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The Influence of Cooling Techniques on the Performance of Pack Carburized Low Carbon Steel Using Cypress Charcoal

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Abstract – This study investigated the impact of different cooling media on the hardness and wear characteristics of low-carbon steel after pack carburizing using cypress charcoal. This research method involves conducting an experimental process known as pack carburizing. It utilizes cypress charcoal as an energizer and sodium carbonate as a catalyst for heat treatment. The cypress charcoal and sodium carbonate volumes comprise 90% ACR and 10% $NaCO_3$. The mixture is heated in a furnace at a temperature of 925 °C for 3 hours and then cooled using different media, including air, SAE 20 oil, salt water, and water. Material testing uses mechanical tests, specifically hardness and wear tests. According to the study findings, the hardness value exhibited a noticeable rise, reaching a peak of 277.694 HV in the air-cooling medium. In contrast, the lowest value of 198.417 HV was observed in the same medium. Additionally, the wear rate is influenced by the cooling medium. The wear rate is highest at 0.0657 grams/sec in air cooling media, while it is lowest at 0.0347 grams/sec in air cooling media. This indicates that the hardness value and wear rate value are inversely related. In other words, materials with higher hardness have smaller wear rates, and vice versa. The variation in cooling rates is primarily due to the differences in viscosity among the cooling media.

Keywords: Cypress charcoal, pack carburizing, sodium carbonate, wear rate, cooling media

Introduction

Low-carbon steel is extensively utilized in several industrial applications for its cost-effectiveness and acceptable mechanical features. Low-carbon steel components and structures undergo fatigue from surface wear owing to alternating tension and bending stress, as well as hardness, ductility, and toughness. (Brnic *et al.*, 2023). These pressures can cause cracks and component failure under cyclic loads. Multiple surface hardening operations must be performed on components to address these concerns. Carbonization (carburizing) increases surface hardness. Carbon is added to the steel's surface layer to increase hardness and wear resistance. (Xiao *et al.*, 2020). High-frequency current induction utilizes electromagnetic fields to rapidly heat the surface, while flame hardening employs a direct flame to both heat and cool the material. A hardened surface layer that resists wear and fatigue can significantly extend the fatigue life of low-carbon steel components.

Steel carbon content affects surface hardening efficacy. Carbon steel is mostly an iron-carbon alloy with tiny quantities of sulfur, phosphorus, silicon, and manganese (Bhardwaj, 2014). These extra components can alter steel characteristics and heat treatment. Silicon increases steel hardness, while manganese increases its hardenability and strength (Harsha *et al.*, 2023). Surface hardening is often achieved through carbonization. Carbon atoms penetrate the steel surface layer during carbonization in a carbon-rich environment at high temperatures. A carbon-enriched surface generates a rigid martensitic structure when quenched. Adjusting process parameters, including temperature, time, and carbon source composition, controls the depth of the hardened layer and the distribution of carbon. Carburizing can be done in pack, gas, or liquid form (Hosseini and Li, 2016). Heat is used in a carbonaceous container with steel to pack carburize it. Gas carburizing employs methane or carbon monoxide to produce the same result, while liquid carburizing immerses steel in a molten carbon-rich solution (Wani and Kumar, 2020).

Pack carburizing hardens a workpiece by adding carbon to its surface to increase wear resistance. (Dai *et al.*, 2022). Coconut shell charcoal, coke charcoal, wood charcoal, leather charcoal, and bone charcoal are used in this method. (Adedipe *et al.*, 2023). Carbon diffusion during carburizing comes from these carbonaceous compounds. Pack carburizing involves placing the workpiece in a sealed box with the desired carburizing media. (Bontong *et al.*, 2024). Carburizing media—selected charcoal powder—provides carbon. The workpiece is thoroughly covered in carburizing material to achieve homogeneous carbon diffusion. Many workpieces are stacked in the box and separated by carburizing material to achieve uniform carbon distribution. The carburizing box is heated in a furnace to 850°C to 950°C when the workpiece is suitably positioned and covered. (Sutresman *et al.*, 2023). The workpiece's surface layer absorbs carbon from the carburizing material at these high temperatures. (Abdulrazzaq, 2016). Carbon penetration and hardened layer thickness depend on the heating procedure, which can take hours.

