Study on Microstructural and Hardness Changes in Medium Carbon Steel with Heat Treatment at Austenizing Temperature

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Abstract. Heat treatment is an important method in materials engineering to improve the mechanical properties and wear resistance of medium carbon steel, especially in engineering applications that experience high friction. This study aims to examine the effect of heat treatment temperature variations on the surface hardness and wear resistance of medium carbon steel. The procedures involved heat treatment with adjustments to the austenitization temperature, succeeded by quick cooling. Vickers hardness testing, wear trace analysis, and optical microscopy were also employed. The findings indicate that a higher treatment temperature leads to a greater presence of the martensite phase. This, in turn, increases the hardness to 310.5 HV and enhances wear resistance, as evidenced by wear marks that are both narrower and smoother. There is a strong negative correlation between hardness and wear volume, where higher hardness results in lower wear rates. The microstructure formed at high temperatures is more stable and resistant to deformation due to friction, making heat treatment temperature control a key factor in optimising steel surface performance for engineering applications requiring high wear resistance.

1 Introduction

Heat treatment is the controlled process of heating and cooling materials to alter their mechanical properties and enhance their strength. This technique is especially crucial after high-stress operations such as welding and forging, where the integrity of the material must be preserved or improved. By carefully managing temperature cycles, engineers can tailor the performance of metals to meet specific functional requirements [1].

The mechanical properties of steel are closely linked to its microstructure, which is significantly influenced by heat treatment [2][3]. Through this process, steel can achieve

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a desirable balance of hardness, tensile strength, and ductility [4]. These characteristics are essential for ensuring that the material performs reliably under various service conditions, particularly in demanding industrial applications.

Material modification through heat treatment serves to optimize the behavior of steel in beneficial ways. Techniques such as stress relieving and cryogenic treatment are employed to extend the service life of components and enhance specific properties [5]. These treatments are not only about improving strength but also about achieving other desirable traits like wear resistance, toughness, and dimensional stability [6].

Heat treatment processes are generally categorized into three main types. Thermal treatments include softening methods like annealing and normalizing, as well as hardening methods such as quenching and tempering. Thermochemical processes involve altering the chemical composition of the surface through carburizing, nitriding, or boronizing. Thermomechanical treatments combine mechanical working with thermal cycles to refine microstructure and improve performance [7].

Heat treatment has not been fully optimized in many industrial applications, especially when steel comes from scrap that has significant compositional variations, requiring special treatment strategies to maintain consistent mechanical properties. Previous research has shown that heat treatment parameters greatly affect the hardness and microstructure of S45C steel; optimization of the arc quenching process can even increase hardness to 453 HV and produce a hardened zone of up to 2500 μm. In addition, other studies confirm that tempering significantly affects grain size and hardness, improving the stability of the material structure. These findings underscore the need for a more precise heat treatment approach [8][9].

This study aims to specifically reveal how temperature variations in heat treatment affect changes in the mechanical properties and microstructural evolution of medium carbon steel, particularly S45C. Unlike previous studies, which generally used a generic approach, this study emphasises detailed analysis of the response of scrap material with an uneven composition. This focus provides novelty by examining the need for heat treatment optimisation based on material variability, thereby producing improvements in hardness, wear resistance, and microstructural stability that are more consistent with the needs of the automotive and manufacturing sectors, which demand high material performance.

2 Method

Material consisting of low-carbon steel with an average chemical composition of 0.18% C; 0.60% Mn; 0.25% Si; 0.04% P; and 0.05% S. This steel was chosen because of its representative properties of low-carbon steel widely used in the automotive and light construction industries. Sample preparation using sandpaper of various sizes and Autosol polish to produce a smooth surface. Furthermore, heat treatment was carried out using a furnace with varying heat treatment temperatures, namely 700 °C, 750 °C, and 800 °C for 15 min (**Fig. 1**), using water as the cooling medium.

To evaluate the effect of each on mechanical properties and microstructure. Hardness testing was carried out using a Vickers hardness testing machine, which provided quantitative data on the surface hardness of the material after heat treatment. Next, wear resistance testing was carried out. For microstructure analysis, an optical metallographic microscope was used, which allowed detailed observation of phase changes and micrograins on the steel surface.

