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EFFECTS OF ANNEALING HEAT TREATMENT ON THE MECHANICAL AND MICROSTRUCTURAL CHARACTERISTICS OF MEDIUM CARBON STEEL.

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Abstract: The mechanical behavior and performance of medium carbon steel can be profoundly modified through thermal processing. This study investigates the effect of annealing temperature on the mechanical and microstructural behaviour of medium carbon steel. Test specimens were subjected to full annealing at various temperatures ranging from 600 °C to 850 °C, followed by controlled furnace cooling. Mechanical properties such as tensile strength, yield strength, hardness, elongation, and impact toughness, were evaluated according to ASTM standards, while microstructural evolution was examined using optical microscopy. Results showed that annealing temperature had a profound influence on material behavior. Tensile and yield strengths decreased initially with rising temperature, reaching a minimum at 650 °C, but recovered progressively at higher temperatures. Elongation and impact energy improved significantly with temperature up to an optimum point (700–750 °C), beyond which ductility and toughness declined, suggesting over-annealing effects. Hardness followed a similar trend, with initial softening and subsequent partial recovery. Microstructural analysis revealed a transformation from fine pearlite-ferrite in the as-received condition to coarser ferrite grains with spheroidized carbides at higher annealing temperatures. These findings underscore the critical role of annealing temperature in optimizing the balance between strength and ductility for enhanced processability and structural performance of medium carbon steel.

Keywords: Annealing temperature, Medium carbon steel, Mechanical properties, Microstructure, Spheroidization, Heat treatment.

1.0 Introduction

Medium carbon steel remains one of the most commonly used engineering materials globally, because of its versatile mechanical properties, cost-effectiveness, and adaptability in a wide range of industrial applications [1]. Among the various classifications of steel, medium carbon steel, typically containing 0.3% to 0.6% [2] carbon is mostly utilized for manufacturing engineering components such as shafts, gears, axles, crankshafts, connecting rods, and railway parts [3,4,5]. This category of steel strikes a balance between strength, hardness, and ductility, making it suitable for applications requiring moderate toughness and wear resistance.

However, the as-received or hot-rolled form of medium carbon steel often contains residual stresses, non-uniform microstructures, and limited ductility, which can impede its machinability and formability. These drawbacks necessitate the use of heat treatment processes to tailor its properties to suit specific performance requirements. One such crucial heat treatment process is annealing [6, 7, 8]. Annealing is a thermal treatment that involves heating the steel to a temperature above its critical transformation point (austenitizing temperature), holding it (soaking) for a specific duration to ensure homogeneity and then cooling it slowly usually within the furnace. Annealing induces microstructural transformations that relieve internal stresses, refine grains, reduce hardness, and enhance ductility of a steel material. During this process, phase transformations and recovery phenomena occur, including recrystallization and grain growth, which ultimately influence the steel's mechanical behavior [9].

The mechanical properties of steel, such as tensile strength**,** hardness**,** elongation**,** and impact toughness are intrinsically linked to its microstructure. Factors such as grain size, phase distribution (ferrite and pearlite), dislocation density, and carbide morphology all change as a result of annealing [10, 11, 12]. Understanding how these microstructural features evolve during heat treatment provides valuable insights into controlling the mechanical properties of steel for engineering applications [13, 14, 15, 16].

Previous researchers have addressed the general effects of heat treatments on carbon steels. However, there remains a need for more focused and quantitative analysis of how varying soaking times and annealing temperature during annealing influence the mechanical and microstructural characteristics of medium carbon steel. Soaking time plays a crucial role in diffusion, grain growth, and homogenization, all of which directly affect the outcome of the treatment [17]. Excessive soaking can lead to undesirable grain coarsening, while insufficient soaking may leave residual stresses unrelieved. In industrial settings, where component reliability, safety, and performance are critical, precise knowledge of how annealing conditions affect material behavior can inform decisions about processing parameters and material selection. This becomes even more pertinent in manufacturing sectors such as automotive, railway, oil and gas, and heavy machinery, where medium carbon steel is often subjected to machining, forming, and cyclic loading.

