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EFFECT OF LAMINARIZATION TEMPERATURE ON MECHANICAL PROPERTIES AND MICROSTRUCTURAL EVOLUTION OF MARTENSITIC MEDIUM CARBON STEEL DEVELOPED VIA THERMAL CYCLING TREATMENT

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Abstract

The mechanical attributes of martensitic medium carbon steel can be enhanced by cyclic quenching and tempering (CQT) heat-treatment methods, since they promote the development of small grain structure. This study intends to investigate the effect of laminarization temperatures on mechanical properties and microstructural evolution of martensitic steel developed via thermal cycling treatment for improving the quality of steel. Initial normalization was performed at 845°C in a muffle furnace on hot-rolled AISI 1040 ribbed steel bars with a 12 mm diameter and contents of 0.40% C, 0.28% Si, and 0.62% Mn. The samples were tempered at 450°C after undergoing thermal

[redacted]

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Laminarization,
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Mechanical,
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cycling in the dual-phase region at 743°C, 761°C, and 779°C, respectively. Optical microscopy (OM) was used to evaluate and characterize the mechanical qualities of the steel developed. The findings demonstrate that the maximum tensile strength, yield strength, percent elongation, and elastic modulus all rose with an increase in laminarization temperature at 779°C while the impact strength declined. The Optical micrographs revealed that the sample contains lath martensite and ferrite and carbide with fine grains after tempered at 450°C. These results suggest that thermal cycling treatment is a useful technique for improving the mechanical properties of high-performance martensitic steel to be used in load-bearing applications.

Introduction

The most significant and adaptable alloy in engineering is steel. Steel is used in engineering applications so widely because of its ability to withstand heat treatment. Heat treatment allows for a very wide range of control and variation in the characteristics of steel (Suresh, 2021). The carbon content of given steel determines the temperature at which it should be heat-treated.

The process of heating a solid metal to a particular temperature, maintaining it there, and then allowing it to cool at an appropriate rate is known as heat treatment. When heat treating a certain type of steel, process control is crucial, and it is implemented through variables including temperature, rate of heating, period and conditions of the furnace. Nevertheless, while steels are being heated, the final structure is determined by the pace of cooling. The temperatures at which the transformation takes place have a direct impact on the final structure produced. To achieve the desired homogenous structure, heating should be gradual and consistent (Suresh, 2021). The chemical makeup of the steel and the desired end qualities mostly control the heat treatment temperature.

Martensite-structured medium carbon steel provides improved formability and the potential to reduce weight, increase efficiency and better corrosion resistance. Over years, manufacturers have become more interested in the enhancement of mechanical qualities of medium carbon steel's. Many studies have been conducted to elucidate the mechanical behavior of medium carbon steels; they include Hu *et al*., (2015), Krauss, (2017), Ma *et al*., (2018), Krolicka *et al*., (2019). The precise impact of the second-phase martensite's morphology has on microstructure and toughness of medium carbon steel is still unknown, despite the fact that this effect is thought to be extremely significant for enhancing the material properties of the steels (Krauss, 2017). The carbon content ranges from 0.25% to 0.6% in medium-carbon steel (Gorni, 2019). The desired properties of medium-carbon steel can be obtained through heat treatment (Suresh, 2021). Carbon steel continues to be the most widely used steel despite the development of numerous alloys due to its affordability, availability, ease of protection, and variety in terms of mechanical behavior. AISI 1040 medium carbon steel is commonly used to construct crank shafts, connectors, carriage anchors, tool screws, and cold-headed fittings. It can also be used for machining; u-bolts, concrete reinforcement rods, and anchor wire (Unueroh *et al.,* 2019). Martensitic steels are frequently utilized in abrasive, tear-resistant, weapons, and other special-purpose metals because of their extreme strength and hardness. Complex service scenarios necessitate the improvement of martensitic steels with a variety of features. Maintaining strict control over carbon addition has been shown to be an effective tactic for improving martensite microstructures; nevertheless, there are notable drawbacks in terms of toughness, plasticity, and weldability. Hu *et al*, (2015) state that adding second-phase martensite can significantly improve the strength and tenacity of low-carbon martensitic steels by enhancing the interactions between grain boundaries and dislocations. Furthermore, the presence of second-phase martensite at elevated temperatures in the rough-grained heat-affected zone (RGHAZ) inhibits grain formation and enhances the weldability of steels (Ma *et al*., 2018). Strengths above 1200 MPa can be achieved by martensite steel with 0.3% carbon content. Consequently, the iron and steel sectors are constantly looking for novel approaches to control the process of improving martensitic steels' strength, toughness, and plasticity while preserving carbon content and guarantee weldability. The microstructure and characteristics of medium-carbon steels quenched to martensite are changed by tempering them for a range of load-bearing applications.. Research has been done on the relationship between microstructure properties and fracture toughness (Zhou *et al*., 2019, Zhou *et al*., 2020). It was proposed that the carbon content of the martensitic microstructure determines its strength (Krauss, 2016). Up to roughly 0.5 weight percent, where martensite is primarily lath martensite, the yield strength rises almost linearly with carbon content; nevertheless, the mechanism underlying this strengthening is still up for debate (Gao, *et al.,* 2019). Hence, this work intends to examine the effect of laminarization temperature on mechanical properties and microstructural evolution of martensitic medium carbon steel developed via thermal cycling treatment