Choosing the right carburizing medium is crucial for obtaining the best possible outcomes in pack carburizing. (Parrish, 1999). Charcoal made from fir wood is known for its high carbon content and eco-friendly properties, making it a reliable carburizing agent. Nevertheless, the cooling phase following carburizing is of significant importance, as it plays a crucial role in determining the treated steel's ultimate microstructure and mechanical properties. The performance and longevity of steel components depend on the varying degrees of hardness, toughness, and wear resistance achieved through different cooling techniques. (Chinchanikar and Choudhury, 2015). A recent study has investigated the pack carburizing process, examining the selection of carburizing media, refining process parameters, and exploring post-carburizing treatments. Research has indicated that the choice of carbonaceous material utilized in pack carburizing can substantially impact the carbon diffusion rate and the resulting case depth. (Ramezani *et al.*, 2015). For example, it has been reported that Cypress charcoal can create a consistent carbon-rich layer, which improves the hardness and wear resistance of low-carbon steel.

The cooling technique used after carburizing is crucial in determining the ultimate properties of the steel. (Abdulrazzaq, 2016). Various cooling methods, such as water quenching, oil quenching, and air cooling, have distinct effects on the microstructure. (Ding *et al.*, 2018). Water quenching is known for its rapid cooling process, which often leads to the formation of martensite. This phase is characterized by its hardness and brittleness, which significantly enhances the steel's hardness and wear resistance. Oil quenching results in a slower cooling rate than water, which allows for the combination of martensite and bainite. This combination can offer a favorable balance between hardness and toughness. When using air cooling, the process tends to result in the formation of pearlite. This particular structure is known for being less complicated but more ductile compared to martensitic structures.

Multiple studies have emphasized the influence of cooling media on the mechanical properties of carburized steel. As shown in a survey conducted by Abdullah et al. (Abdullah *et al.*, 2022)It was found that water quenching yielded the highest hardness values compared to other cooling methods. On the other hand, oil quenching was found to offer a more favorable balance between hardness and toughness—similarly, Guo et al. (Guo *et al.*, 2023) Discovered that the durability of carburized steel was greatly improved by employing fast cooling methods. Among these techniques, water-quenched samples demonstrated the lowest rates of wear.

Despite these advancements, it is important to understand how various cooling techniques impact the performance of low-carbon steel pack carburized with cypress charcoal. Understanding the relationship between the carburizing medium, cooling rate, and resulting microstructure is an essential subject of study. This study aims to address this gap by conducting a comprehensive analysis of the impact of water quenching, oil quenching, and air cooling on the hardness and wear resistance of pack carburized low-carbon steel using cypress charcoal.

Materials and Methods

The materials utilized in this work are depicted in Figure 1, which visually illustrates the essential components integrated into the pack carburizing process. Each material was carefully selected for its specific function in the trial procedure to achieve the optimal hardness and wear resistance results. The experimental material chosen for the investigation was low-carbon steel (Figure 1a). Industrial applications extensively utilize this specific form of steel, which generally has a carbon content of less than 0.3%, owing to its ductility, machinability, and cost-

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effectiveness. Nevertheless, the comparatively low carbon content of the material limits its surface hardness, making it an appropriate choice for carburizing, a thermal treatment aimed at enhancing its surface characteristics.

The carburizing agent employed in this investigation is cypress charcoal, as shown in Figure 1b. The selection of cypress charcoal was based on its high carbon content and eco-friendly characteristics, rendering it an extremely efficient medium for the pack carburizing reaction. Charcoal serves as the primary carbon source, releasing carbon atoms during thermal treatment at high temperatures. The diffusion of carbon atoms into the surface of the low-carbon steel results in the formation of a carbon-enriched layer that exhibits greater hardness and wear resistance than the core substrate. To improve the effectiveness of the carburizing process, sodium carbonate ($NaCO_3$) was used as an energizer (Figure 1c). An essential function of $NaCO_3$ in this process is to act as a catalyst, facilitating the separation of carbon from the charcoal and promoting its diffusion into the steel surface. The inclusion of $NaCO_3$ expedites the absorption of carbon by reducing the activation energy required for the carburizing process, resulting in a more consistent and reduced case depth within a shorter time.

