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Tempering Heat Treatment Impact on Medium Carbon Steel: Microstructure and Mechanical Behaviour

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ABSTRACT

The paper presents the study to explored the influence of tempering temperature on medium carbon steel based on microstructural evolution and its impact on tensile strength, hardness, ductility, and toughness. ***.*** *Medium carbon steel undergoes significant changes in microstructure and mechanical behavior when subjected to heat treatment processes such as tempering heat treatment. Tempering after quenching, is a critical step in refining medium carbon steel's martensitic microstructure to improve ductility and toughness while relieving brittleness. The tempering temperature plays a crucial role in determining the final microstructure and mechanical properties of the steel. At lower tempering temperatures (100°C - 150°C), the medium carbon steel samples retain much of martensitic structure, preserving high hardness and strength, with minimal improvements in ductility. As the tempering temperature increases (300°C - 400°C), the martensite gradually decomposes, forming cementite and ferrite which improves ductility and toughness but reduces hardness and strength. The initial increase in the impact toughness increased the tempering temperature when the martensite starts to relieve internal stresses and temper, making the material less brittle. Beyond 300°C, the impact toughness begins to decline gradually, due to the onset of* ***over-tempering,*** *where carbide particles coarsen, and spheroidization occurs, resulting in a softer, more ductile but less tough material. The decrease in toughness at higher temperatures indicates that the steel becomes too soft to absorb high-energy impacts effectively. The study highlights how the tempering heat treatment process can be tailored to optimize the trade-off in mechanical properties of medium carbon steel for specific engineering applications, demonstrating the critical relevance of tempering temperature in achieving the desired performance in medium carbon steel.*

Keywords: Tempering, Heat Treatment, Martensite, Cementite, Ferrite, Medium carbon steel

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I. Introduction

Steel is one of the most widely used materials in engineering and manufacturing, owing to its versatility and remarkable mechanical properties, including strength, hardness, and wear resistance. [1] These properties can be further improved through heat treatment, a process which involves controlled heating and cooling to alter the microstructure of steel [1]. Heat treatment techniques such as quenching, tempering, and annealing are commonly employed to achieve the desired properties for specific applications [2]. The heat treatment and post treatment are essential processes in the engineering of steels, profoundly influencing the mechanical properties and microstructural characteristics of the treated steels [1]. Considering the various heat treatment methods that can be used to optimize the performance of steels, tempering process is critical for refining the mechanical properties of quenched steel by relieving internal stresses and modifying its microstructure [3]. Tempering is carried out after quenching, which leaves the steel material in a hard but brittle martensitic phase. [4] The tempering process allows for controlled adjustment of hardness, strength, and toughness by the decomposition of martensite and the formation of secondary phases. One of the key factors influencing the outcome of tempering process is the temperature at which the process is conducted. [5]. Tempering temperatures range from low (100-300°C) to high (500-700°C), each producing unique influence in the steel's microstructure. lower tempering temperatures, are characterized by fine carbides, which precipitates within the martensite matrix, resulting in high hardness but limited ductility of the material. Increased tempering temperature, brings about the martensite transformation into ferrite and cementite, and the carbide particles coarsen, which leads to a decline in hardness but improves the toughness and ductility [6]. Thus, tempering temperature becomes a critical parameter in controlling the balance of strength and ductility, especially in high-performance applications where steels are subjected to dynamic and static loads [4].

The effects of tempering temperature on the mechanical behaviour of steel are of great industrial importance such as areas of automotive, aerospace, and heavy machinery, where steel components must exhibit a specific and excellent balance between toughness, wear resistance, hardness, and fatigue resistance. Engineering components that are subjected to cyclic stresses require a higher toughness to resist fracture while components exposed to wear and tear need higher hardness. The changes in microstructure are caused by different tempering temperatures, which can be observed as carbide precipitation, matrix softening, and phase transformation, directly affect these mechanical properties. The effectiveness of heat treatment can be influenced by various parameters, among which soaking time and applied load play crucial roles [1]. Understanding the effects of soaking time and applied load on the wear and mechanical behavior of heat-treated steel is of paramount importance in optimizing the performance and reliability of engineering components across diverse industries such as automotive, aerospace, manufacturing, and construction [7]. Notably, optimizing the tempering process is not only important for achieving the desired mechanical properties but also for improving the wear resistance and extending the service life of steel components [8]. Depending on the intended application, steels are tempered at different temperatures to tailor their performance, higher tempering temperatures are preferred for applications requiring high impact toughness while lower tempering temperatures are chosen for situations where hardness and wear resistance are paramount [9].

