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RESEARCH

The Influence of Waste Palm Oil Cooling Media on the Pack Carburizing Quenching Process of ASTM A36 Steel

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A B S T R A C T

This study investigates how four cooling media SAE 40 oil, palm oil, waste palm oil and water affect the surface hardness and impact toughness of pack carburizing quenching ASTM A36 steel. While conventional quenching practices rely on petroleum based oils or water, the use of waste palm oil as an alternative cooling medium has not been widely investigated. The carburizing media is a mixture of charcoal powder and $BaCO_3$ as energizer. It was conducted at 900 °C with a soaking time for 2-6 h, followed by quenching in each cooling media. The results indicate that both hardness and toughness are strongly dependent on the cooling media. Water produced the highest hardness, reaching up to 616 HV at 6 h, but caused a substantial reduction in impact toughness approximately 60% lower than the oil based cooling media. Waste palm oil generated slightly lower hardness yet provided a more desirable hardness and toughness balance due to its more moderate cooling rate. Palm oil yielded intermediate hardness and toughness, while SAE 40 oil resulted in the lowest hardness but the highest toughness. Significantly, waste palm oil produced a balanced hardening response, offering higher toughness than water and a stronger hardening effect than palm oil and SAE 40 oil, suggesting its potential as a sustainable, technically advantageous option. This work is novel in establishing waste palm oil as a viable, eco friendly cooling media that can improve the functional reliability of pack carburizing quenching ASTM A36 steel components.

1. INTRODUCTION

The success of agricultural mechanization in attaining food self-sufficiency is closely related to the use of top-notch agricultural equipment. The longevity and effectiveness of agricultural machinery are determined almost entirely by the sharpness of its parts, which again is largely determined by the hardness of the material that was used in making it. The sharpness of the implements that are used in agriculture like cutting, tilling, and plowing significantly influences the effectiveness, speed, and quality of the operations [1]. Sharp tools not only improve productivity but also take care of the quality of the harvest and relieve the operators of fatigue. In contrast, blunt tools increase effort as they take more energy to operate, which results in higher costs and tiring of the workers [2,3].

Low-carbon steels like ASTM A36 are favored for making agricultural tools due to their good forming, joining, and cost advantages over high-alloy or stainless steels [4,5]. However, one of the biggest problems with A36 is that, besides being in the category of low-carbon steels, it is very low in the hardness of its surface and has other disadvantages such as wear resistance and impact toughness [6]. In order to provide solutions, the various surface hardening techniques, especially pack carburizing quenching (PC-Q), have been the subject of much research aimed at enhancing mechanical properties like hardness, wear resistance, tensile strength, and impact toughness.

Many scientists have gone into analyzing how temperature, soaking time, particle size, and energizer composition can affect the mechanical properties of low-carbon steel. Carburizing time has a direct influence on surface hardness and case depth of mild steel. Longer soaking promotes deeper carbon diffusion, reflected by strong correlation coefficients for hardness (+0.98) and effective case depth (+0.91). Increasing the carburizing temperature further enhances carbon mobility; specimens treated at 900–1035 °C consistently develop higher hardness and deeper cases than those carburized at lower temperatures [7,8].

Palm-oil-based quenchants exhibit moderate cooling severity compared with water and mineral oils. Their slower cooling rate favors the formation of bainite within a ferrite matrix instead of predominantly martensitic structures, resulting in lower hardness but improved dimensional stability and reduced cracking tendency [9]. Hardness values obtained with palm kernel oil are significantly lower than those from water quenching, confirming its milder quenching performance [10]. Compared with oils such as SAE 40, palm oil provides a controlled cooling rate that reduces thermal shock while still producing sufficient hardness for components requiring stability and toughness.

The thermophysical properties of waste palm oil play an important role in its quenching behavior. Its relatively high viscosity stabilizes the vapor blanket during the early film-boiling stage, delaying the onset of nucleate boiling and producing a more uniform cooling rate. The moderate heat capacity and lower thermal conductivity, compared with water, reduce thermal shock and suppress excessive martensite formation. As a result, waste palm oil provides a controlled cooling severity capable of achieving adequate hardness while maintaining higher impact toughness than water quenching. Previous studies also report that palm-based oils, including palm kernel oil, can yield moderate cooling rates and competitive hardness levels relative to other vegetable oils [11–14].

