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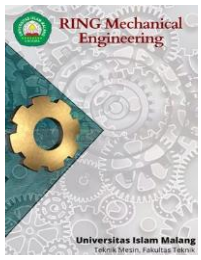

COMPARATIVE ANALYSIS OF THE EFFECTS OF ANNEALING, NORMALIZING, AND HARDENING HEAT TREATMENTS ON THE CHARACTERISTICS OF ST60 STEEL

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ABSTRACT

ST60 steel is widely used in manufacturing applications, including components of agricultural machinery such as shafts, transmission elements, and structural parts that require adequate strength and durability. Heat treatment is a commonly applied process to modify the microstructure and mechanical properties of ST60 steel according to specific engineering requirements. This study aims to comparatively analyze the effects of annealing, normalizing, and hardening heat treatments on the hardness and microstructural characteristics of ST60 steel. The experimental procedure involved heating ST60 steel specimens to the austenitizing temperature, followed by different cooling methods corresponding to each heat treatment process. The treated specimens were subsequently evaluated through Rockwell hardness testing and optical microscopy observations. The results showed that heat treatment significantly influenced the hardness and microstructure of ST60 steel. The highest average hardness was obtained from the hardening process, reaching 87.4 HRC, due to the formation of a predominantly martensitic microstructure during rapid cooling. The normalizing process produced an average hardness of 53.9 HRC and was characterized by the formation of fine pearlite, providing a balance between strength and toughness. Meanwhile, the annealing process yielded the lowest average hardness of 29.5 HRC, associated with the development of coarse pearlite, which enhanced ductility and machinability. Microstructural analysis confirmed a strong relationship between cooling rate, phase transformation, and hardness variation. These findings demonstrate that the selection of an appropriate heat treatment method is crucial for tailoring the properties of ST60 steel to meet the performance requirements of agricultural machinery and other industrial applications.

Keywords: ST60 Steel, Heat Treatment, Microstructure, Hardness

INTRODUCTION

Steel remains one of the most widely used engineering materials in manufacturing industries due to its favorable combination of strength, toughness, machinability, and economic value [1]. Among various grades of carbon steel, ST60 steel is commonly utilized in the fabrication of mechanical components that require moderate to high strength [2]. In the agricultural sector, ST60 steel is frequently employed in the production of shafts, transmission components, rotary tiller parts, machine frames, and other structural elements of agricultural machinery [3], [4]. These components are continuously subjected to mechanical loads, impact forces, friction, and cyclic stresses during operation, making their mechanical properties critical for ensuring reliability and service life [5].

The performance of agricultural machinery components is strongly influenced by the microstructure of the material [6]. Components such as drive shafts and transmission systems require adequate hardness and wear resistance to withstand prolonged operation, while maintaining sufficient toughness to prevent premature failure [7]. However, the as-received condition of ST60 steel may not always provide the optimal balance between hardness, strength, ductility, and machinability required for specific agricultural applications. Therefore, heat treatment processes are commonly applied to tailor the properties of the material according to operational requirements [8].

Heat treatment is a thermal process involving controlled heating and cooling cycles to modify the microstructure and mechanical characteristics of metallic materials [9]. Among the most widely applied heat treatment methods are annealing, normalizing, and hardening. Annealing involves slow cooling within the furnace, promoting the formation of coarse pearlite and improving ductility and machinability [10]. Normalizing utilizes air cooling after austenitization, resulting in a finer and more uniform microstructure that generally improves strength and toughness [11]. In contrast, hardening employs rapid quenching to produce martensitic structures, significantly increasing hardness and wear resistance [2]. The distinct cooling rates associated with these treatments lead to different phase transformations and consequently different mechanical behaviors.

The effectiveness of a heat treatment process is closely related to the phase transformations that occur during cooling [12]. When steel is heated into the austenitic region, its microstructure becomes unstable upon cooling and transforms into different phases depending on the cooling rate. Slow cooling generally promotes the formation of coarse pearlite, while moderate cooling rates lead to finer pearlitic structures [13]. Rapid cooling, on the other hand, suppresses diffusion-controlled transformations and encourages the formation of martensite, a supersaturated phase characterized by high hardness and strength. Consequently, controlling the cooling rate is one of the most important factors in determining the final properties of steel components [14].