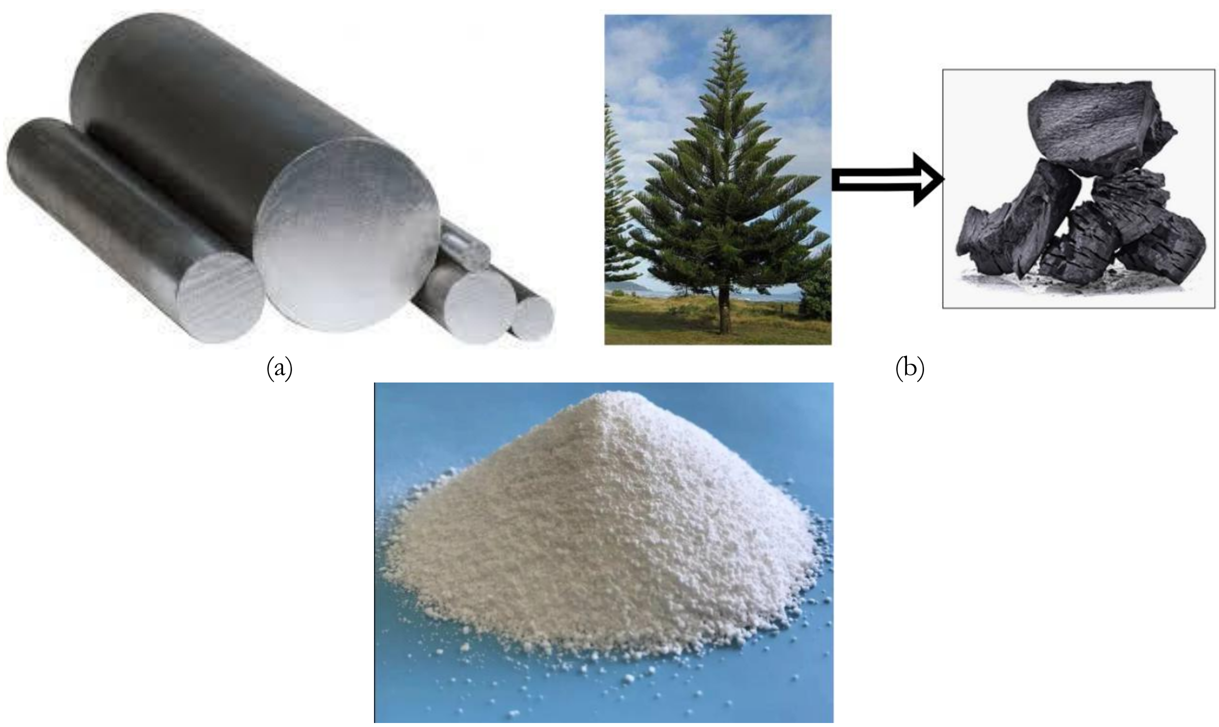
(a) (b) (c)

Figure 1. (a) Low carbon steel, (b) cypress charcoal, and (c) $NaCO_3$

Figure 2 shows the experimental procedure for this research. The research begins with careful selection and procurement of low-carbon steel. Since it is widely used in engineering applications, its cost-effectiveness, mechanical qualities, and ease of manufacture make it a good option for further improvement. With a carbon concentration of less than 0.3%, low-carbon steel is ductile and strong but lacks hardness and wear resistance. By increasing its surface hardness and wear resistance, the carburizing process makes the material more suitable for demanding applications. After buying raw materials, preparing low-carbon steel specimens is necessary. It requires precision measuring and cutting into standardized test samples. To ensure test sample homogeneity, these specimens are meticulously sized and shaped. This standardization reduces size and shape variances that could affect testing results.

The cypress charcoal used in this study was made by hand carbonizing dry cypress wood, which included branches and small trunk sections from cypress trees. The first step in preparing was to select clean, dry wood. Then, the wood was cut into even pieces and left to dry in the air for a few days to remove excess moisture. This step of drying was crucial to ensure that carbonization was adequate and complete, as excessive humidity can slow down the process and compromise the quality of the charcoal. After they were scorched, the pieces of wood were put into a closed metal drum made for making charcoal. The drum didn't allow a lot of oxygen, which allowed pyrolysis to occur without complete combustion. An outside cypress tree was used to heat the drum, which started the carbonization process. This process was watched for 6 to 8 hours. The color of the smoke emanating from the drum indicated the progress of the carbonization. When the smoke changed from thick white to thin blue, it meant that the wood had turned into charcoal.