Research Methodology

Materials

The material used in this research was hot-rolled, AISI 1040 ribbed medium carbon steel bars with 12 mm diameter. The medium carbon steels (Sunflag products) were obtained from Ikorodu Lagos. The chemical composition of the steel shown in Table 1 was determined with the aid of optical emission spectrometer which indicates that the steel is classified as medium carbon since its carbon concentration is between 0.25% and 0.6% (Gorni, 2019).

Table 1: Spectrometric Analysis of the AISI 1040 Martensitic Medium Carbon Steel

ELEMENT	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V	Fe
CONTENT (wt%)	**0.349**	**0.283**	**0.621**	**0.033**	**0.032**	**0.014**	**0.014**	**0.090**	**0.148**	**0.005**	**98.41**

Experimental Procedure

Thermal cycling in steels refers to the process of repeatedly heating and cooling the materials through specific temperature range. This process can significantly impact the mechanical properties and microstructure of the steel.

The experimental procedure for martensitic steel developed via thermal cycling treatment is displayed in Figure 1. The samples obtained were machined into forty (40) tensile test specimens and thirty six (36) test specimens out of forty (40) produced were first normalized in a muffle furnace at heat treatment laboratory, Federal University of Technology, Akure. Twelve (12) samples each were thereafter subjected to thermal cycling and then tempered at 450°C, as shown in Figure 1. The remaining four (4) samples were used as a control