Some researchers using seashell powder, animal bones, coconut shell charcoal, and palm kernel shells as carbon sources found substantial surface hardness and carbon diffusion improvements at 900–1000 °C for 4–8 h soaking [15,16]. The longer and hotter soaking time results in better carbon diffusion, leading to thicker and harder carburized layers. Pre-treatment methods like cold rolling and applying various cooling media (water, oil, or ice water) have been implicated in the hardness and microstructure of carburized steels, with rapid cooling being a factor in martensitic formation [17-23].

In addition, recent work has also looked into the application of nanocarbon and nano-energizers: coconut shell nanocarbon and pearl oyster shell nanocatalyst, in particular, to enhance the carburization process that already gives surface hardness of 399 HV and deeper carbon diffusion layers [24-25]. Among the other methods that have been able to harden surfaces, gas carburizing and laser hardening, the low-alloy steels reached the highest microhardness level (up to 922 HV) and also had their wear resistances improved [26-29]. Elements like Ni, Cr, and Mo have been demonstrated to have positive effects on the carbon diffusivity and carbide phase formation, thus areas of the total strengthening of carburized steels have been implicated [30].

Although several studies have explored various vegetable oils as cooling media, the use of waste palm oil has not been systematically investigated, particularly for carburized low carbon steels. Existing reports focus mainly on fresh palm oil, leaving a clear knowledge gap regarding whether waste palm oil, given its altered viscosity, thermal properties, and chemical composition, can provide comparable or even improved quenching performance. Addressing this gap is essential, particularly in the context of sustainable and cost effective heat treatment practices. Hence, the present research examines the potential of waste palm oil as an alternative cooling media and evaluates its influence on the hardness, impact toughness response of pack carburizing quenching ASTM A36 steel.

2. MATERIALS AND RESEARCH METHODS

2.1. Materials

The specimen material used in this study was low carbon steel plate ASTM A36 purchased from Tira Austenite Ltd., located in Surabaya, Indonesia. The chemical composition of the specimen as shawn in Table 1.

Table 1. Chemical composition of the ASTM A36 steel.

Element / Steel specimen	C	Si	Mn	P	S	Cu	Fe
Chemical composition [%]	0.25-0.29	0.280	1.03	0.04	0.050	0.20	≈ 98.0

Mechanical properties Tensile strength specimen as shawn in Table 2.

Table 2. Mechanical properties of the tested steel.

Tensile strength, σUTS (MPa)	400–550
Yield strength, σy (MPa)	≥250
Elongation (%)	20–23
Young's modulus, E (GPa)	200
Density (g/cm^3)	7.85
Surface hardness (HV)	127 HV

The steel plate was cut for surface hardness test according to ASTM E 384 and SAE J423 standards. Surface hardness measurement at the layer depth by the Vickers method using a Reichert hardness tester. The charpy impact test method refers to ASTM E23 test standard, as shown in Figure 1.

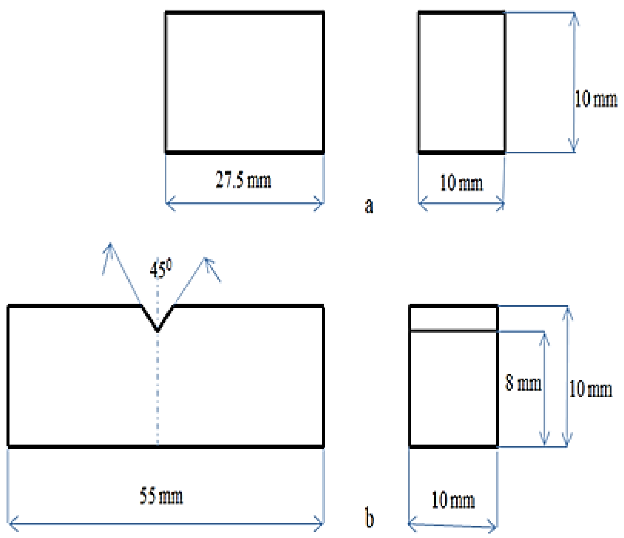


Fig. 1. (a) The surface hardness test ASTM E 384 standart, (b) The specimen impact test ASTM E23 standard.

