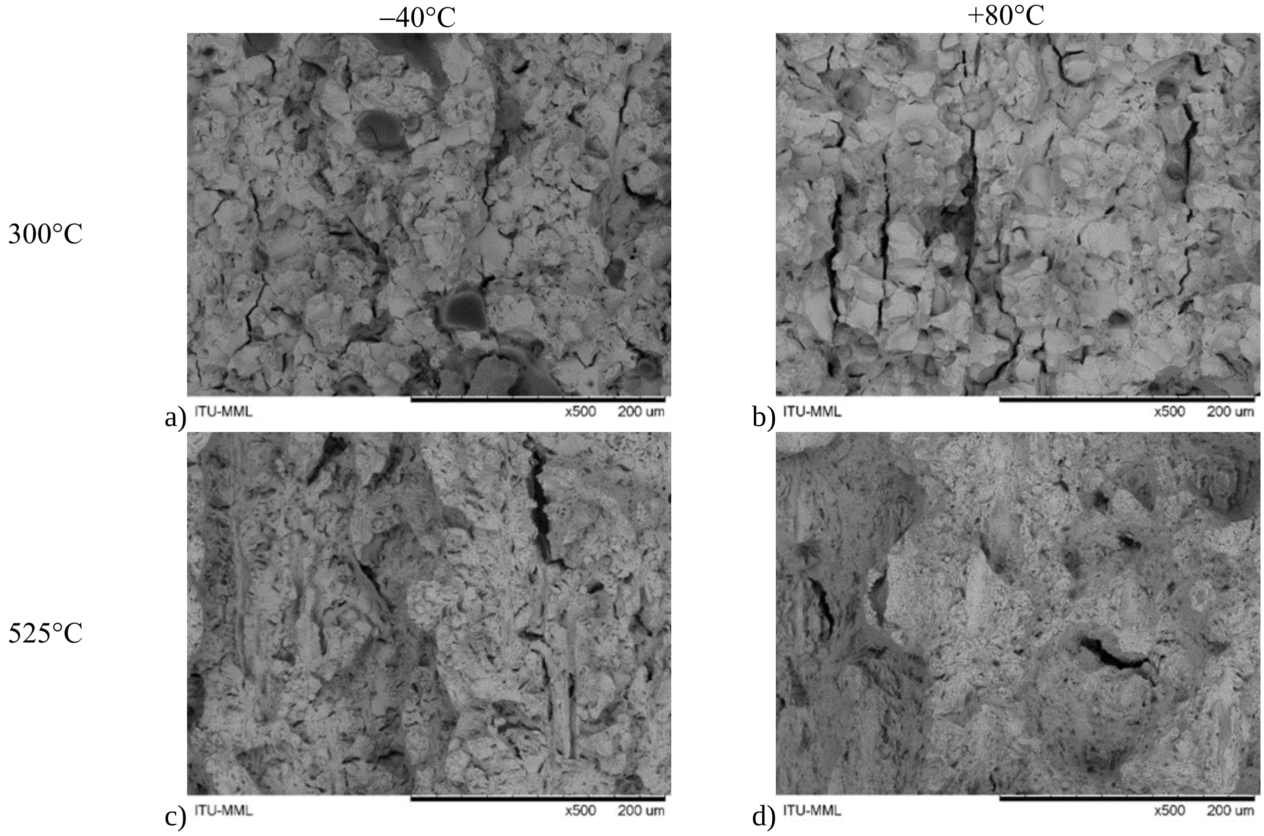

Figure 6. Fracture surfaces of 55Cr3 steel tempered at low and high tempering/testing temperatures, a) 300°C/–40°C, b) 300°C/+80°C, c) 525°C/–40°C and d) 525°C/+80°C

4. Conclusion

Upon examining the fractured surfaces of quenched and tempered 51CrV4 and 55Cr3 steels under dynamic (impact) loading at various testing temperatures, it is evident that either the tempering or the testing temperatures influence the morphology of the fracture mode. Typically, all the broken surfaces exhibit ductile mixed brittle characteristics, matching quasi-cleavage type, with secondary cracks present. By enhancing the tempering and testing temperatures, the occurrence and the amount of ductile fracture were augmented through the formation of dimples, but the number of secondary cracks was reduced. Fracture surfaces of steels were relevant to their percent elongation and impact energy values. In other words, a greater percentage of elongation and impact values correspond to a larger occurrence of ductile fracture with many dimple formations. On the other hand, grain boundaries in normalized steels adversely affected ductile fracture by exhibiting a greater tendency for cleavage-type fractures, while having high impact energies. Fracture modes are defined not only by ductility but also by the form of microstructures. After assessing fracture type, impact energy, and static strengths, it was determined that the ideal tempering temperature for both steels was 525°C.

Article Information Form

Acknowledgments
The authors would like to thank Prof. Dr. Murat Baydoğan for his contributions.

Funding
This study was supported by Balikesir University Scientific Research Projects Unit with Grant Number 2022/078.

Authors' Contribution
The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

Copyright Statement

References

[1] N. Kumar, Y. Chaubey, C. Kumar, S. Chauhan, "Failure Analysis of Automotive Suspension System (Leaf & Helical Spring): A Review," in Vth International Symposium on "Fusion of Science & Technology", New Delhi, India, 2016, pp. 66-74.

[2] S. P. Yakovleva, I. I. Buslaeva, S. N. Makharova, A. I. Levin, "Fatigue Damage, Impact Toughness and Micromechanisms of Fracture of Spring Steel After Operation at Low Climatic Temperatures," Procedia Structural Integrity, vol. 30, pp. 193–200, 2020.