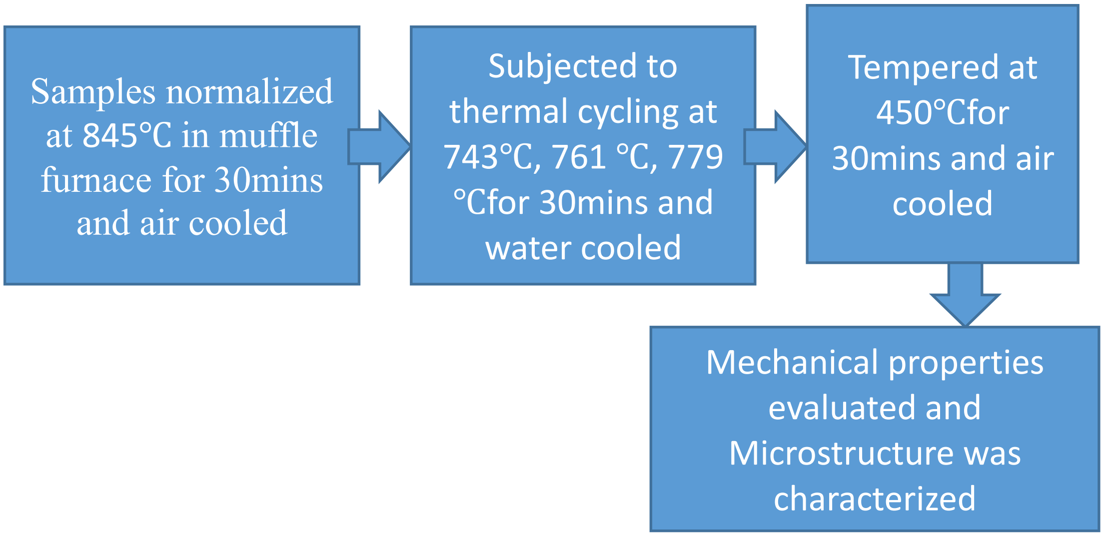


Figure 1: Flow Chart for Martensitic Steel Developed

Results and Discussion

Mechanical Test Results

Table 2: Mechanical Properties of the Sample

Sample Temp. (°C)	Length (mm)	Diameter (mm)	YS (MPa)	UTS (MPa)	% EL	ModulusE (MPa)	FS (MPa)	Impact strength J/mm^2	Hardness(Brinell) BHN
(Control, A)	25.00	5.00	250.00	554.36	0.71	2249.93	426.19	2.64	93.66
743 (B)	25.00	5.00	316.66	567.12	0.74	2465.22	422.63	2.99	137.53
761 (C)	25.00	5.00	426.66	582.69	0.80	2820.95	415.15	2.89	152.53
779 (D)	25.00	5.00	433.33	610.74	0.82	3334.43	405.70	2.73	163.49

Table 2 displays the results of the tensile test performed on the tensile samples. The findings demonstrate that, following tempering at 450°C, both ultimate tensile stress (UTS) and 0.2% yield strength (YS) rise steadily with rising temperatures. It is clearly seen that the modulus of elasticity and percentage elongation both rise at the same tempering temperature, suggesting strong ductility and low dislocation density (Saastamoinen *et al*; 2018). The average tensile test result for the samples is displayed in Table 2. With increasing laminarization temperature, the specimens' elastic modulus, yield strength, %elongation, and ultimate (maximum) tensile strength all increased while their fracture strength decreased as shown in Table 2 and Figure2 - 4, indicating an increase in ductility that improved the tested steel's performance and formability.

Table 2 further shows that mechanical attributes are significantly influenced by the tempering and laminarization temperature. As seen in Figure 4, the control sample has a very low hardness in comparison to the tempered samples, whereas the tempered samples at 450°C have the highest hardness at 779°C. The crystals structure change from face center cubic to body center tetragonal and austenite to martensite. In the martensite, it generates a high dislocation density, which raises the hardness (Dudko *et al.*, 2023). Martensite lath changes to ferrite and carbides during the tempering process. As carbon diffuses into carbides, martensite's carbon concentration is reduced. At the same time, the atoms rearrange and the dislocation density decreases, the internal stress will also be relieved simultaneously. This improved the mechanical characteristics of the samples.

Based on secondary fractures that indicate the occurrence of induced martensitic transformation, Figure 6, which displays the impact test results in this work, demonstrates that the impact strength decreases as the laminarization temperature rises. The impact strength and grain sizes, which transformed into martensite, were shown to be adversely influenced by the presence of block austenite during dynamic loading. The impact strength may increase with an increase in film-like austenite content. Additionally, the average values of homogeneous hardening under strain (or "YS/UTS" ratio) for each of the heated samples at the laminarization temperatures are displayed in Figure 7. As observed from these figures, despite variations in the phase mixture formed after applying different cycling treatments, all specimens display a constant yielding behavior. This indicates that every single specimen show a seamless change in behavior from elastic to plastic. Regarding the "YS/UTS" ratio—which indicates a material's propensity to undergo plastic deformation—all heat-treated tensile specimens exhibit a comparable capacity for strain hardening. This ratio, which ranges from 0.56 to 0.71, is consistent with the work of these researchers Bagliani *et al*., (2013) and Mandal *et al*., (2016) as typical YS/UTS ratios in multiphase steels