2.2 Equipment

Carburizing heat treatment was carried out in a Thermolyne F6010 box furnace (maximum temperature 1100 °C). A Tes 1310 K-type thermocouple was used to monitor furnace temperature. In the present investigation, the primary apparatus included Microhardness Testers (Vickers/Knoop) from the DuraScan Series – ZwickRoell. These testers facilitate both automatic and semi-automatic assessments within a loading spectrum of 500 gf to 1 kgf. Charpy Impact Testers (Pendulum Impact Testers – ZwickRoell) were also used. They are capable of executing pendulum impacts of up to 750 joules for metallic specimens, accommodating both Charpy and Izod testing methodologies.

2.3 Experimental procedure

The sequence of the pack carburizing quenching (PC-Q) process is as follows: The specimen is positioned within a 250 mm x 250 mm x 155 mm AISI 309 steel (a heat-resistant alloy) carburizing box, as illustrated in Figure 2. The specimen is meticulously arranged and uniformly enveloped in the carburizing medium. This medium consists of charcoal powder and an energizer, $BaCO_3$, in a weight percentage ratio of 70:30. Subsequently, the specimens were heated in an electric furnace at a carburizing temperature of 900°C. Soaking time varied from 2 to 6 h. This thermal treatment is followed by a cooling phase using a variety of cooling media. These include water, SAE 40 oil, palm oil, and waste palm oil. After the PC-Q process, hardness evaluations are conducted using the Vickers method, while impact assessments are performed via the Charpy methode.

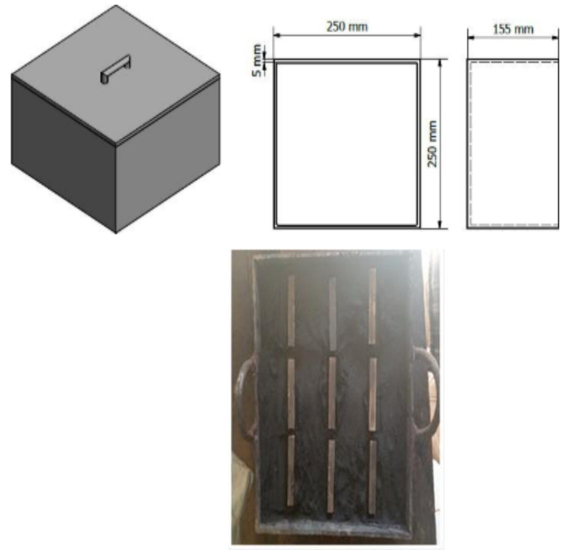


Fig. 2. Carburizing box AISI 309 steel (heat-resistant steel).

In the pack carburizing methodology utilizing an electric furnace, the regulation of temperature is a critical determinant due to the pronounced effect of temperature on carbon diffusion kinetics. The temperature within the electric furnace is meticulously regulated via a thermocouple strategically positioned within the furnace chamber. This thermocouple transmits a temperature signal to the proportional-integral-derivative (PID) controller. The temperature within the electric furnace is meticulously regulated via a thermocouple strategically positioned within the furnace chamber. This thermocouple transmits a temperature signal to the proportional-integral-derivative (PID) controller. The electric furnace employs a thermocouple to establish the thermal conditions within the furnace chamber. This thermocouple transmits a temperature signal to the proportional-integral-derivative (PID) controller. The temperature escalates during the pack carburizing process in the following manner: during the initial 0-120 minutes, the furnace transitions from ambient temperature (25 °C) to 900 °C, followed by a soaking time extending from 120 to 360 minutes. The temperature is maintained at a constant 900 °C to facilitate optimal carbon diffusion. The terminal phase involves controlled cooling to approximately 200 °C over a duration from 360 to 480 minutes, subsequent to which quenching is performed utilizing various cooling media.

3. RESULTS AND DISCUSSION

3.1. The effect of carburising quenching treatment on the surface hardness of ASTM A36 steel

Surface hardness characteristics of samples (ASTM A36 steel) treated with PC-Q using various cooling media, measured using the Direct Surface Hardness Measurement method with Microhardness Testers (Vickers/Knoop) DuraScan Series–ZwickRoell. Beseta rata-rata diagonal *(μm).* The specimen is placed on the test table, and the indenter (a diamond pyramid shaped cone with a 136° angle) is lowered/pressed with a load ranging ,from 500 gf to 1 kgf. The test was repeated three times. The measured value was the diagonal depth of the indentation, and the Vickers hardness value was calculated using the formula:

$$HV = \frac{0.102.F}{d^2} \quad (1)$$

HV: Surface hardness number (kg/mm^2), F: Load (kg), d: average diagonal indentation (mm).