In agricultural machinery applications, the selection of an appropriate heat treatment process is particularly important because different components operate under different service conditions [15]. Components such as machine frames and supporting structures primarily require good toughness and machinability, whereas shafts, gears, rotary tiller blades, and transmission elements demand higher hardness and wear resistance due to continuous contact, friction, and repetitive loading during field operations. Improper material properties may result in excessive wear, dimensional instability, or premature component failure, leading to increased maintenance costs and reduced operational efficiency. Therefore, understanding the relationship between heat treatment parameters, microstructural evolution, and mechanical properties is essential for improving the performance and durability of agricultural machinery components [16].

Furthermore, the growing demand for efficient and reliable agricultural equipment has increased the need for materials with optimized mechanical characteristics [17]. Heat treatment offers a practical and cost-effective approach to enhancing the performance of existing steel materials without altering their chemical composition. By modifying the microstructure through controlled thermal cycles, manufacturers can tailor the properties of ST60 steel to meet specific engineering requirements [18]. Such optimization is particularly beneficial for agricultural machinery, where components are often exposed to harsh environmental conditions, fluctuating loads, and abrasive operating environments.

Numerous studies have reported the influence of heat treatment on the properties of carbon steels. However, comparative investigations specifically focusing on ST60 steel remain relatively limited, particularly in relation to applications involving agricultural machinery components. A comprehensive understanding of how different heat treatment methods affect hardness and microstructural evolution is essential for selecting the most suitable treatment process based on the intended service conditions. Therefore, this study aims to comparatively analyze the effects of annealing, normalizing, and hardening heat treatments on the hardness and microstructural characteristics of ST60 steel.

METHOD

1. Research Design

This study employed an experimental method to investigate the effects of different heat treatment processes on the hardness and microstructural characteristics of ST60 steel [19]. Three heat treatment methods, which were annealing, normalizing, and hardening, were applied to compare the resulting mechanical and metallurgical properties [2]. The independent variable was the heat treatment method, while the dependent variables were hardness and microstructure. The research flowchart used in this study was presented in Figure 1.