The drum was sealed entirely after the carbonization process was complete, so that air couldn't get in and ignite the hot charcoal. The contents were then left to cool naturally for approximately 24 hours. After it cooled, the cypress charcoal was removed from the drum and carefully broken into smaller pieces. A mesh size of 30 was used to sieve the charcoal, ensuring it was uniform enough for pack carburizing. To keep the final product clean and dry, it was kept in an airtight container. This method of preparation ensured that the cypress charcoal used in the experiment had particles of uniform size, high carbon content, and the appropriate reactivity for carburizing low-carbon steel.

A pack carburizing technique enriches low-carbon steel with carbon to improve its surface qualities. While maintaining ductility and hardness, this technique hardens the steel's surface. In pack carburizing, cypress charcoal is the primary carbon donor. Cypress charcoal is a steady and regulated carbon source that burns cleanly and reduces contaminants that could damage the steel's surface. While carburizing, cypress charcoal carbon diffuses into the steel, increasing its carbon content and allowing it to harden when cooled. $NaCO_3$, a minor component, is added to the carburizing mixture at a concentration of 10%. It's an energizer, essential to pack carburizing. Through carbon activity, energizers accelerate the carburizing reaction by increasing carbon transfer from charcoal to steel. Heat the specimens to 925°C in a furnace, a crucial carburizing temperature. Austenitizing steel microstructures allows carbon diffusion at this high temperature.

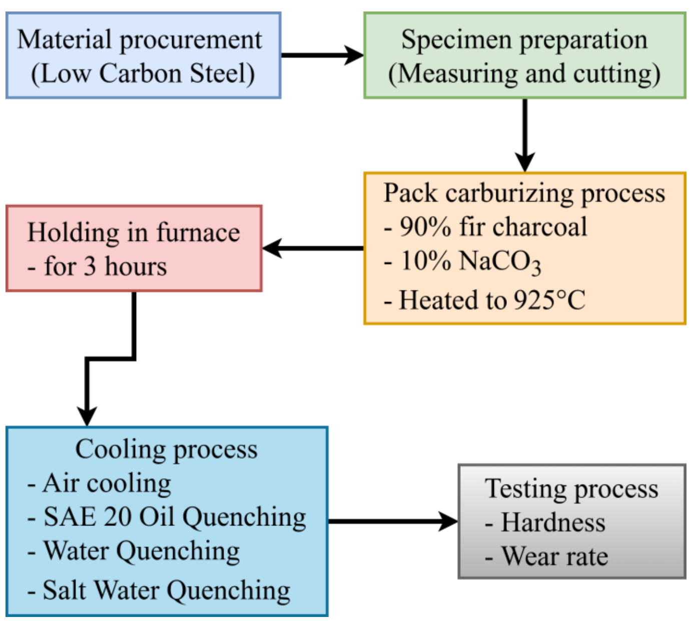

Figure 2. Experimental procedure

The furnace holds the specimens for 3 hours at 925°C for carburizing. The steel's surface must fully absorb and integrate the carbon atoms from the cypress charcoal during this holding period to prepare for carburizing. As carbon atoms diffuse into the austenitic matrix of the steel, they migrate from high carbon concentrations at the surface to lower concentrations deeper within the steel. The 3-hour holding time is calculated based on the desired case depth, the thickness of the carbon-enriched layer, and the specific application requirements. Longer holding times allow carbon to permeate the steel more deeply, thereby thickening the hardened layer. However, excessive carbon penetration can cause brittleness or carbide networks that reduce steel toughness; thus, the process must be carefully regulated.

After carburizing, the specimens are subjected to different cooling processes to study the effects on hardness and wear resistance. The cooling processes include air cooling, SAE 20 oil quenching, water quenching, and saltwater quenching. Finally, the cooled specimens are subjected to a series of tests to evaluate the outcomes of the carburizing and cooling processes. Measuring the surface hardness of the specimens to assess how the different cooling media influenced the hardness of the carburized layer. Determining the wear resistance of the specimens by measuring the wear rate under standardized conditions.