2.0 Materials and Methods.

2.1 Material composition

The material investigated in this study is a commercial-grade medium carbon steel, containing 0.352% carbon, and is specifically designed for heat treatment. The full chemical composition is presented in Table 1, as determined using optical emission spectroscopy.

Table 1: The full chemical composition of the commercial-grade medium carbon steel.

S/N	**Elements**	**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

2.2 Sample Preparation

The medium carbon steel bar as-received was machined into standard test specimens for mechanical testing such as tensile, impact, and hardness tests in accordance with ASTM standards. Additional specimens were prepared for metallographic analysis. All the samples were surface cleaned to get rid of oxides and contaminants before heat treatment.

2.3 Heat Treatment

The test specimens labelled as sample A, B and C were subjected to annealing heat treatment after which the surface characterization and mechanical test were conducted. The heat treatment process was done in a Carbolite Muffle Furnace.

2.3.1 Annealing procedure

Annealing is a heat treatment process used to soften metals, improve their machinability, and reduce internal stresses. The annealing process was carried out using the Muffle furnace. The test samples were meticulously cleaned to eliminate any surface contaminants or oxides to ensure optimal results. The muffle furnace was then set to the appropriate temperature range for medium carbon steel annealing, ranging between 600°C to 850°C. Gradual heating of the test samples commenced, allowing the samples to reach the designated annealing temperature gradually. Throughout this process, precise temperature control was maintained within the furnace to ensure uniform heating and prevent overheating or underheating of the test samples. When the annealing temperature was reached, the samples were held at that temperature for the recommended duration, typically ranging from 30 minutes to 2 hours. This soaking period allowed for the transformation of the medium carbon steel's microstructure, relieving internal stresses and promoting softening. Following the annealing cycle, the furnace was gradually cooled down along with the work pieces to prevent rapid cooling and minimize the risk of thermal shock. After reaching a safe handling temperature, the annealed samples were carefully removed from the furnace and inspected for desired annealing effects, such as reduced hardness and improved machinability.

2.4 Mechanical Testing

Mechanical testing was conducted to determine the effect of annealing heat treatment on the mechanical behavior of medium carbon steel. The mechanical tests carried out include tensile testing, hardness measurement, and impact toughness evaluation, all performed in accordance with relevant ASTM standards.

2.4.1 Tensile Testing

After the Annealing heat treatment process, the various heat-treated samples were subjected to tensile test, using the Standard Universal Testing Machine. Tensile testing was conducted following the ASTM standard using a universal testing machine with a maximum load capacity of 100 KN. Standard round tensile specimens with a gauge length of 50 mm and a diameter of 12.5 mm were machined and properly aligned in the machine’s grips. The load was applied axially at a constant crosshead speed of 2 mm/min until the specimen fractured. During the test, data which include tensile strength, yield strength, and percentage elongation were recorded.

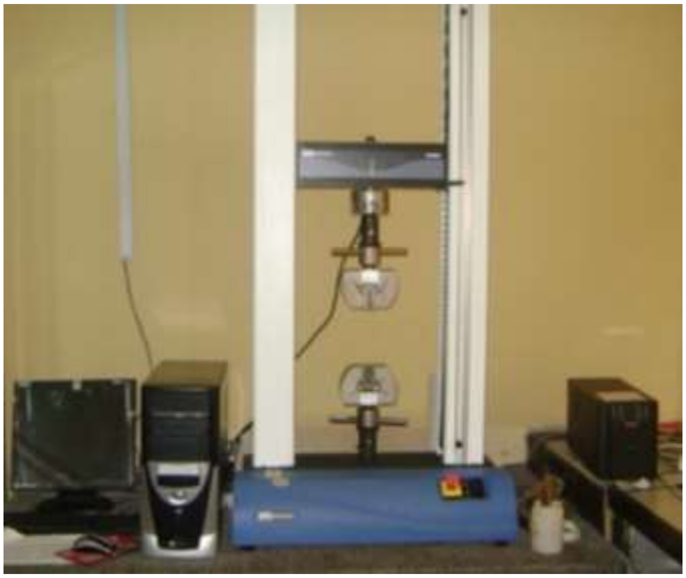

Figure 1: Universal Instron Machine (Modell 3369, Maker Instron)