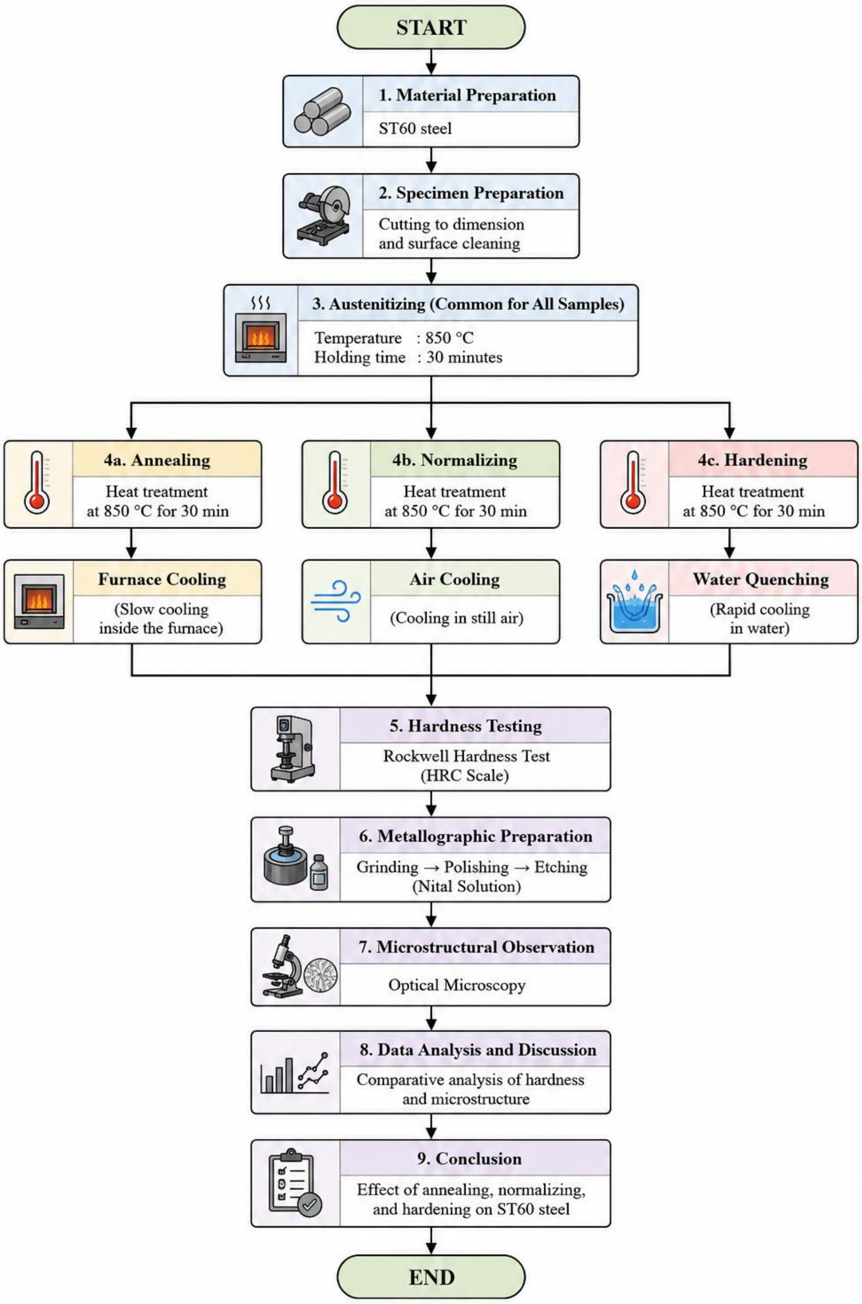


Figure 1. Research Flowchart

2. Material Preparation

The material used in this study was commercially available ST60 steel [20]. The ST60 steel specimens were cut into dimensions suitable for hardness testing and metallographic examination. Prior to heat treatment, all specimen surfaces were cleaned to remove contaminants that could affect heat transfer and the uniformity of the heating process. A total of three specimens were prepared, with one specimen assigned to each heat treatment condition, which were annealing, normalizing, and hardening. The chemical composition of the ST60 steel used in this study is presented in Table 1.

Table 1. Chemical Composition of ST60 Steel

Element	C	Si	Mn	P	S	N	Fe
Content (wt.%)	0.40	0.60	1.70	0.06	0.06	0.01	Balance.

Source: Hidayat et.al, 2020 [21]

3. Heat Treatment Process

The heat treatment process was carried out using an electric furnace. ST60 steel specimens were heated to 850°C and held for 30 minutes to achieve complete austenitization [2]. Subsequently, the specimens were subjected to different cooling methods: furnace cooling for annealing, still-air cooling for normalizing, and water quenching for hardening. The different cooling rates were intended to produce distinct microstructural transformations, allowing the effects of each heat treatment on the hardness and microstructure of ST60 steel to be evaluated. The heat treatment process was presented in Figure 2.