This study focuses on exploring the effects of tempering temperature on the microstructure and mechanical properties of medium carbon steel by carefully examining the correlation between tempering conditions and resulting mechanical properties which includes hardness, tensile strength, and toughness. The research aims to provide deeper insights into the optimal heat treatment parameters for steels used in various demanding applications and proper understanding of this relationship is crucial for steel manufacturing industries and other industries where the performance of steel under various service conditions is critical for safety, reliability, and durability.

II. Materials and Methods

2.1 Sample selection and preparation.

Carbon steel with Chemical composition of 0.352 % carbon steel was selected as the test material to investigate the influence of tempering heat treatment on its mechanical behaviour. The composition of the test material as received is presented in the table 1.

Table 1 Element composition of the Test material.

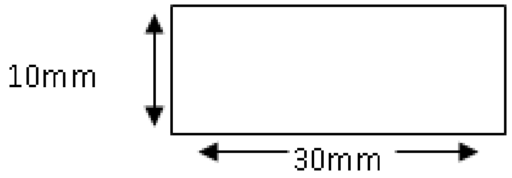
S/n	Element	Weight (%)
1	C	0.352
2	Si	0.148
3	Mn	0.524
4	P	0.044
5	S	0.055
6	Cr	0.224
7	Mo	0.104
8	Ni	0.104
9	Cu	0.250
10	V	0.006
11	Nb	< 0.0002
12	N	0.0013
13	B	0.0028
14	Al	0.0036
15	Sn	0.030
16	Fe	98.241

The test material received in ribbed form, was prepared by machining to standard gauge diameter and length. The specimens were prepared for mechanical tests and microstructural examination. The test specimens were subjected to different mechanical test after preparation and Tempering heat treatment.

2. 2 Metallographic Examination

Metallographic examination is a crucial technique for characterizing the microstructure of metals and alloys, providing valuable insights into their properties and performance. The procedure for metallographic examination specifically for medium carbon steel test specimen is as follows

2.2.1 Sample Preparation:
The sample to be examined is selected and a section of the sample to be examined is cut using a saw.



2.2.2 Grinding and Polishing procedure.

2.2.2.1 Grinding:
The mounted sample is subjected to a series of grinding steps using progressively finer abrasive papers such as SiC papers starting from 120 grit and progressing to 1200 grit). Grinding removes any surface defects introduced during sectioning and creates a smooth flat surface.
2.2.2.2 Polishing:
Following grinding, a final polishing step is performed using a polishing wheel and a polishing media (alumina suspension). This step removes residual scratches from grinding and creates a mirror-like finish for optimal observation under the microscope.

Fig 1: Grinder /Polisher Machine,Model 900,Maker(South bay Technology)

2.2.2.3 Etching:
Etching is a process commonly used in metallurgy and materials science to selectively remove material from a solid surface. It is particularly important in metallography, where it is employed to reveal the microstructure of metals and alloys. The process involves applying a chemical reagent, known as an etchant, to the surface of a metal specimen for a controlled period of time. The etchant interacts with the surface, dissolving certain phases or grain boundaries while leaving others unaffected, thus highlighting the microstructural features of the material. To reveal the microstructure of the of medium carbon steel, an etching solution is applied to the polished surface. The etchant selectively attacks different phases in the steel at varying rates, highlighting the grain boundaries, carbides, and other microstructural features. The choice of etchant depends on the specific type of medium carbon steel and the desired features to be revealed which in this research, Nital (a solution of nitric acid and ethanol) was utilized.

2.3 Heat Treatment
The test specimens were subjected to Hardening and Tempering heat treatments after which the surface characterization and mechanical test were conducted. The heat treatment process was carried out in a Carbolite Muffle Furnace.

2.3.1 Hardening

The Test Specimens were heated to a temperature of 950^0C. At this temperature, the samples were soaked for 1 hour to ensure homogeneity in temperature, after which, the red-hot samples in the furnace were cooled rapidly to bring about hardness. The samples were quenched in water at a temperature above room temperature to avoid quench crack defect.