Figure 3. Hardness test specimen

The specimen prepared for hardness testing, a critical procedure in assessing the material's capacity to withstand deformation under an applied force, is seen in Figure 3. The specimen has undergone meticulous preparation to meet the specific criteria of the hardness test, which typically requires a level and polished surface that allows for accurate indentation by the hardness tester. Achieving homogeneity on the surface of the specimen is crucial, as any deviations may result in imprecise measurements, thereby undermining the dependability of the findings. The evaluation of hardness, commonly conducted using techniques such as Vickers, Rockwell, or Brinell, provides a significant understanding of the mechanical characteristics of a material following processes like carburizing and quenching. By quantifying the depth or magnitude of the depression created by the indenter, the hardness value is determined, therefore exposing the impact of various cooling procedures on the material's ability to withstand surface deformation.

Figure 4. Wear resistance test specimen

In comparison, the specimen ready for wear resistance testing is shown in Figure 4. This specimen is designed to evaluate the material's resistance to operational wear and abrasion, which is crucial for components that encounter frictional forces in real-world applications. Specimens are typically subjected to controlled abrasive conditions during wear resistance testing. This means that a standard load is applied to the material surface as it interacts with an abrasive counterpart, like a spinning disc or abrasive paper. Measurements of material loss, typically expressed as weight loss or wear volume, are then used to evaluate the material's wear resistance after a predetermined period or number of cycles. The specimen's shape is meticulously adjusted to ensure reliable and consistent findings across samples, thereby dispersing wear uniformly across the test surface.

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Results

Figure 5 shows the hardness values obtained using different cooling media. This demonstrates the significant impact of the cooling technique on the material's mechanical properties. An initial hardness value of 75.620 HV indicates that the raw material is somewhat pliable. The hardness values significantly increase after carburizing and being treated with different cooling media. This means that carburizing improved the mechanical performance of the steel by creating a harder outer layer by increasing the carbon concentration on its surface. The hardness increased significantly to 197.417 HV when air was used as the cooling medium, outperforming all others. This demonstrates that the retained carbon in the material enables a tougher surface layer to form, even with slow cooling in air. The sluggish cooling rate of air cooling allows for some carbon diffusion and the formation of softer microstructures, such as ferrite and pearlite; therefore, it does not provide the highest hardness values.

With SAE 20 oil as the cooling medium, the hardness reaches 235.983 HV, an even higher rise. Oil quenching prevents austenite from undergoing phase transformations into softer forms by providing a more rapid cooling rate than air. It encourages the production of martensitic structures characterized by their high hardness. In oil quenching, the cooling rate is carefully controlled, which reduces deformation and thermal stresses while significantly increasing hardness. The hardness is further enhanced by saltwater quenching, reaching a value of 266.839 HV. When exposed to salt water, austenite is more efficiently transformed into martensite, which has a faster cooling rate owing to its superior heat extraction capability. Due to its increased heat conductivity and decreased production of vapor bubbles, which could function as insulators, saltwater cools more quickly than ordinary water.