2.4.2 Hardness Testing:

Hardness testing was conducted using the Rockwell hardness tester following the ASTM standard. Each of the specimens were prepared by grinding and polishing to obtain a smooth and clean surface. Using the C-scale, a minor load of 10 gf was first applied, followed by a major load of 150 kgf using a diamond cone (Brale) indenter. After the required dwell time, the major load was released and the hardness value was read directly from the dial. Three hardness measurements were taken at different points on each sample, and the average value was reported to ensure accuracy and repeatability.

2.4.3 Impact Testing

Impact toughness was evaluated using the Charpy V-notch test in accordance with ASTM. Standard specimens measuring 10 mm × 10 mm × 55 mm were machined with a centrally located 2 mm deep V-notch. Each specimen was placed on the Charpy impact tester's anvil with the notch facing away from the pendulum. The pendulum hammer was released to strike the specimen at the notch, and the energy absorbed during fracture was recorded in joules. Three samples were tested under each condition, and the average impact energy was used for analysis.

2.4.4 Elongation

The elongation of the medium carbon steel specimens was determined during the tensile test in accordance with ASTM. Before testing, the gauge length of each specimen was carefully marked and measured using a calibrated micrometer. The specimen was then mounted in the grips of a universal testing machine, and a uniaxial tensile load was applied at a constant crosshead speed of 2 mm/min until the specimen fractured. After fracture, the two broken pieces were carefully fitted back together, and the final gauge length between the original gauge marks was measured using a vernier caliper or micrometer. The percentage elongation was then calculated using the formula:

$$\text{Elongation (\%)} = \frac{L_f - L_0}{L_0} \text{ x } 100$$

Where L_f is the final gauge length after fracture and L_0 is the original gauge length before the test. The result provides an indication of the material's ductility, and the average value from at least three specimens was reported to ensure accuracy and repeatability.

2.4.5 Yield strength.

The yield strength of the medium carbon steel specimens was determined using a universal testing machine in accordance with ASTM. Standard round tensile specimens were prepared with a gauge length of 50 mm and mounted securely in the machine. A uniaxial tensile load was applied at a constant crosshead speed of 2 mm/min, and the load-extension data were recorded continuously. The yield load was divided by the original cross-sectional area of the specimen to calculate the yield strength in MPa. The average value from three test replicates was reported.

$$\text{Yield Strength } (\delta_y) = \frac{P_y}{A_0}$$

Where P_y = load at yield point (N)

A_0 = Original cross sectional area of gauge length (mm^2)

2.5 Metallographic Characterization

Microstructural examination of the as-received and annealed specimens was carried out using the Accuscope metallurgical microscope. Each sample was carefully ground 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 (grain distribution morphology and phase distribution) of the samples were all photographically recorded with magnification of 400.

3.0 Results and Discussion

3.1 Microstructural View of the Samples before and After Annealing Heat Treatment.

Fig 2. The samples as-received exhibited fine pearlite-ferrite microstructures with lamellar morphology. 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.

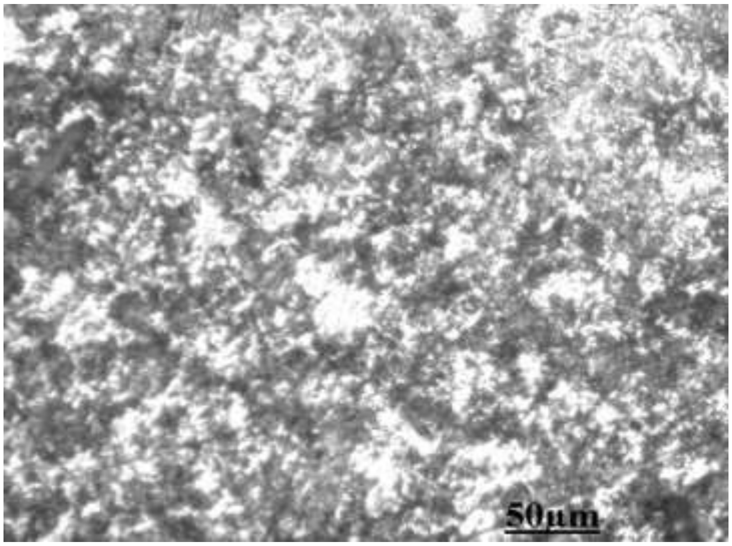

Figure 2: The Microstructural view of the test material as- received.