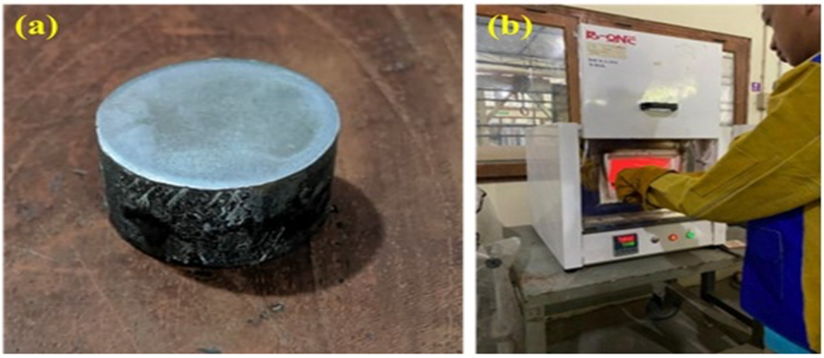

Fig. 1. (a) Medium carbon steel specimen, (b) Heat treatment process.

3 Results and discussion

3.1 Mechanical properties

Hardness testing using the Vickers method was conducted to determine the effect of austenitization temperature variations on the hardness of medium carbon steel. **Table 1** shows that at temperatures of 700°C and 750°C, the hardness values were the same at 215.3 HV. However, there was a significant increase at 800°C, where the hardness value reached 310.53 HV.

Table 1. Specimen hardness after heat treatment

Temperature (°C)	Hardness (HV)
700	215.3
750	215.3
800	310.5

This condition indicates that the austenitization temperature has a significant effect on the formation of a harder microstructure. At temperatures of 700°C and 750°C, it is possible that the steel has not completely undergone a phase transformation into austenite evenly, so that the cooling results do not produce a dominant martensite structure. This results in a relatively low hardness value and no significant change between the two temperatures.

In contrast, at 800°C, the steel is likely to have reached the optimum austenitizing temperature shown in **Fig. 2**, in which the phase transformation to austenite occurs completely. When rapidly cooled (quenched), a more dominant martensite structure is formed, which is known to have high hardness. This is what causes the drastic increase in hardness values at that temperature.

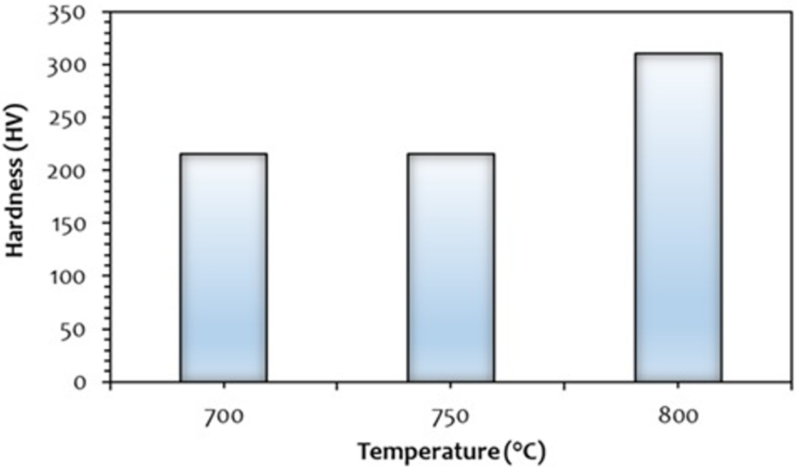

Fig. 2. Hardness values of specimens after heat treatment

This increase in hardness also indicates that higher austenitizing temperatures can increase the strength of the material, but this must be balanced against other properties such as ductility and toughness. If the temperature is too high, there is also a risk of grain growth and a reduction in other mechanical properties. The 800°C temperature proved to yield the best hardness results within the tested temperature range, making it the optimal candidate for applications requiring high surface strength.

3.2 Microstructure

Fig. 3 presents microstructural observations of medium carbon steel after heat treatment at 700°C, 750°C, and 800°C, highlighting clear changes in phase distribution and grain morphology. At 700°C, the microstructure is dominated by ferrite with a small amount of pearlite, indicating that the austenite transformation has not yet occurred completely. This results in a cooling process that does not produce a dominant martensite phase, leaving the structure relatively soft and homogeneous. When the temperature is increased to 750°C, the volume of the austenite phase increases, and after rapid cooling (quenching), a combination of ferrite and martensite is formed. This structure is known as dual-phase, which provides a balance between strength and toughness.