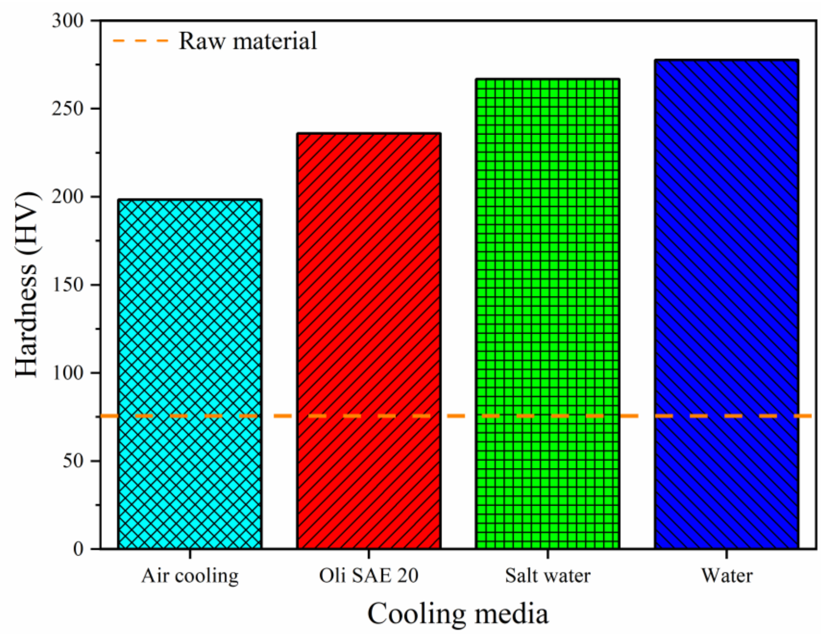

Figure 5. Material hardness at various cooling variations

Quenching in water results in the most excellent hardness value (277.794 HV), suggesting that water offers the most rapid cooling rate compared to the other media examined. A martensitic phase is formed when carbon atoms are trapped within the crystal structure of steel due to the quick quenching process, which hinders their diffusion. While this rapid cooling produces the hardest materials, it also increases the risk of breaking and distortion in some uses due to residual stresses. These results show that the choice of cooling media is critical for the hardness of carburized steel. The microstructure of the steel is affected by the varying rates of cooling. Media that cool the steel more quickly, like water or salt water, create more complex surfaces because martensite

10.13170/aijst.14.1.44224

is formed. On the other hand, microstructures become mixed up with slower cooling rates (as in air and oil), which results in lower hardness values but maybe better toughness.

Figure 6 shows that the wear rate of low-carbon steel is significantly reduced after carburization. The carburizing process adds carbon to the steel surface, causing a dramatic change that makes the material much more complicated and more resistant to wear. Due to its soft microstructure, low-carbon steel is prone to abrasion and surface degradation when subjected to mechanical loads or frictional forces; this method is particularly useful for overcoming these limitations. The initial wear rate of 0.1640 grams per second in the raw material indicates that it requires improvement by carburization and regulated cooling due to its inadequate wear resistance. All specimens treated with various cooling solutions exhibited a significant reduction in wear rates after carburization, indicating that the procedure enhanced surface performance. Specimens chilled in the air showed a marked improvement over the untreated material, with a wear rate drop of 0.0657 g/s. This decrease is because a carbon-enriched surface layer forms, which fortifies the material and makes it more resistant to wear caused by friction.

With SAE 20 oil cooling, the wear rate decreased to 0.0523 g/s, showing that this cooling medium effectively increased the wear resistance of carburized low-carbon steel. Oil quenching, with its modest cooling rate, allows for higher martensite development in the surface microstructure compared to air cooling. Fast cooling of austenite traps carbon atoms within the crystal structure of the steel, forming martensite, a hard and extremely wear-resistant phase. The enhanced hardness and wear resistance in the oil-quenched specimens are directly attributable to the higher martensite composition. Among the many benefits of SAE 20 oil quenching is its compromise between hardness and toughness. Its regulated cooling reduces the likelihood of thermal stresses, cracking, or warping, which are more prevalent with aggressive quenching procedures; nonetheless, it does not reach the severe cooling rates of water or saltwater quenching. For this reason, oil quenching is ideal for gears, shafts, bearings, and other components subject to impact loads and frictional wear. Complementing improved wear resistance with dependable toughness, oil-quenched components deliver optimal performance even in highly dynamic operational environments.