It shows that the as-received samples exhibit pearlite lamella morphology that will lead to undesirable mechanical properties in high stressed applications. Figure 3 shows the microstructural view of the material after annealing. The annealing process transformed the microstructure of the medium carbon steel test sample, significantly impacting its mechanical properties. The annealing process metamorphosed the pearlite and ferrite nature of the received samples due to thermal exposure. The thermal exposure during annealing promotes the existing ferrite grains to enlarge (the transformation from lamellar pearlite to dispersed spheroidal carbides within a matrix of larger ferrite grains).

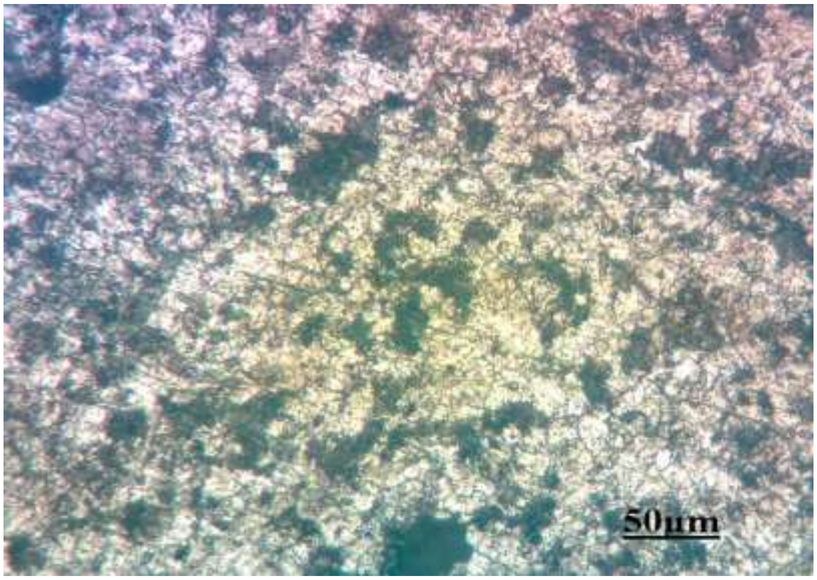

Figure 3: Microstructural View of the annealed samples.

The larger ferrite grains with fewer grain boundaries offers less resistance to dislocation movement within the material's crystal structure. This translates to a softer and more workable material. Also, Spheroidization, which is the key transformation that occurs within the pearlite region. The iron carbide (Fe3C) lamellae gradually morph into spheroidal (rounded) particles. This process, driven by time and temperature, significantly alters the pearlite's morphology The Spheroidized carbides, compared to the sharp lamellae, offers less resistance during deformation, further enhancing the ductility. of the material.

3.2 Results of the Effect of Annealing Temperature on the Mechanical behavior of the Test Samples.

Figure 4 shows the "Effect of Annealing Temperature on Tensile Strength of the Test Materials" it shows how the tensile strength of the three different samples (Sample A, Sample B, and Sample C) changes with varying annealing temperatures.it can be seen that at 600°C, all three samples started with a tensile strength of approximately 490 MPa. As the temperature increases from 600°C to 650°C, there is a noticeable decrease in tensile strength for all samples, reaching a minimum at around 650°C.The lowest tensile strength for all samples is around 460 MPa. Beyond 650°C, the tensile strength begins to recover and increases steadily up to 850°C.All samples show a similar trend in recovery, with tensile strength increasing back to about 490 MPa at 800°C and continuing to rise slightly above 490 MPa by 850°C.