2.3.2 Tempering

The test samples for tempering were cleaned to remove dirt and other contaminants. The Muffle furnace was set to the appropriate tempering temperature range between 300°C to 600°C.The test specimens were loaded into the furnace with adequate spacing for uniform heating and were gradually heated to the tempering temperature while controlling the heating rate to prevent thermal shock and as well, holding the samples at the tempering temperature for a duration of 1 to 2 hours while monitoring the furnace temperature to maintain stability. The test samples were cooled in air ensuring a slow cooling rate to minimize thermal stresses after the sampled were removes from the furnace once it has reached a safe handling temperature. The tempered test specimens were inspected and cleaned for mechanical testing.

2.4 Mechanical Test

2.3.1 Tensile Testing

After the Tempering heat treatment operation, the various heat-treated samples were subjected to tensile test using the Standard Universal Testing Machine shown in figure 2.

Fig 2: Universal Instron Machine (Modell 3369, Maker Instron)

2.3.2 Hardness Test.

The Tempered specimens were subjected to hardness test. The hardness of the samples as received and the tempered samples were Tested using the Brinell hardness Tester. Different hardness tests were conducted on each sample and the average results taken.

2.4 Microstructure Examination.

Microstructure examination of the as-received and heat-treated specimens was carried out using the Accuscope microscope. Each sample was carefully grounded progressively on emery paper in decreasing coarseness. The grinding surface of the samples were polished using Al_2 O_3 carried on a micro clothe. The crystalline structure of the specimens was made visible by etching using solution containing 2% Nitric acids and 98% methylated spirit on the polished surfaces. Microscopic examination of the etched surface of various specimens was undertaken using a metallurgical microscope with an inbuilt camera through which the resulting microstructure of the samples were all photographically recorded with magnification of 400.

III. Results and Discussion

3.1 Microstructural View of the Samples Before and After Tempering Heat Treatment

The microstructural view of the test samples as-received is shown in figure 3. The dark region, which is more on the micrograph is pearlite (a lamellar (layered) mixture of two phases: ferrite (α-iron, a relatively soft and ductile phase with low carbon solubility) and cementite (Fe_3C, a hard and brittle iron carbide) and the white region (not too many) is ferrite. It shows that the as-received samples contain pearlite lamella morphology that will lead to undesirable mechanical properties in high stressed applications.

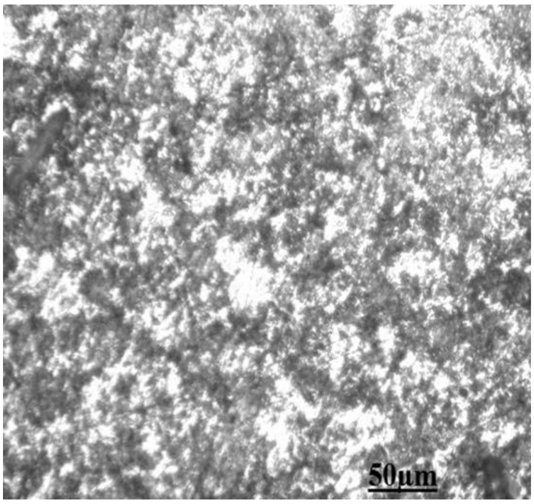


Fig 3 The Microstructural view of the test material as- received.

It can be observed that the microstructure of tempered martensite in medium carbon steel is characterized by a finer grain structure compared to the initial quenched martensite samples as depicted in figure 4. The internal stresses within the steel are significantly reduced as a result of the tempering heat treatment process, leading to improved ductility and reduced brittle microstructure. It was also evident that the tempered martensite phase consists of a mixture of ferrite and fine carbide particles which are more evenly dispersed all through the microstructure compared to the original martensite samples. This carbide particles dispersion contributes to the enhanced toughness and ductility of the tempered medium carbon steel samples.

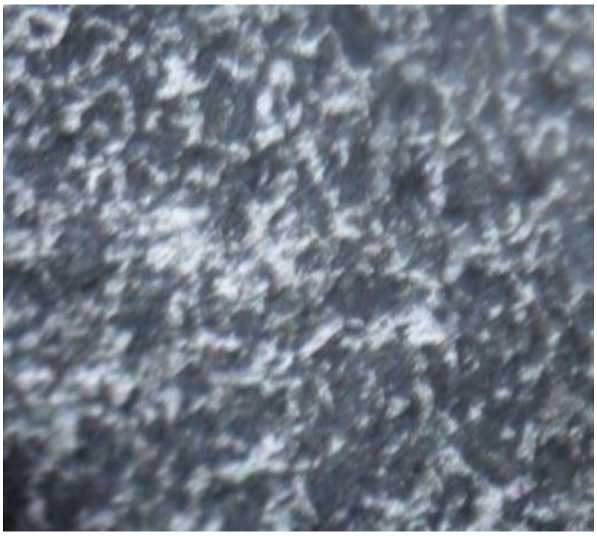


Fig 4 Microstructural View of the tempered Martensite

3.2 Effect of Tempering Temperature on Mechanical Properties of the Test Samples.

Table 2: Result of the effect of tempering temperature on the mechanical behavior of the medium carbon steel samples before and after heat treatment.