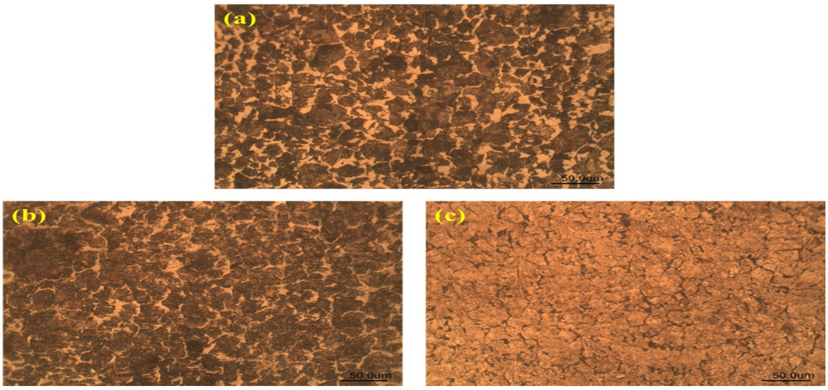

Fig. 3. Microstructure of specimens after heat treatment at: (a) 700 °C, (b) 750 °C, and (c) 800 °C.

At 800°C, the austenite transformation is almost complete, so that after cooling, most of the structure is transformed into martensite. Martensite has high hardness and appears as dark, fine areas on the micrograph, indicating a significant improvement in mechanical properties, particularly strength and hardness. This change is consistent with the phase transformation theory in low-carbon steel, where higher austenitization temperatures result in a larger volume of austenite and more dominant martensite after cooling. However, it should be noted that excessively high temperatures also risk causing excessive grain growth, which can reduce the ductility and toughness of the material. Therefore, selecting the appropriate austenizing temperature is key to optimising the mechanical properties of medium-carbon steel.

3.3 Wear resistance

Fig. 4 shows that the effect of temperature on wear in medium carbon steel is closely related to changes in microstructure that occur during the heat treatment process. Based on the analysis of wear scar micrographs and surface hardness measurements, it can be inferred that increasing the heat treatment temperature enhances the material’s hardness, which in turn leads to improved wear resistance.

The microstructure formed at low temperatures (700°C) tends to consist of ferrite and pearlite phases, which have relatively low hardness. This causes the material surface to undergo plastic deformation and abrasion more easily when subjected to friction, resulting in wider and deeper wear marks. Conversely, at high temperatures (up to 800°C), a harder and denser martensitic structure is formed, making the material surface more resistant to friction and showing narrower and smoother wear marks.

Fig. 5 shows wear on medium carbon steel specimens that have undergone heat treatment at temperatures of 700°C, 750°C, and 800°C. Wear resistance increases (wear volume decreases) as the heat treatment temperature rises.

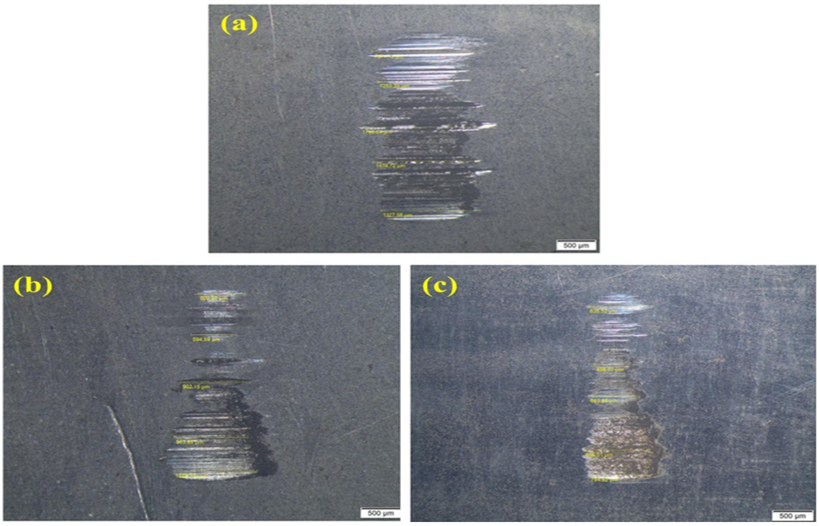

Fig. 4. Microstructure of wear marks on specimens after heat treatment at (a) 700°C, (b) 750°C, and (c) 800°C with water cooling.