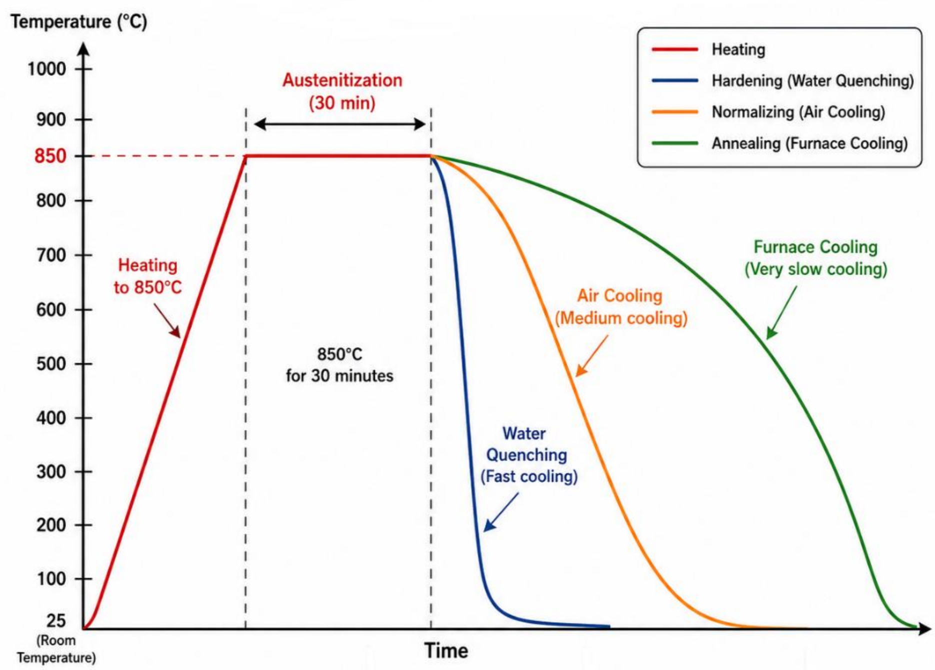


Figure 2. Heat Treatment Process

4. Hardness Testing

The hardness of each specimen was measured using a Rockwell Hardness Tester on the C scale (HRC) in accordance with ASTM E18. The test was conducted using a diamond cone (Brale) indenter, with a minor load of 10 kgf followed by a major load of 150 kgf. Hardness measurements were performed at three different locations on the surface of each specimen to ensure measurement reliability, while maintaining sufficient spacing between indentations and specimen edges. The hardness values obtained from these three measurements were averaged and reported as the representative hardness for each heat treatment condition.

5. Metallographic Testing

Microstructural analysis was performed using optical microscopy. The specimens were prepared through grinding, polishing, and etching using Nital solution. The observed microstructures were identified and compared to determine the phase transformations resulting from each heat treatment process.

6. Data Analysis

The hardness values obtained from each treatment were compared to evaluate the influence of cooling rate on mechanical properties. Microstructural observations were analyzed qualitatively to identify the dominant phases formed after annealing, normalizing, and hardening. The relationship between microstructural evolution and hardness variation was subsequently discussed based on phase transformation theory.

RESULT AND DISCUSSION

1. Hardness Testing Results

The hardness values of the ST60 steel specimens under different heat treatment conditions are presented in Table 2.

Table 2. Hardness Test Results of ST60 Steel

Treatment Condition	Point 1 (HRC)	Point 2 (HRC)	Point 3 (HRC)	Mean (HRC)	Standard Deviation (SD)	Error Bar (SE)
Raw Material	43.83	42.18	52.05	46.02	5.46	3.15
Annealing	27.64	28.08	32.79	29.50	2.84	1.64
Normalizing	49.49	57.57	54.74	53.93	4.17	2.41
Hardening	81.60	91.71	89.03	87.45	4.98	2.87

Information:

- SD (Standard Deviation) represents the variation in hardness values measured at three different locations on a single specimen.
- SE (Standard Error) was used as the error bar in the graph and was calculated using the equation $SE = SD / \sqrt{n}$, where $n = 3$.

The results indicate that the heat treatment process significantly affected the hardness characteristics of ST60 steel [22]. The standard deviation values indicate the variability of hardness measurements taken at three different locations on each specimen. Among the heat treatment conditions, annealing exhibited the lowest standard deviation (2.84 HRC), indicating the most uniform hardness distribution across the specimen surface. In contrast, the raw material showed the highest standard deviation (5.46 HRC), suggesting greater hardness variation. The relatively low standard deviation values obtained for all specimens indicate that the hardness measurements were reasonably consistent and that the heat treatment processes produced fairly uniform hardness distributions. Furthermore, the small standard error values demonstrate that the average hardness values are representative of the measured data and can be used reliably to compare the effects of different heat treatment conditions.

Among all treatment conditions, the highest average hardness was obtained in the hardening specimen, reaching 87.45 HRC, while the lowest hardness was observed in the annealed specimen, with an average value of 29.50 HRC. The normalized specimen exhibited an intermediate hardness value of 53.93 HRC. The hardness of the raw material was measured at 86.75 HRC, which was slightly lower than that of the hardened specimen.