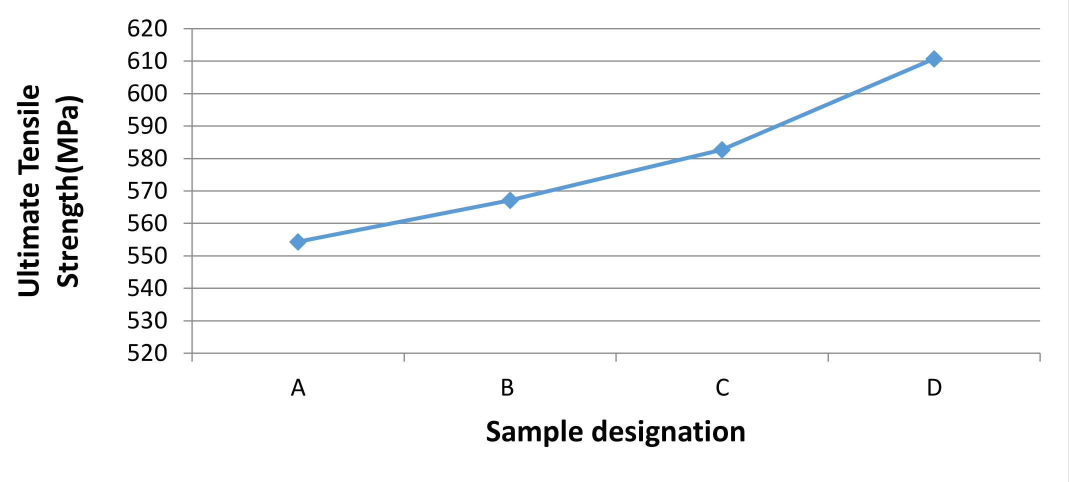


Figure 2: Engineering Stress of the Sample

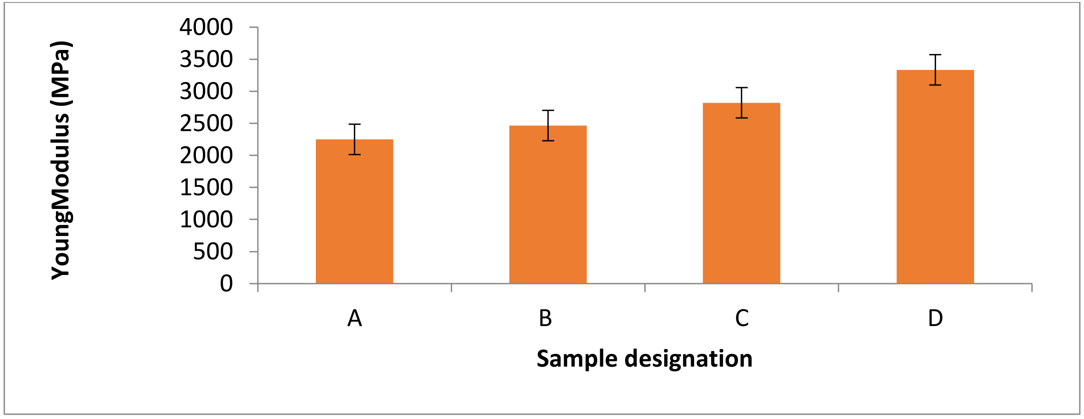


Figure 3: Young Modulus of the Sample

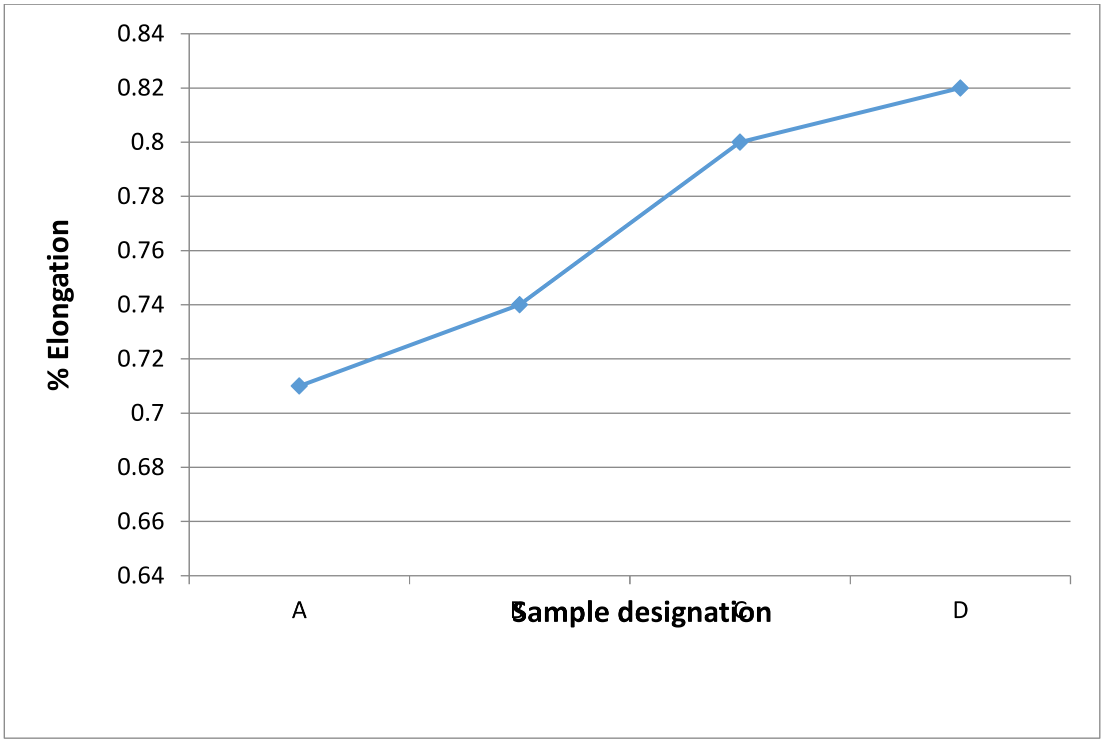


Figure 4: Percentage Elongation of the Sample

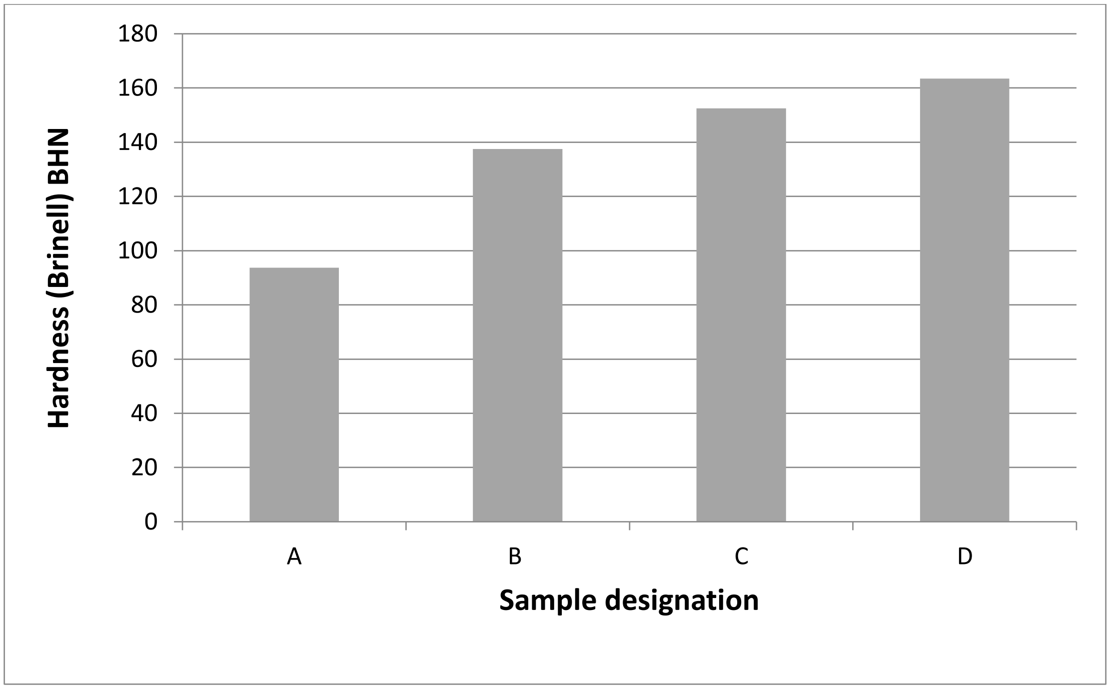


Figure 5: The Hardness of the Samples