Tempering (O^c)	Specimen	Hardness (BHN)	Tensile strength(MPa)	Impact Strength (J)	Ductility (% elongation)
As- received (Martensite)	-	450	800	8	7.0
100	A	400	680	15	12.0
	B	410	690	14	11.8
	C	390	675	16	12.2
150	A	380	660	18	14.0
	B	390	665	17	13.8
	C	370	650	19	14.2
200	A	360	640	22	16.0
	B	370	645	21	15.8
	C	350	630	23	16.2
250	A	330	610	28	18.5
	B	340	615	27	18.2
	C	320	600	29	18.8
300	A	280	550	35	22.0
	B	290	560	34	21.8
	C	270	540	36	22.2
350	A	230	500	42	25.0
	B	240	510	41	24.8
	C	220	490	43	25.2

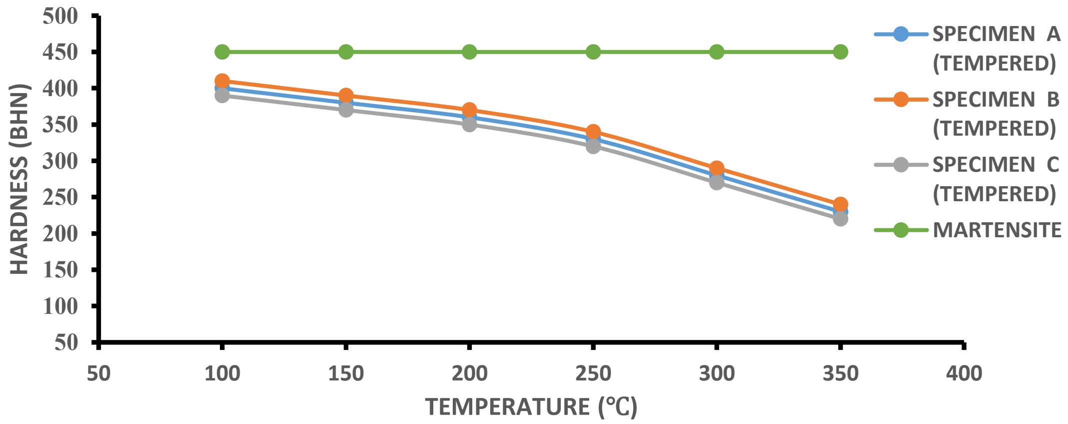


Fig 5: Effect of tempering temperature on hardness

The effect of tempering temperature on the hardness (BHN) of medium carbon steel test materials in both the martensitic and tempered conditions is illustrated. In the martensic condition, the steel maintains consistently high hardness (approximately 450 BHN) across all temperatures, as it has not undergone tempering. This high hardness results from the fully martensitic microstructure formed during quenching which is characterized by high residual stresses and a dense dislocation structure. For the tempered specimens (A, B, and C), the hardness decreases progressively with increasing tempering temperature. At low tempering temperatures (100–150°C), there is a slight reduction in hardness (around 370–410 BHN) due to the relief of residual stresses and the formation of fine carbides within the martensitic structure. As the temperature increases to the intermediate range (200–250°C), the hardness decreases further (320–370 BHN) as the martensite begins to decompose into tempered martensite and carbon redistributes to form more stable carbide precipitates. At higher tempering temperatures (300–400°C), there is a significant drop in hardness (220–290 BHN) because of the complete relief of residual stresses, coarsening of carbide particles, and the transformation of the microstructure into a ferrite-carbide matrix. This softening effect is more pronounced in this range, making the steel more ductile and tougher though less hard. Overall, the graph demonstrates the controlled softening achieved through tempering, with each temperature range providing a balance between hardness, toughness, and ductility suitable for various applications.