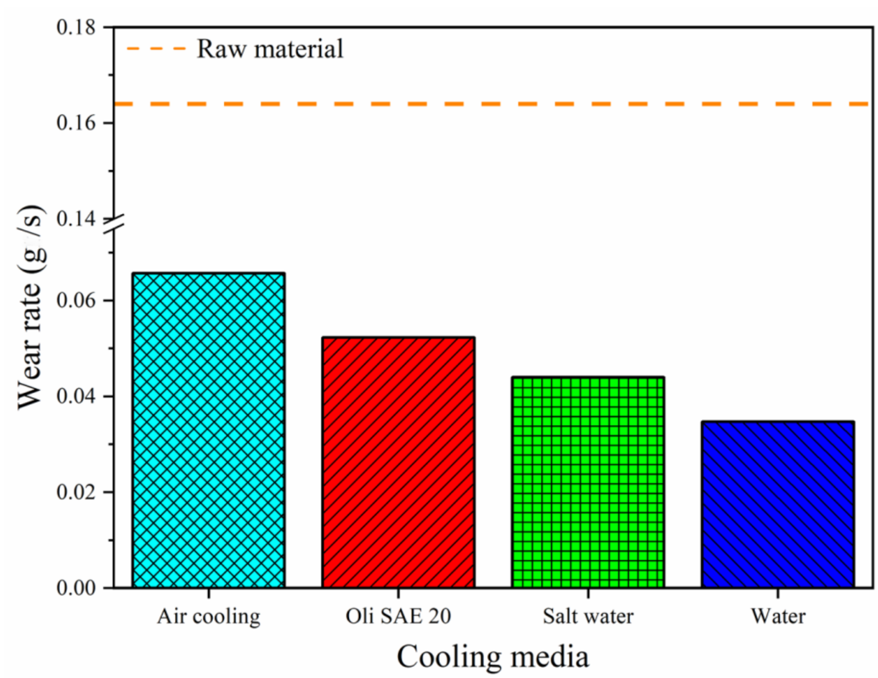

Figure 6. Wear rate at various cooling variations

An additional reduction in the wear rate to 0.0440 g/s is achieved through saltwater quenching, illustrating the impact of a quicker cooling rate on wear resistance. Salt enhances thermal conductivity and dissolves vapor barriers, making water ideal for more efficient heat extraction. With a higher fraction of martensite formed, the surface is more rigid and more wear-resistant than with oil quenching. Elements subjected to intense frictional stresses, such as machine parts, cutting tools, and blades, benefit significantly from the finer and more uniform martensitic structure that may be attained through saltwater quenching. In conclusion, the water quenching approach demonstrated the strongest correlation between cooling rate and wear resistance, with a wear rate of 0.0347 g/s. The fastest way to extract heat, resulting in more martensite forming on the surface, is through water quenching. The production of ferrite or pearlite, which are softer phases, is prevented by this quick cooling rate, which "freezes" the carbon atoms in place. The end product is a very durable surface resistant to wear and tear.

Discussion

The results show that the hardness increases significantly after air cooling compared to the raw material, reaching 197.417 HV. This indicates that the carburization process successfully raises the surface carbon content of the steel, imparting a higher hardness, even when the cooling rate is rather sluggish. The increased mechanical capabilities result from the more rigid surface layer that the retained carbon shapes. However, of all the examined cooling mediums, air cooling did not yield the most favorable results. The austenite phase might partially change into ferrite and pearlite instead of the more rigid martensitic structure brought about by the progressive cooling rate. (Zhao and Palmiere, 2017). As carbon atoms have more opportunity to disperse during slower cooling processes, the possibility of producing a martensitic structure is reduced. Because of this, the material's wear resistance is lower than that of steel quenched in more aggressive media, such as salt water, oil, or water, as it does not reach absolute hardness.

Compared to air cooling, SAE 20 oil quenching considerably increases the hardness of low-carbon steel, reaching 235.983 HV, according to the data. The increased rate is due to the fact that austenite has less time to change into softer phases, such as ferrite and pearlite, because of the oil's rapid cooling rate—the increased hardness results from a structural transition into martensite, a complex and brittle phase. Oil quenching is superior to air cooling in achieving a balance between hardness and dimensional stability. Compared to fast quenching methods like water or saltwater cooling, the controlled cooling rate in oil helps reduce internal strains and distortions. Because of this, oil-quenching is the method of choice for parts that require a high level of hardness while being somewhat challenging and crack-resistant. Previous research has shown that medium-viscosity oils, like SAE 20, offer a good balance between hardness and structural integrity; this conclusion is consistent with the results of oil quenching. (Zordão *et al.*, 2019). In contrast to water quenching and other extreme cooling procedures, oil produces a martensitic microstructure without causing the material to become too brittle.

Saltwater quenching exhibits a markedly higher hardness than air and oil quenching, reaching a hardness value of 266.839 HV. Since salt increases heat dissipation and decreases vapor blanket production, it accelerates the cooling process, thereby enhancing the water's overall quality. Vegetable vapor bubbles can encase steel when cooled in pure water, creating an insulating barrier and delaying the cooling rate. The addition of salt, however, destroys this vapor barrier, increasing the direct contact between the steel and the cooling medium and hastening the austenite–martensite transition. The noticeable improvement in hardness is due to the more thorough and consistent martensitic transition achieved when using salt water, thanks to its superior cooling efficiency. This phenomenon has been extensively studied in metallurgy, where saltwater quenching is acknowledged as a top technique for attaining maximal hardness in ferrous materials. (Zhai *et al.*, 2021). A post-quenching temper is required to alleviate residual stresses and improve toughness, as the fast-cooling rate increases the risk of internal strains and fracture.