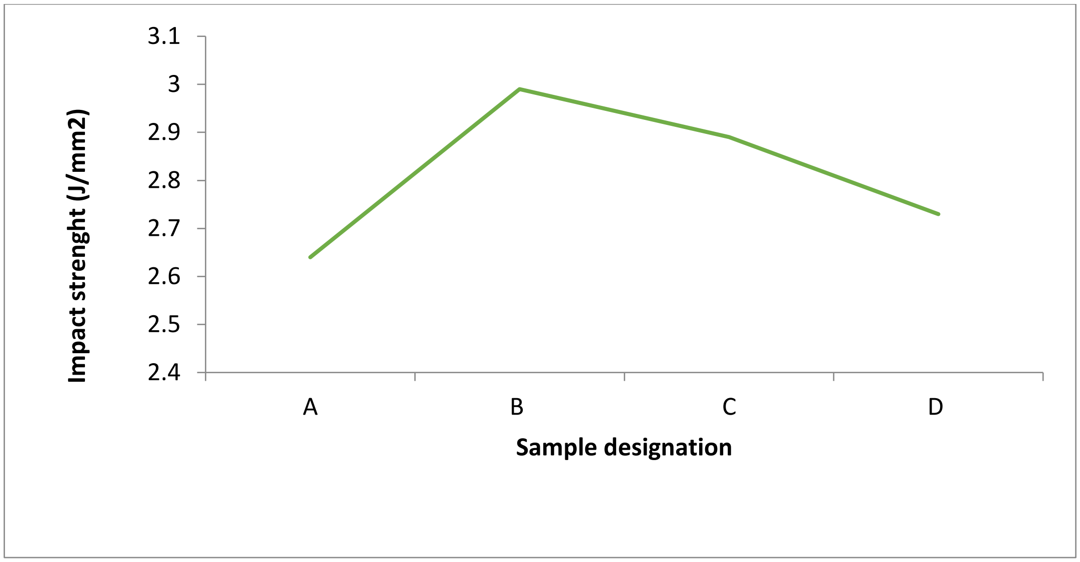


Figure 6: Impact Strength at Different Temperature

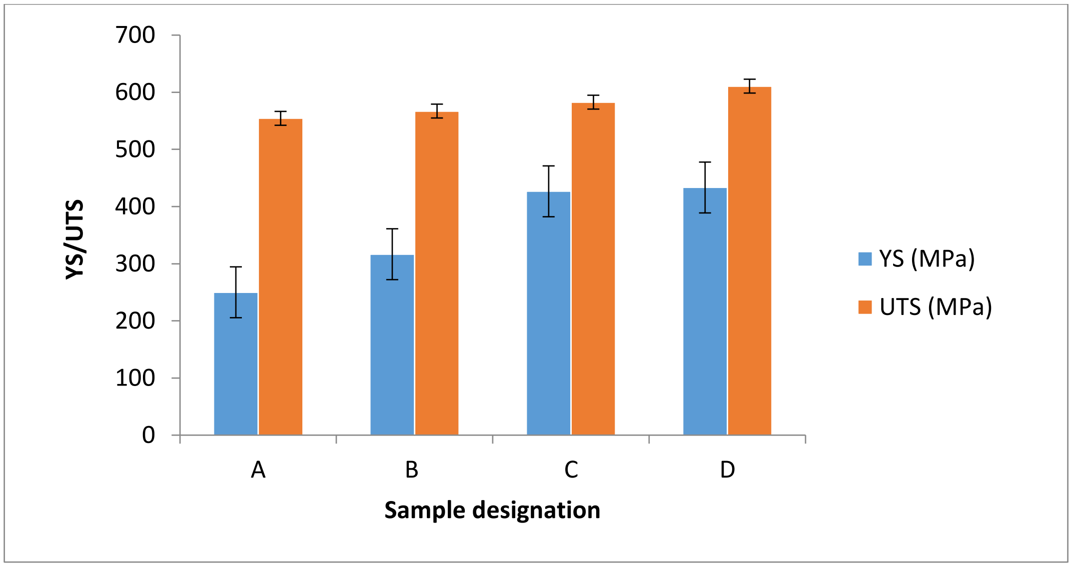


Figure 7: YS/UTS of the Sample

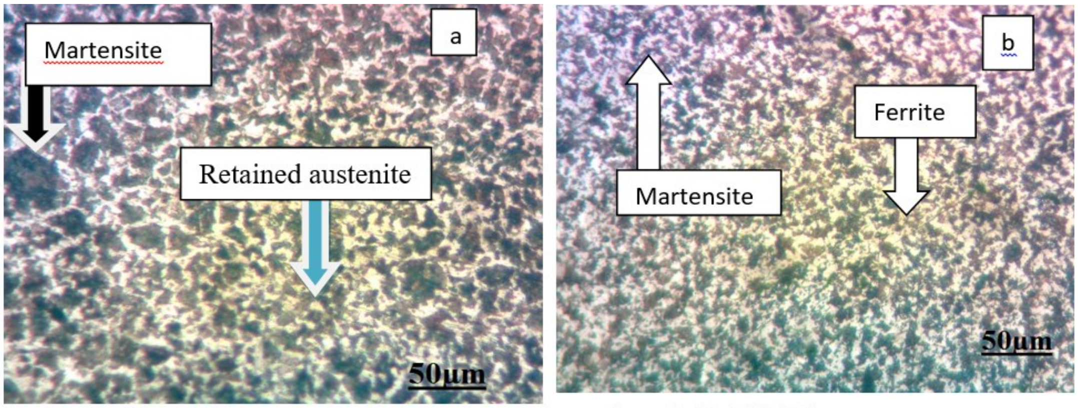
Microstructure of the Sample

Figure 8 (b–d) displays the optical micrographs of AISI 4040 steel that has been normalized and tempered at 450°C. The sample that was tempered at 450°C is seen to contain fine-grained rod-shaped carbide, ferrite, and lath martensite.

The lath martensite changes into ferrite and carbides as the laminarization temperature rise. On the other hand, retained austenite with coarse grains (blue arrow) which is also composed of blocks lath martensite (black arrow) is shown in Figure 8a (control). The change from austenite to martensite occurs in the crystal structure. Comparable amounts of retained austenite were found at laminarization temperatures of 743°C and 761°C. On the other hand, austenite concentration peaked at 779 °C, the highest tested temperature.