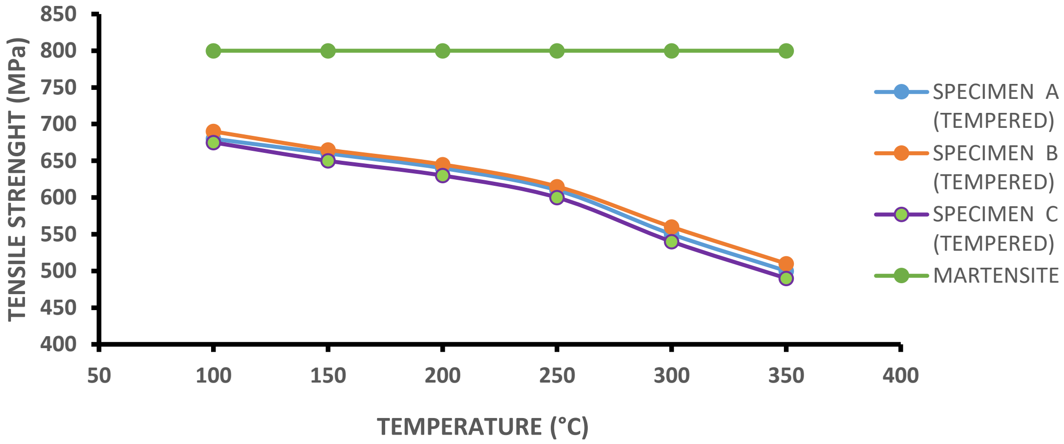


Fig 6: Effect of tempering temperature on the tensile strength

The effect of tempering temperature on the tensile strength of medium carbon steel specimens in tempered conditions is depicted in figure 6. In the as-received condition, the steel exhibits consistently high tensile strength (approximately 800 MPa) across all temperatures due to its fully martensitic structure, which provides excellent strength but limited ductility.

For the tempered specimens (A, B, and C), the tensile strength decreases progressively with increasing tempering temperature. At low tempering temperatures (100–150°C), the tensile strength reduces slightly (660–690 MPa) as residual stresses are relieved and the martensitic structure begins to stabilize through the formation of fine carbides. In the intermediate tempering range (200–250°C), tensile strength decreases further (610–645 MPa) as the martensite decomposes into tempered martensite accompanied by the precipitation of more stable carbides. At high tempering temperatures (300–350°C), tensile strength reduces significantly (490–560 MPa) due to the coarsening of carbide particles and the transformation of the microstructure into a ferrite-carbide matrix, which is softer and less resistant to deformation. This trend highlights the trade-off between strength and ductility, where higher tempering temperatures reduce tensile strength but enhance toughness and ductility, making the steel more suitable for dynamic and impact-loaded applications.

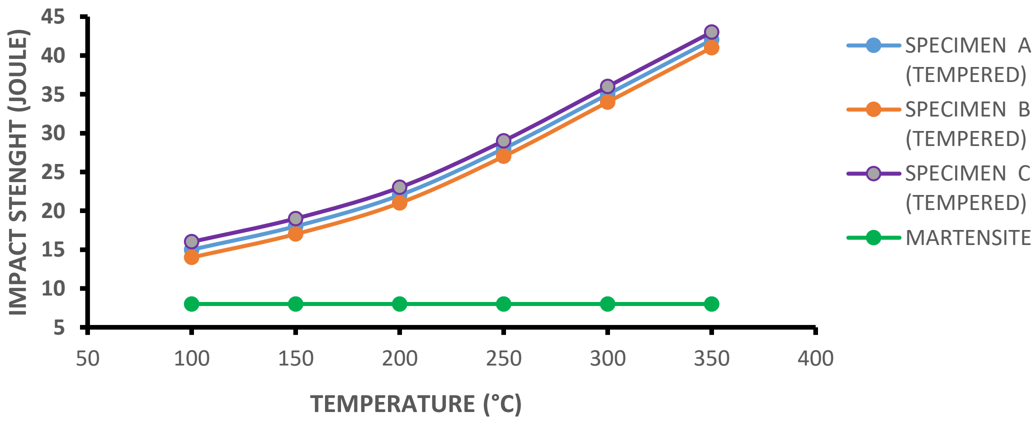


Fig 7: Effect of tempering temperature on impact strength

The effect of tempering temperature on impact strength is being illustrated in figure 7. Notably, in the martensitic condition, the impact strength is very low (approximately 8J) as a result of the steel's microstructure being dominated by untampered martensite, which is brittle due to high residual stresses and limited capacity to absorb energy under impact.