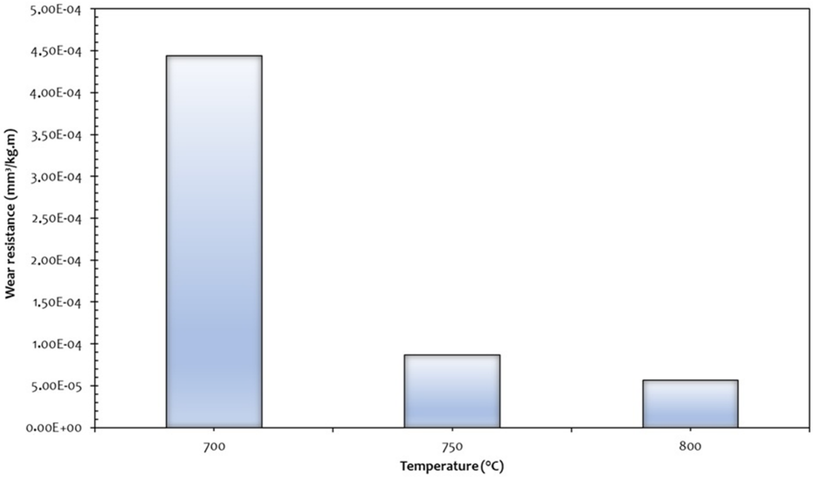

Fig. 5. Wear resistance of specimens after heat treatment with water cooling

The increase in heat treatment temperature causes the formation of harder microstructures, such as martensite, which directly increases the hardness value of the material. Higher hardness makes the material surface more resistant to plastic deformation and friction, resulting in less wear. Conversely, at lower temperatures, the microstructure formed tends to be softer (such as pearlite or ferrite), resulting in decreased hardness and increased wear.

Accordingly, there is a negative correlation between hardness and wear: the higher the hardness of the material, the lower the wear rate. This correlation is important in engineering applications, particularly for components operating in high-friction environments, where increasing hardness through heat treatment can significantly extend the service life of the material.

3.4 Discussion

Variations in austenitization temperature cause significant changes in mechanical properties due to phase transformation mechanisms that are highly influenced by thermal energy. At 700°C and 750°C, the heat energy supplied is insufficient to allow carbon to diffuse evenly into the austenite FCC lattice, so the transformation does not occur completely. As a result, the final structure is still dominated by ferrite–pearlite with low dislocation resistance, so that hardness does not increase significantly [10]. This phenomenon is consistent with the finding that materials that do not reach optimal austenitization conditions are unable to form martensite effectively during rapid cooling. Conversely, at 800°C, the heat energy is sufficient to allow austenite homogenisation, so that rapid cooling can produce martensite in large fractions. This explains the surge in hardness also observed in arc-quenching studies, where optimal heating parameters increase hardness to 379–453 HV [8].

The microstructural changes observed at each temperature can also be explained by the dynamics of carbon diffusion and transformation kinetics. At low temperatures, ferrite and pearlite form due to the low rate of carbon diffusion, limiting the transformation to martensite after quenching. As the temperature rises to 750°C, some austenite forms, resulting in a dual-phase microstructure that offers a balance between strength and toughness. At 800°C, the increase in austenite volume allows for the formation of finer and denser martensite, as also noted in the S45C microstructure transformation study, which shows a correlation between high temperature, fine martensite grains, and increased strength and mechanical stability of the material [11].

The phenomenon of increased wear resistance with increasing austenitization temperature can be explained by the influence of martensite as a very hard phase. Martensitic surfaces have high dislocation density, which inhibits the initiation of plastic deformation during friction contact. At low temperatures, ferrite–pearlite is susceptible to micro-penetration and abrasion, resulting in greater wear marks [12]. Wear studies on S45C show that martensite strengthening due to heat treatment directly reduces wear volume and increases component service life [13]. In addition, the principle of tribology states that an increase in hardness is inversely proportional to the wear rate, and this is also confirmed by research on medium carbon steel heat treatment, which reports a linear relationship between the martensite fraction and abrasion resistance [14][15]. Thus, a temperature of 800°C offers optimal conditions where a balance between hardness, microstructure, and wear resistance is achieved without posing a significant risk of reduced ductility due to excessive grain growth.

4 Conclusion

Heat treatment with varying temperatures has a significant effect on the mechanical properties and wear resistance of medium carbon steel. The higher the treatment temperature, the greater the formation of martensite phase, which increases the surface hardness of the material to 310.5 HV. High hardness contributes directly to increased wear resistance, as indicated by narrower and smoother wear marks. There is a strong negative correlation between hardness and wear volume. The higher the hardness, the lower the wear rate. The microstructure formed at high temperatures is more stable and resistant to deformation due to friction. Therefore, heat treatment temperature control is a major factor in optimising the surface performance of steel for engineering applications that require high wear resistance.

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