The annealing treatment reduced the hardness of ST60 steel by approximately 66% compared to the raw material condition. This reduction can be attributed to the slow cooling process inside the furnace, which allowed sufficient time for carbon diffusion and the formation of a coarse pearlitic microstructure. The resulting microstructure contained larger pearlite colonies with lower resistance to plastic deformation, leading to improved ductility and machinability but reduced hardness [10].

In contrast, the normalizing treatment increased the hardness compared to the annealed condition while remaining lower than that of the hardened specimen. The average hardness of 53.93 HRC indicates that air cooling produced a finer microstructure than furnace cooling. The relatively faster cooling rate promoted the formation of fine pearlite, resulting in improved strength and hardness while maintaining adequate toughness. Consequently, normalizing provides a balanced combination of mechanical properties suitable for components subjected to moderate loading conditions [11].

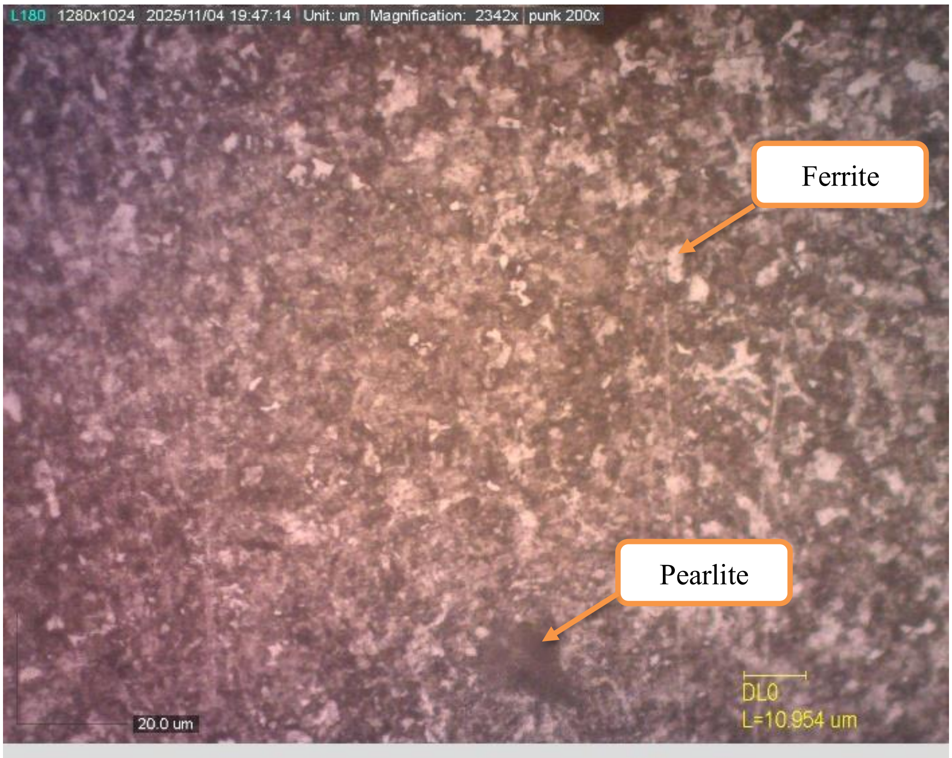
The highest hardness was obtained after the hardening treatment. Rapid cooling through water quenching suppressed diffusion-controlled phase transformations and promoted the formation of martensite. Martensite is characterized by a highly distorted crystal structure and high dislocation density, which significantly increases resistance to indentation. As a result, the hardness increased to 87.45 HRC, representing the highest value among all heat-treated specimens. This characteristic is advantageous for agricultural machinery components that require high wear resistance, such as shafts, transmission elements, and rotary tiller components [23].