The findings from the assessment of surface hardness are presented in Figure 3. This figure illustrates the correlation between variations in cooling media (namely water, palm oil waste, palm oil, and SAE40 oil) and the resultant surface hardness values (expressed in terms of Vickers Hardness) of low carbon steel specimens identified as ASTM A36, which underwent pack carburizing followed by quenching at a temperature of 900°C, with differing carburizing durations (soaking times) of 2, 4, and 6 h. Specimens that did not receive treatment (untreated) UT function as the control group. The observed trend in surface hardness enhancement indicated that the initial specimen (UT) consistently exhibited a surface hardness value of approximately 125 HV across all carburizing conditions and soaking durations. This observation suggests that the absence of heat treatment results in no substantial alteration in the microstructure of the steel. Utilizing SAE40 oil as the cooling medium resulted in a progressive increase in surface hardness corresponding to the elongation of soaking time, escalating from roughly 130 HV at 2 h to approximately 280 HV at 6 h. This enhancement is relatively moderate in comparison to the other cooling media. Palm oil displayed a more pronounced increase relative to SAE40 oil, attaining an approximate surface hardness of 400 HV after 6 h of soaking. The utilized waste palm oil demonstrated superior surface hardness compared to palm oil across all soaking durations, achieving approximately 500 HVat the 6-hour mark. Water as a cooling medium produced the most elevated results among all tested media, reaching around 550 HVat a soaking duration of 6 h.

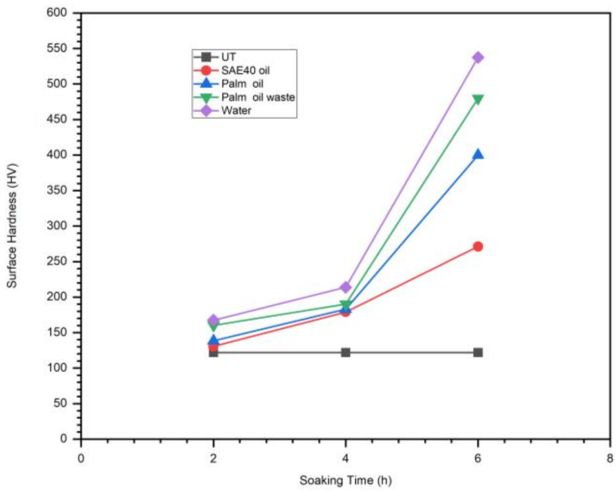


Fig. 3. Surface hardness test results of specimens.

The use of Microhardness Testers (Vickers/Knoop) Duratest Series - Zwickroell allows one to indicate the carbon content percentage at a given depth. The underlying idea is that carbon content results in hardness of martensite increasing. When the specimen (or standard sample) is brought to austenitic condition and quenched without any further heat treatment, the whole surface turns into martensite and the HV value at a given depth corresponds to the local %C. Figure 4 presents the Depth (mm/μm) - %C graph illustrating the variation of carbon content in a specimen which went through pack carburizing quenching with waste palm oil as the cooling medium. The graph depicts the connection of carbon content (%) with the depth from the surface for three soaking times: 2 h, 4 h, and 6 h. This examination is regularly conducted during the pack carburizing method where at elevated temperatures carbon is transferred from the surface into the material. The carbon distribution reveals that all the curves have the surface (0 mm) with the maximum carbon content which then tapers off towards the core (greater depth) as one moves inward. The Soaking time of 6 h has been noted to have the highest carbon content on the surface (0.80%) and the greatest depth of carbon diffusion. The Soaking time of 4 h is in between, displaying a slightly lower surface carbon content (0.78%) than that of 6 h and a less deep diffusion profile. Soaking time of 2 h has the least surface carbon content (0.75%) and the shallowest diffusion depth.

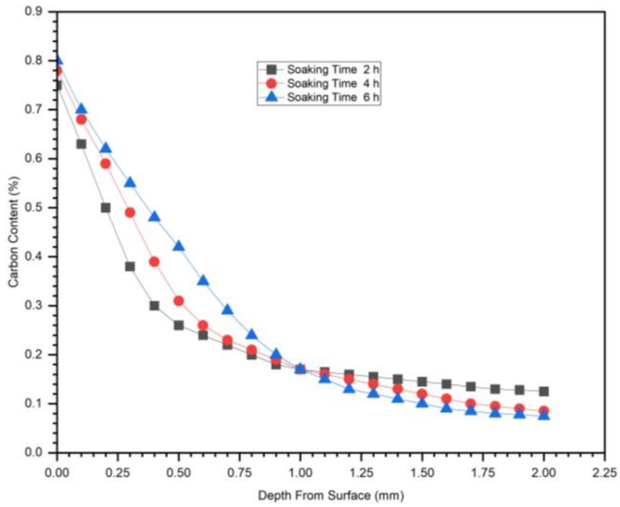


Fig. 4. The distribution of carbon content in specimens with pack carburizing quenching using waste palm oil cooling media.