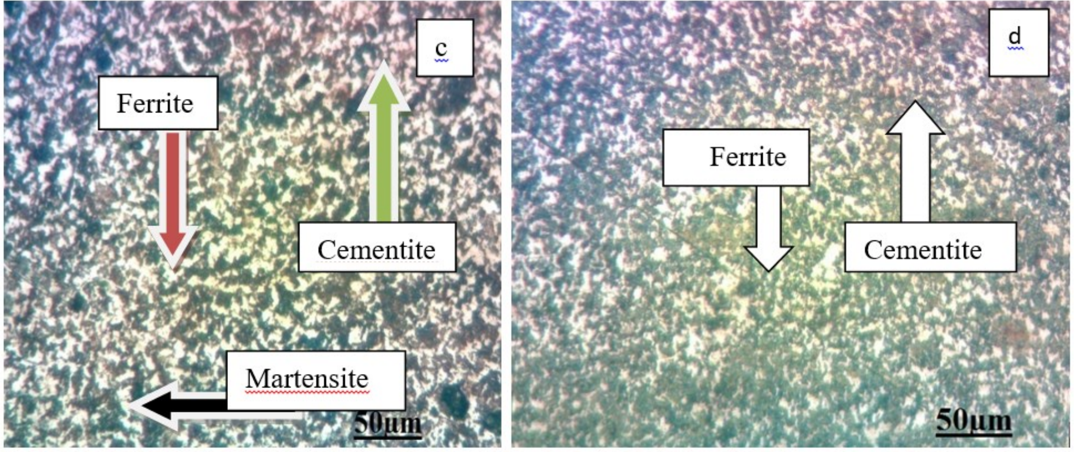
Retained austenite that had cooled from a lower temperature demonstrated increased carbon supersaturation and stability during tensile tests. However, during tensile testing at higher laminarization temperatures, it experienced martensitic transformation to a greater extent due to the transformation-induced plasticity (TRIP) effect, which enhanced its elongation. Therefore, it is possible to increase impact toughness and resistance to cleavage failure by reducing the amount of carbides in the final microstructure. Conversely, the toughness and ductility improved by the fine austenite films that are present in between the ferrite laths. Indeed, austenite films have the ability to blunt cracks. Moreover, at ambient temperature, retained austenite with carbon enrichment is a metastable state (Leiro, 2014). It can change into martensite when subjected to extreme stress.

In general, the development of cementite particles large enough to be clearly visible at intermediate magnification was the end result in all the compositions used. Cementite particles were clearly apparent in all of the steels upon tempering at 450°C. Cementite particles are finely dispersed throughout the ferrite grain in Figure 8b, which is consistent with Unueroh *et al*., (2013) and indicates poor strength and high ductility as well as the inability to be used in load-bearing applications. Larger, less noticeable black spots in Figure 8c likely reflect second phase precipitate with some austenite still present, whereas the white color stands for ferrite. This suggests that the material is strong and ductile, making it suitable for load-bearing applications. With pro-eutectoid ferrite present, Figure 8d displayed a pearlitic structure. A greater portion of the sample composed of martensite, which had a lower retained austenite percentage. Though it contains some spheroidal-shaped carbide precipitate (cementite) and lath martensite and ferrite, the bainite structure depicted in Figure 8b was coarser than that seen in Figure 8c. Martensite laths made up the steel, as seen in Figure 8b, and the interior of the laths exhibits a higher density dislocation



Sample A (Control)

Sample B (743°C)



Sample C (761°C)

Sample D (779°C)

Figure 8: Optical Micrographs of Steel Samples

Conclusion

This research looked at the effect of laminarization temperature on mechanical properties and microstructural evolution of martensitic medium carbon steel developed via thermal cycling treatment. Followings were the conclusions drawn from the findings.

i. Thermal cycling treatment is an effective method for producing high-performance martensitic steel with improved mechanical properties and microstructures

ii. The mechanical properties are influenced by increase in the laminarization temperature. At 779°C, the maximum tensile strength, yield strength, hardness, percent elongation, and elastic modulus of the samples increased to 610.74 MPa, 433.33 MPa, 163.49 BHN , 0.82, and 3334.43 MPa respectively, while the fracture strength and impact strength decreased to 405.70 MPa and 2.73 J/mm^2 respectively. These results suggest an increase in ductility and toughness, which enhanced the performance and formability of the tested steel.

iii. The optical micrographs of the samples tempered at 450°C showed fine- grain size and distribution of carbide, martensite, and ferrite, resulting in an improved mechanical properties.

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