The comparison of hardness values demonstrates a clear relationship between cooling rate and mechanical properties. Slower cooling rates produced lower hardness values, whereas faster cooling rates resulted in higher hardness. This trend confirms that the selection of an appropriate heat treatment process can effectively tailor the hardness of ST60 steel according to specific engineering requirements. Annealing is suitable when improved machinability and ductility are required, normalizing provides a balance between strength and toughness, and hardening is preferred when maximum hardness and wear resistance are desired.

2. Microstructural Characterization of ST60 Steel

The variation in hardness observed among the specimens is closely related to the microstructural transformations occurring during cooling [24]. The annealed specimen exhibited the lowest hardness due to the formation of coarse pearlite, which contains relatively large lamellar spacing and therefore offers lower resistance to deformation. The normalized specimen developed a fine pearlitic structure with smaller interlamellar spacing, resulting in higher hardness than the annealed condition. Meanwhile, the hardened specimen was dominated by martensite, a supersaturated phase formed during rapid quenching, which is responsible for the substantial increase in hardness.

These findings demonstrate that the microstructural evolution induced by different heat treatment processes plays a crucial role in determining the mechanical performance of ST60 steel. The observed hardness trend is consistent with the expected sequence of microstructures, namely coarse pearlite (annealing), fine pearlite (normalizing), and martensite (hardening), confirming the effectiveness of the applied heat treatment procedures [25].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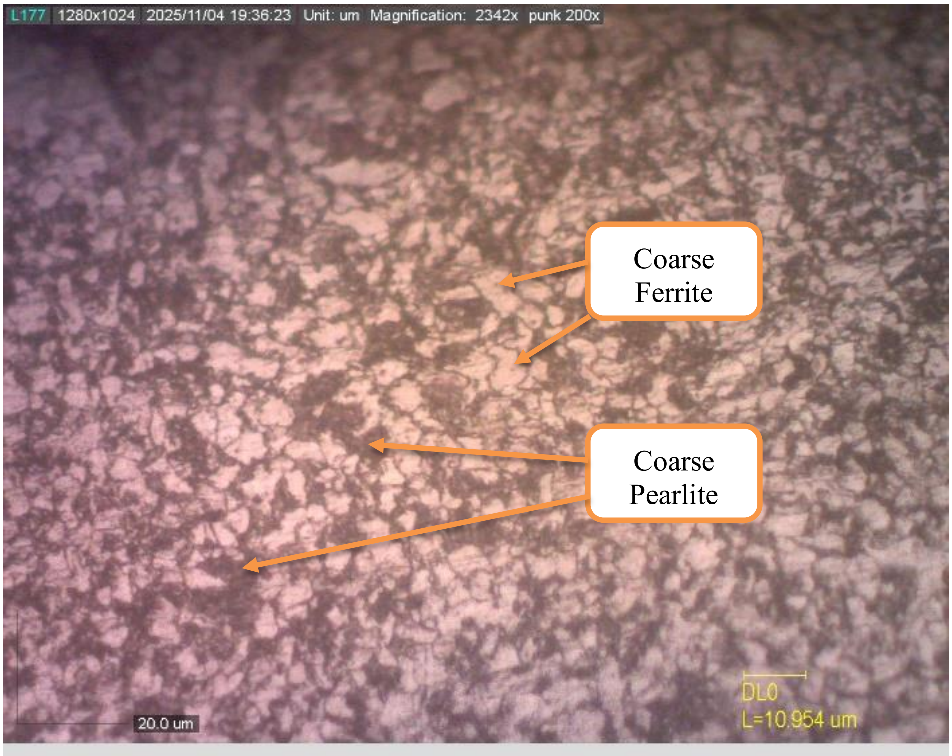
(a)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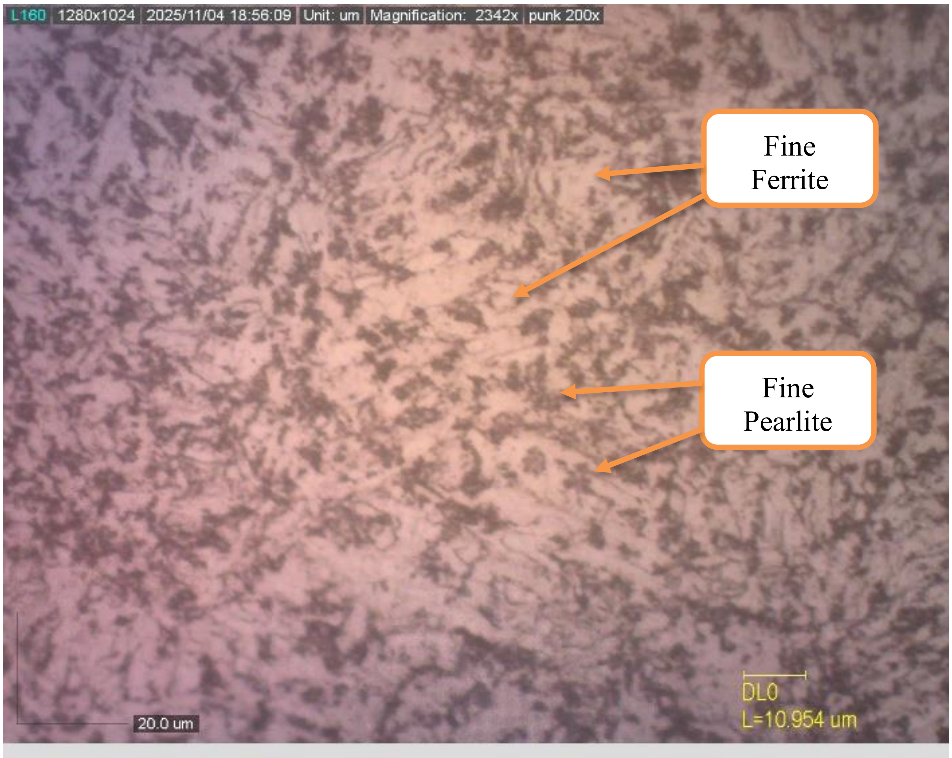
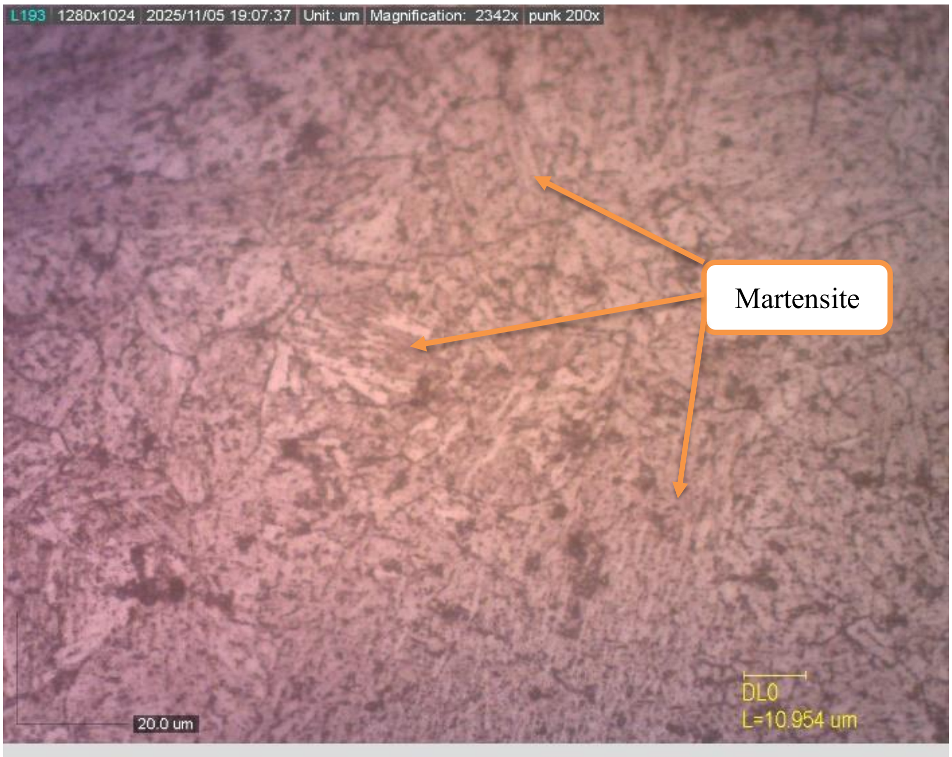
(b)