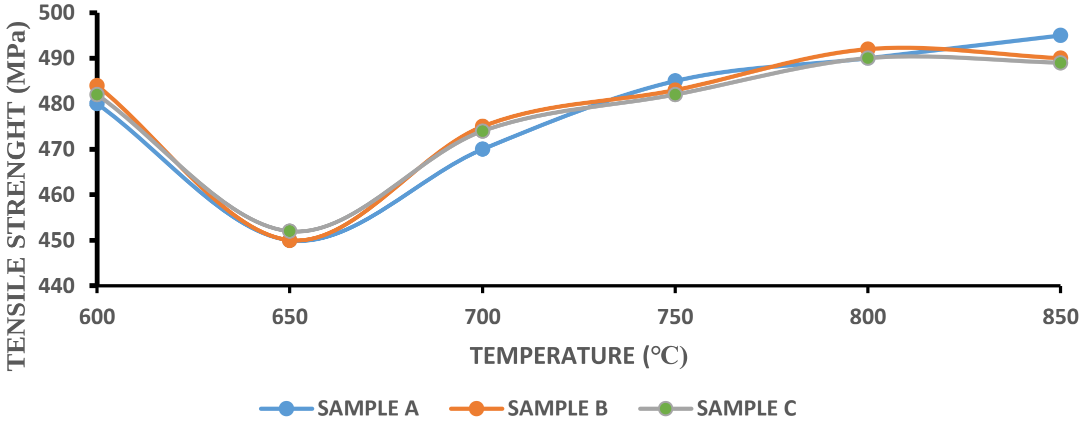

Figure 4: Effect of Annealing Temperature on Tensile Strength of the Test Samples.

The graph indicates that annealing at temperatures between 600°C and 650°C reduces the tensile strength of the materials, possibly due to microstructural changes like grain growth or phase transformations. After 650°C, the tensile strength increases, indicating that higher annealing temperatures (above 650°C up to 850°C) are beneficial for recovering and even enhancing the tensile strength of the materials. This shows that annealing temperature significantly influences the tensile strength of the test materials, with a dip around 650°C and a gradual recovery and enhancement as the temperature increases up to 850°C.

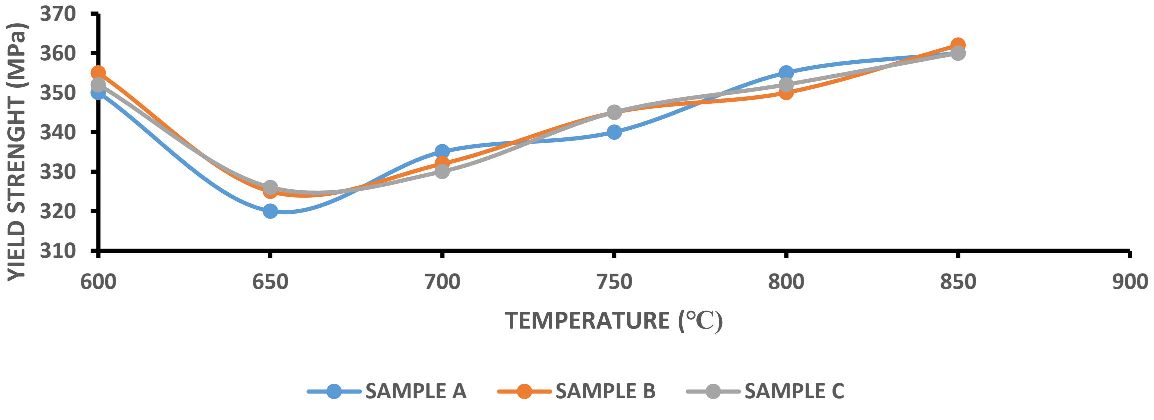

Figure 5: Effect of Annealing Temperature on Yield Strength of the Test Samples.