[3] N. Singh, "General Review Of Mechanical Springs Used in Automobiles Suspension System," International Journal of Advanced Engineering Research and Studies, pp.115-122, 2013.

[4] A. Tump, R. Brandt, "Graded High-Strength Spring-Steels by a Special Inductive Heat Treatment," in IOP Conference Series: Materials Science and Engineering 118, 2016, 012021.

[5] O. Meigui, Y. Chunlin, Z. Jie, X. Qifan, Q. Huina, "Influence of Cr Content and Q-P-T Process on the Microstructure and Properties of Cold-Coiled Spring Steel," Journal of Alloys and Compounds, vol. 697, pp.43-54, 2017.

[6] S. H. Kim, K.-H. Kim, C.-M. Bae, J.S. Lee, D.-W. Suh, "Microstructure and Mechanical Properties of Austempered Medium-Carbon Spring Steel," Metals and Materials International, vol.24, pp.693-701, 2018.

[7] C. Zhang, L. Zhou, Y. Liu, "Heredity in the Microstructure and Mechanical Properties of Hot-rolled Spring Steel Wire 60Si2MnA during Heat Treatment Process," Journal of Materials Science and Technology, vol. 29, no. 1, pp. 82-88, 2013.

[8] L. Zhang, D. Gong, Y. Li, X. Wang, X. Ren, E. Wang, "Effect of Quenching Conditions on the Microstructure and Mechanical Properties of 51CrV4 Spring Steel," Metals, vol.8, 2018, 1056.

[9] E. Giannakis, M. Malikoutsakis, G Savaidis, "Fatigue Design of Leaf Springs for New Generation Trucks," IOP Conference Series: Materials Science and Engineering, vol. 161, 2016, 012065.

[10] R. C. Özden, M. Anik, "Enhancement of the Mechanical Properties of EN52CrMoV4 Spring Steel by Deep Cryogenic Treatment," Materialwiss. Werkstofftech, vol.51, pp. 422–431, 2020.

[11] Y. Nishimura, K. Yanase, Y. Ikeda, Y. Tanaka, N. Miyamoto, S. Miyakawa, M. Endo, "Fatigue Strength of Spring Steel with Small Scratches," Fatigue and Fracture of Engineering Materials Structure, vol. 41, pp. 1514–1528, 2018.

[12] S. R. Kumar, M. Sreearravind, S. Sainathan, A. Venkat, S. Rahulram, S. S. Kumar, S. S.l Kumaran, "Low Cycle Fatigue Behavior of Heat Treated EN-47 Spring Steel," Materials Today: Proceedings, vol. 22, pp.2191-2198, 2020.

[13] H. Wei, Y. Chen, W. Yu, L. Su, X. Wang, D. Tang, "Study on Corrosion Resistance

of High-Strength Medium-Carbon Spring Steel and its Hydrogen-Induced Delayed Fracture," Construction and Building Materials, vol. 239, 2020, 117815.

[14] S. Rzepa, T. Bucki, P. Konopík, J. Džugan, M. Rund, R. Procházka, "Influence of Specimen Dimensions on Ductile-to-Brittle Transition Temperature in Charpy Impact Test," IOP Conference. Series: Materials Science and Engineering, vol. 179, 2017, 012063.

[15] M. Abro, M. M. Bloch, M. H. Jokhio, "Effect of Temperature on the Toughness of Locally Manufactured Low Alloy Steel SUP9 Used for Manufacturing Leaf Springs," Mehran University Research Journal of Engineering and Technology, vol. 30, no. 4, pp. 635-644, 2011.

[16] S. Manjula, K.V. Arun, "Influence of Edge and Corner Cracks on the Impact and Bending Behavior of Spring Steel," Materials Today: Proceedings, vol. 42, no. 2, pp.1251-1257, 2021.

[17] N. Choupani, V. Asghari, H. Kurtaran, "Fracture Characterization of Base Metal, Seam Weld, and Girth Weld of Welded Line Pipe Steel at Room and Low Temperatures", Journal of Materials Engineering and Performance, vol. 32, pp.1046-1053, 2021.

[18] V. Asghari, N. Choupani, M. Hanifi, "CVN–K_{JC} Correlation Model for API X65 Gas Pipeline", Engineering Failure Analysis, vol. 79, pp.51-63, 2017.

[19] K. Chen, Z. Jiang, F. Liu, J. Yu, Y. Li, W. Gong, C. Chen, "Effect of Quenching and Tempering Temperature on Microstructure and Tensile Properties of Microalloyed Ultra-High Strength Suspension Spring Steel," Materials Science & Engineering A, vol. 766, 2019, 138272.

[20] Y. Zhang, J. Yang, D. Xiao, D. Luo, C. Tuo, H. Wu, "Effect of Quenching and Tempering on Mechanical Properties and Impact Fracture Behavior of Low-Carbon Low-Alloy Steel", Metals 2022, 12, 1087.

[21] ASM Handbook, Fractography, ASM International, vol. 12, 9th Edition, 1987.

[22] W. Peng, J. Zhang, X. Yang, Z. Zhu, S. Liu, "Failure Analysis on the Collapse of Leaf Spring Steels During Cold-Punching," Engineering Failure Analysis, vol. 17, pp. 971-978, 2010

[23] V. I. Zurnadzhy, V. G. Efremenko, K. M. Wu, A. Y. Azarkhov, Y. G. Chabak, V. L. Greshta, O. B. Isayev, M. V. Pomazkov, "Effects of Stress Relief Tempering on Microstructure and Tensile/Impact Behavior of Quenched and Partitioned Commercial Spring Steel", Materials Science and Engineering A, vol.745, pp.307-318, 2019.