(c)



(d)

Figure 3. Microstructures of ST60 Steel at 200× Magnification (a) Raw Material; (b) Annealing; (c) Normalizing; (d) Hardening

Figure 3(a) shows the microstructure of the raw material, which is predominantly composed of a relatively uniform distribution of ferrite and pearlite. The light regions represent the ferrite phase, while the dark regions correspond to pearlite colonies. The grain size appears relatively fine, and the considerable amount of pearlite contributes to the material’s relatively high strength and hardness. The average hardness value of the raw material, 86.75 HRC, indicates that the initial material already possessed a relatively hard microstructure, possibly resulting from previous manufacturing processes such as rolling or thermomechanical treatment [26].

During the annealing treatment, the specimen was heated to 850°C, allowing the formation of the austenite phase, and was subsequently cooled very slowly inside the furnace. The slow cooling rate provided sufficient time for carbon atoms to diffuse and form an equilibrium microstructure. The microstructure shown in Figure 3(b) is characterized by the predominance of ferrite and coarse pearlite, with larger grain sizes compared to the raw material. The pearlite formed exhibits wider interlamellar spacing due to the extremely slow cooling rate. This condition resulted in a significant decrease in hardness to 29.50 HRC. The reduction in hardness can be attributed to grain growth, increased pearlite lamellar spacing, and reduced resistance to dislocation movement. Consequently, the annealing process produced a softer and more ductile material than the initial condition [27].

During the normalizing process, the steel was heated to 850°C and then cooled in still air. The cooling rate was faster than that of annealing, resulting in the transformation of austenite into a finer microstructure. Figure 3(c) shows a ferrite and fine pearlite microstructure with smaller grain sizes and a more uniform distribution compared to the annealed specimen. The pearlite formed is more compact due to the shorter time available for carbon diffusion. This condition produced an average hardness of 53.93 HRC, which is higher than that of the annealed specimen but still lower than that of the raw material and hardened specimen. The increase in hardness compared to annealing is attributed to the reduced pearlite interlamellar spacing, finer grain size, and the greater number of grain boundaries that impede dislocation movement [28].

According to the experimental procedure, the hardening process was carried out using water cooling. As shown in Figure 3(d), the resulting microstructure is denser and finer than those observed in both the annealed and normalized conditions. This microstructure likely consists of very fine pearlite, bainite, or partially formed martensite, depending on the carbon content and the actual cooling rate achieved. The average hardness value of 87.45 HRC was the highest among all treatment conditions and was slightly higher than that of the raw material. This increase in hardness is attributed to the formation of a finer and denser microstructure, the possible presence of bainite or partial martensite phases with inherently high hardness, and the increased resistance to plastic deformation [29]. These results indicate that the cooling rate has a significant influence on the microstructure and mechanical properties of ST60 steel. Slower cooling rates promote the formation of coarser microstructures, leading to lower hardness values. Conversely, faster cooling rates produce finer microstructures and enhance the hardness of the material.

CONCLUSION

Heat treatment at 850°C for 30 minutes successfully modified the microstructure and hardness of ST60 steel. Annealing produced a coarse ferrite–pearlite microstructure with the lowest hardness value of 29.50 HRC, while normalizing generated a finer ferrite–pearlite structure with an intermediate hardness value of 53.93 HRC. Hardening resulted in the finest microstructure and the highest hardness value of 87.45 HRC. These results confirm that increasing the cooling rate refines the microstructure and increases material hardness. For agricultural machinery applications, hardened ST60 steel is suitable for wear-resistant components such as plowshares and tillage blades, normalized steel is appropriate for structural parts requiring balanced strength and toughness, and annealed steel is advantageous for components requiring good machinability and formability. The findings provide practical guidance for selecting heat treatment processes according to component functions and contribute to the understanding of the relationship between cooling rate, microstructural evolution, and hardness of ST60 steel for agricultural machinery material development.

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