The effect of Annealing Temperature on Yield Strength of the Test Materials is shown in figure 5. It shows how the yield strength of the three different samples (Sample A, Sample B, and Sample C) changes with varying annealing temperatures. It can be seen that at 600°C, all three samples started with a yield strength of approximately 350 MPa. As the temperature increases from 600°C to 650°C, there is a noticeable decrease in yield strength for all samples, reaching a minimum at around 650°C. The lowest yield strength for all samples is around 320 MPa. Beyond 650°C, the yield strength begins to recover and increases steadily up to 850°C. All samples show a similar trend in recovery, with yield strength increasing back to about 350 MPa at 800°C and continuing to rise slightly above 360 MPa by 850°C. The graph indicates that annealing at temperatures between 600°C and 650°C reduces the yield strength of the materials, possibly due to microstructural changes like grain growth or phase transformations. After 650°C, the yield strength increases, indicating that higher annealing temperatures (above 650°C up to 850°C) are beneficial for recovering and even enhancing the yield strength of the materials. This shows that annealing temperature significantly influences the yield strength of the test materials, with a dip around 650°C and a gradual recovery and enhancement as the temperature increases up to 850°C.

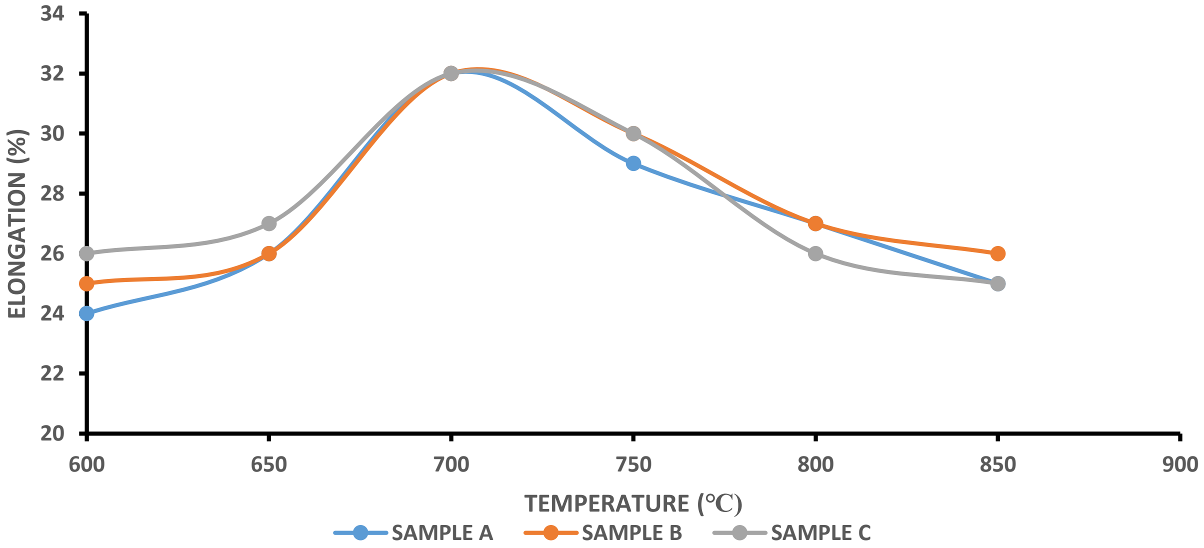

Figure 6: Effect of Annealing Temperature on the Elongation of the Test Samples.

Figure 6. Shows the "Effect of Annealing Temperature on the Elongation of the Test Materials." It shows how the elongation of the three different samples (Sample A, Sample B, and Sample C) changes with varying annealing temperatures. It can be seen that at 600°C, all three samples started with an elongation of approximately 24-26%. As the temperature increases from 600°C to 650°C, there is a noticeable increase in elongation for all samples. The elongation peaks around 700°C, beyond 700°C, the elongation begins to decrease steadily up to 850°C. The graph indicates that annealing at temperatures between 600°C and 700°C increases the elongation of the materials, possibly due to microstructural changes like grain growth that enhance ductility. After 700°C, the elongation decreases, suggesting that higher annealing temperatures (above 700°C up to 850°C) may lead to over-annealing, resulting in reduced ductility. This shows that annealing temperature significantly influences the elongation of the test materials, with an increase in ductility up to 700°C and a gradual decrease as the temperature increases further to 850°C.