Water quenching is the most effective cooling method for generating maximum hardness, as the findings clearly show that it produces the highest hardness value of 277.794 HV. This is because the phase change from austenite to martensite, which is extremely hard, is accelerated by the quick heat extraction from water. (Steeb, 2012). The production of softer phases, such as ferrite and pearlite, is prevented by water quenching, in contrast to slower chilling approaches, by minimizing the time available for carbon diffusion. Water quenching has several downsides, despite increasing hardness. As a result of the intense internal pressures caused by the rapid cooling, the material may crack, warp, or distort. Striking a balance between achieving high hardness and maintaining structural integrity is a common challenge in industrial heat treatment operations. Post-quenching tempering is sometimes required in many applications to prevent the material from becoming too brittle and to alleviate internal tensions. (Graf *et al.*, 2020).

Wear rate reduction in SAE 20 oil-quenched specimens demonstrates how regulated cooling helps refine the material's microstructure. Oil quenching has the opposite effect of air cooling, which speeds up the transformation into pearlite and ferrite, and instead forms a martensite microstructure, which is stronger and more complex than the others. Due to this change, the steel is significantly more resistant to surface erosion caused by friction. The moderate cooling rate of oil quenching is a significant benefit since it helps to reduce brittleness and excessive internal tensions. Although quenching in water or salt water increases the hardness values, it also increases the likelihood of microcracks and distortion caused by fast thermal contraction. (Arma *et al.*, 2023). However, oil provides a regulated heat extraction process, which helps the steel build a fine martensitic structure with just the right amount of hardness and toughness.

Results from saltwater quenching show that quick cooling significantly reduces wear rate, which means wear resistance has been improved. Saltwater quenching offers a more efficient heat extraction process than oil quenching, leading to a more homogeneous and thorough martensitic transformation. The primary benefit of using salt water instead of ordinary water is the prevention of vapor film development. This is when a layer of steam forms around the hot steel, temporarily insulating it and slowing down its cooling process. This insulating effect is eliminated by salt water, which guarantees a faster and more consistent quenching process, leading to a harder and more polished microstructure. Components endure repetitive mechanical stress in high-friction situations, making this wear resistance enhancement more appealing. Creating a fine martensitic structure makes the material more resistant to abrasive wear, capable of withstanding prolonged contact and friction without greatly degrading. (Liu *et al.*, 2016). Therefore, cutting tools, machine components, and heavy-duty gears are among the many uses for saltwater-quenched steel, ideal for tasks necessitating exceptional durability.

The water-quenched material's extremely low wear rate of 0.0347 g/s further supports the long-established correlation between increased hardness and enhanced resistance to wear. Due to water's extraordinarily rapid cooling rate, austenite is transformed into martensite, producing an ultra-hard surface highly resistant to wear and tear. Due to its exceptional resistance to material loss, water-quenched steel significantly increases the durability of components subjected to continuous wear and tear. But there's a significant downside to this enhanced hardness—brittleness. Quick quenching causes carbon atoms to be trapped inside the crystal lattice of steel, which can increase the material's susceptibility to cracking or abrupt failure when subjected to impact loads or dynamic pressures. (Kobasko, 2010). Though it is very resistant to wear, water-quenched steel might not be the best choice for uses that demand a lot of toughness or flexibility.

Conclusion

The impact of cooling media on the hardness and wear resistance of low-carbon steel, which is carburized using cypress charcoal, has been investigated and found to be effective. Based on research and extensive discussions conducted using the experimental results, it can be determined that low-carbon steel hardness depends on the cooling media employed after carburizing. The hardest cooling method is water cooling, with 277.694 HV. Water's quick quenching increases martensitic microstructure. Martensite, a hard material, is formed when carbon atoms are retained in the steel's crystal lattice during rapid cooling, preventing them from spreading and creating ferrite or pearlite. Air cooling has the lowest hardness of 198.417 HV due to its slower cooling rate. Slower cooling creates pearlite and lowers hardness. Cooling speed directly affects microstructure, as air and water cool at different rates, leading to significant variations in hardness. The hardness decreases in low-carbon steel wear. The study found that hardness decreases wear rate and vice versa. This association is seen across all media. The lowest-hardness air-cooled specimens wear 0.0657 grams/second. The lower hardness makes steel more prone to surface wear and abrasion, contributing to material loss during frictional contact. Highly hard water-cooled specimens wear 0.0347 grams/second, the lowest. Water quenching increases steel hardness, reducing material loss in abrasive environments. For applications needing high durability and surface life, water cooling is the best way to minimize wear in carburized low-carbon steel.

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