For tempered specimens (A, B, and C), the impact strength increases progressively with tempering temperature. At low tempering temperatures (100–150°C), there is a slight improvement in impact strength (9–13J) as residual stresses are partially relieved, prompting reduction in brittleness while maintaining a predominantly martensitic structure. At intermediate temperatures (200–250°C), the impact strength increases further (14–20 J) as the martensite decomposes into tempered martensite, a structure with better toughness and energy absorption. At elevated tempering temperatures (300–350°C), the impact strength shows a significant rise (23–32 J) due to the microstructure that transits to a ferrite-carbide matrix. This softer and more ductile structure can absorb more energy during impact, making the steel less prone to brittle failure. The trade-off is a reduction in hardness and tensile strength, but the improved impact strength makes the material more suitable for applications involving dynamic or impact loads.

The effect of tempering temperature on ductility of medium carbon is depicted in figure 8. Specimens steel is very low (approximately 5% elongation). This is because the microstructure is dominated by un-tempered martensite, which is hard and brittle with minimal capacity for plastic deformation.

For tempered specimens (A, B, and C), ductility increases progressively with tempering temperature. **At** low tempering temperatures **(100–150°C)**, there is a slight improvement in ductility (7–11% elongation) as residual stresses are partially relieved. However, the microstructure remains predominantly martensitic, so the increase in ductility is limited.

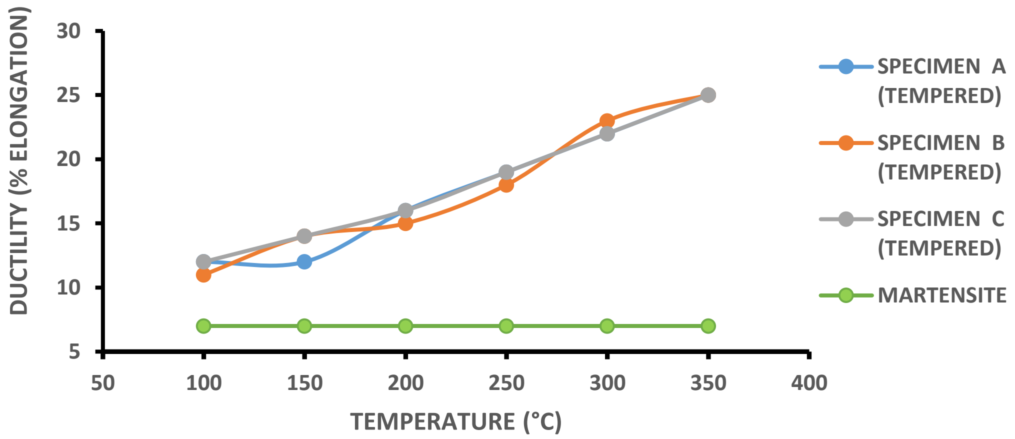


Fig.8: Effect of tempering temperature on ductility

At intermediate tempering temperatures (200–250°C), ductility improves further (11–16% elongation) as the martensite decomposes into tempered martensite, which has better capacity for plastic deformation. This change allows the material to stretch more before fracture. At high tempering temperatures (300–350°C), ductility shows a significant rise (19–28% elongation) due to the transformation of the microstructure into a ferrite-carbide matrix. This softer and more ductile structure allows the material to accommodate larger strains, making it more suitable for applications where flexibility and toughness are required.

The observed trend highlights the balance between hardness and ductility, where higher tempering temperatures result in improved ductility at the cost of reduced hardness and tensile strength. This makes tempering a critical process for tailoring the material properties to suit specific engineering applications.

IV. Conclusion

In this study, we have been able to investigate the impact of tempering heat treatment on the mechanical properties and microstructure of medium carbon steel without altering its geometry and size. The results show that tempering heat treatment significantly influenced both the microstructure and mechanical behavior of medium carbon steel. At lower tempering temperatures (100–150°C), the steel retained a predominantly martensitic structure, maintaining high hardness and strength but limited ductility. With increasing tempering temperature

(300–400°C), the microstructure evolved into a mixture of ferrite and fine carbides which in turn, enhance ductility and toughness but reduces hardness and strength. Higher temperatures led to carbide coarsening and a further reduction in both hardness and impact toughness, indicating that the steel became too soft to absorb high-energy impacts effectively. The study demonstrates that careful selection of tempering temperature is essential to achieve the desired combination of mechanical properties in medium carbon steel, providing practical guidance for optimizing heat treatment processes in engineering applications.

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