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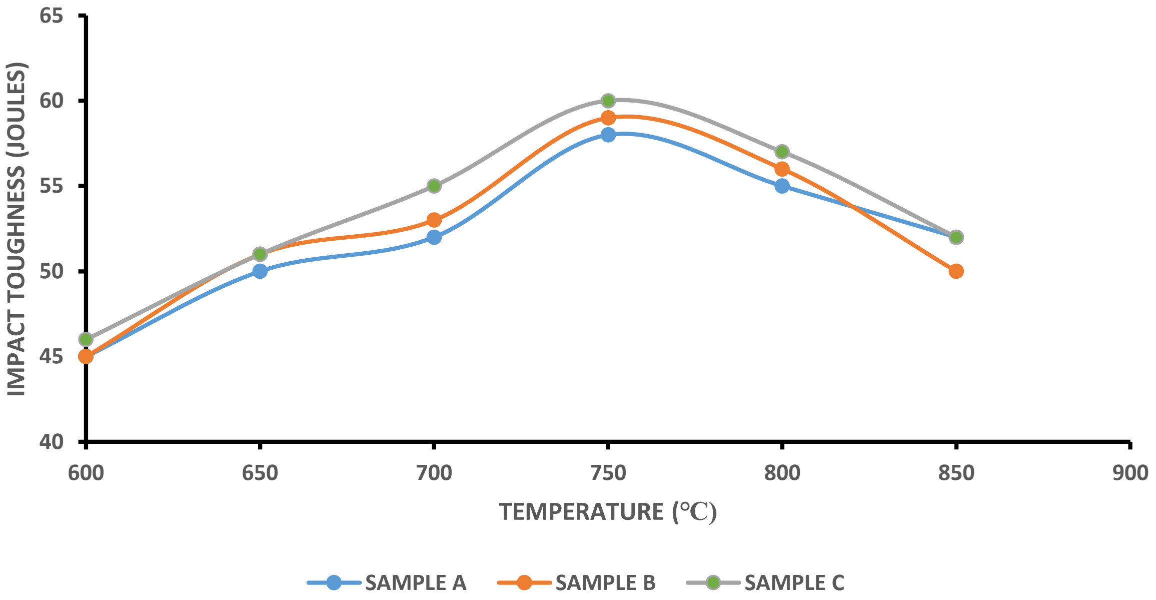

Figure 7: Effect of Annealing Temperature on Impact Toughness of the Test Samples.

Fig 7. Shows the "Effect of Annealing Temperature on Impact Toughness of the Test Materials." It shows how the impact toughness of the three different samples (Sample A, Sample B, and Sample C) changes with varying annealing temperatures. It can be seen that at 600°C, all three samples started with an impact toughness of approximately 45 Joules.

As the temperature increases from 600°C to 750°C, there is a noticeable increase in impact toughness for all samples. Beyond 750°C, the impact toughness begins to decrease steadily up to 850°C. At 850°C, the graph indicates that annealing at temperatures between 600°C and 750°C increases the impact toughness of the materials, possibly due to microstructural changes like grain growth that enhance toughness. After 750°C, the impact toughness decreases, suggesting that higher annealing temperatures (above 750°C up to 850°C) may lead to over-annealing, resulting in reduced toughness. This shows that annealing temperature significantly influences the impact toughness of the test materials, with an increase in toughness up to 750°C and a gradual decrease as the temperature increases further to 850°C.

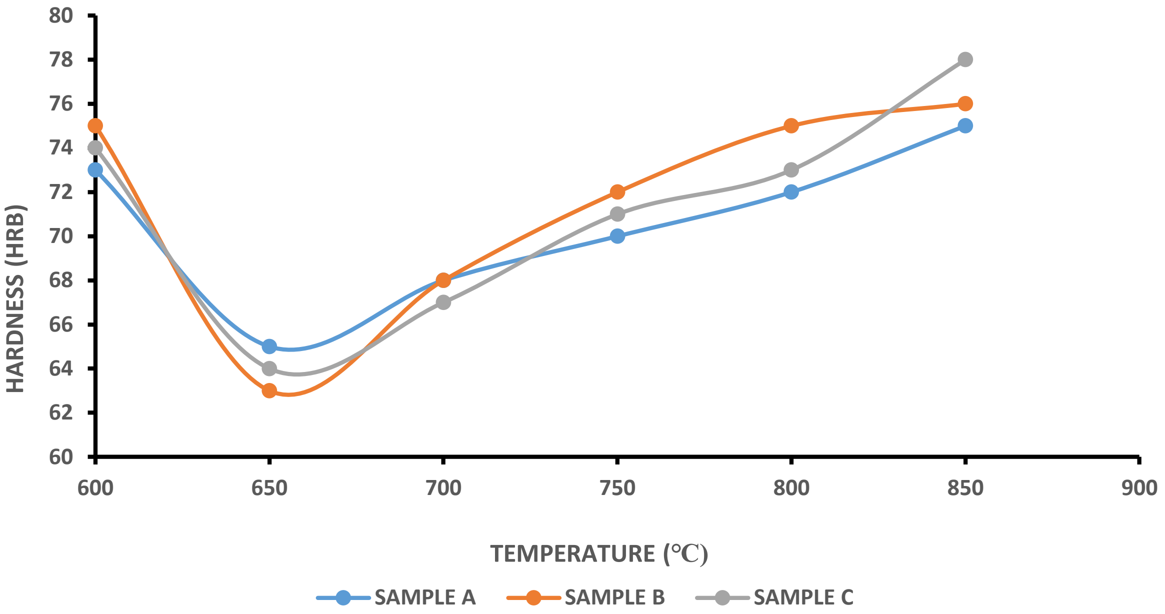

Figure 8: Effect of Annealing Temperature on the Hardness of the Test Samples.

Figure 8. Shows the "Effect of Annealing Temperature on the Hardness of the Test Materials." It shows how the hardness of the three different samples (Sample A, Sample B, and Sample C) changes with varying annealing temperatures. It can be seen that at 600°C, all three samples started with a hardness of approximately 74HRB.

As the temperature increases from 600°C to 650°C, there is a noticeable decrease in hardness for all samples, reaching a minimum at around 650°C. Beyond 650°C, the hardness begins to recover and increases steadily up to 850°C. The graph indicates that annealing at temperatures between 600°C and 650°C reduces the hardness of the materials, possibly due to microstructural changes such as grain growth or phase transformations. After 650°C, the hardness increases, indicating that higher annealing temperatures (above 650°C up to 850°C) are beneficial for recovering and even enhancing the hardness of the materials. This shows that annealing temperature significantly influences the hardness of the test materials, with a dip around 650°C and a gradual recovery and enhancement as the temperature increases up to 850°C.

4.0 Conclusion

The study revealed that annealing temperature has a significant influence on the mechanical and microstructural characteristics of medium carbon steel. As the annealing temperature increased from 600 °C to 850 °C, both tensile and yield strengths initially declined due to microstructural coarsening and stress relief, reaching their lowest values around 650 °C. However, a progressive recovery in strength was observed at higher temperatures, particularly beyond 700 °C. Conversely, ductility and impact toughness improved with increasing temperature, reaching optimum levels around 700 °C to 750 °C, after which a slight reduction was observed, indicating the onset of over-annealing. Microstructural examination confirmed the transformation from fine pearlite-ferrite lamellae in the as-received samples to coarser, equiaxed ferrite grains with spheroidized carbides at elevated temperatures. These changes facilitated improved plasticity and reduced resistance to deformation. Overall, the findings establish that the annealing temperature range of 700 °C to 750 °C is optimal for achieving a balance between improved ductility and adequate strength, making it suitable for applications requiring enhanced formability and moderate mechanical performance. Controlled annealing within this temperature window can therefore be employed to tailor medium carbon steel for use in structural, automotive, and manufacturing components.

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