Longer soaking times allow greater diffusion of carbon atoms from the carburizing media pack into the steel. After 6 h, carbon is more present not only on the surface but also in the lower layers (still at a depth of 1 mm about 0.2% C is present). Conversely, after 2 h, carbon content drops very sharply at depths of ±0.25 mm and more quickly approaches the core content 0.15% C. This is according to Fick's diffusion law, which states that longer soaking times result in increased diffusion distance. The consequence for surface hardness is that the high carbon content at the surface will lead to a harder martensitic layer post-quenching. The thickness of the carbon-rich layer indicates the case depth; the layer being deep means greater surface wear resistance. This connection clarifies the reason that, at the 6 h mark, surface hardness and hard layer thickness are more pronounced than at the 2-hour mark.

3.2. The effect of carburizing quenching treatment on the surface impact energy and impact toughness of ASTM A36 steel

Specimens for impact testing refer to ASTM E23 standards with dimensions of 55 mm x 10 mm x 10 mm. The impact testing method used is the Charpy method. For testing, Charpy Impact Testers (Pendulum Impact Testers – ZwickRoell, pendulum impact testers up to 750 joules for metals, supporting Charpy and Izod test methods) are used. For the Charpy impact testing method, each specimen was placed vertically and struck in the centre using a swing hammer. The results of the impact test are shown in Figure 5. and Figure 6.

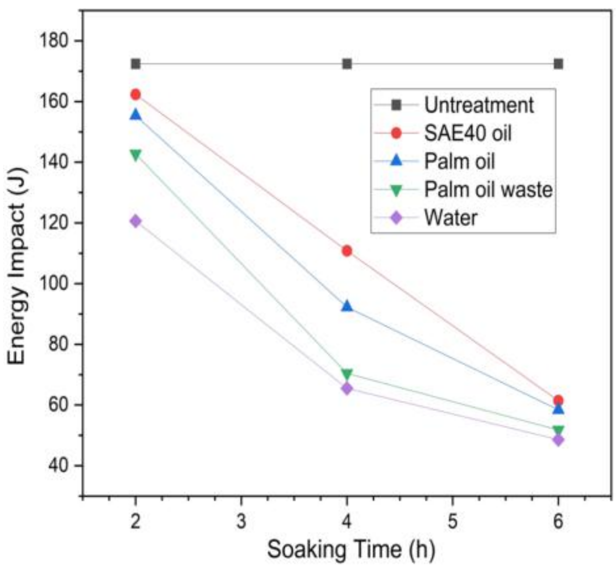


Fig. 5. The effect of cooling media on energy impact on specimens.

According to Figure 5, the Impact Energy value for all the media tested except the untreated specimen shows a trend of decreasing with increasing immersion time (2 h → 4 h → 6 h). The untreated specimen, on the other hand, remained at around 170 J during the whole experiment period. The Impact Energy decrease is associated with a decrease in the toughness of the material due to the media penetration which eventually led to property degradation. The cooling medium, SAE40 oil, presents the highest among every immersion time and the highest Impact Energy value of all immersion media. At 2 h, it was about 162 J which went down to 110 J at 4 h and 61 J at 6 h. Palm oil cooling medium was closely in line with SAE40 oil with an initial value of about 155 J (soaking time 2 h) reducing further to 93 J (4 h) and 59 J (6 h). Waste palm oil displayed an even more considerable decrease from 142 J (2 h) to 68 J (4 h) and 51 J (6 h). Water cooling media initiated the lowest impact energy at the beginning; about 120 J (2 h), dropping to 65 J (4 h) and 48 J (6 h).

The water cooling media produced the lowest impact energy from the start, around 120 J (2 h), decreasing to 65 J (4 h) and 48 J (6 h). Figure 5. displays the toughness order from highest to lowest at all immersion times: Untreated > SAE40 oil > Palm oil > Waste palm oil> Water. Oil-based cooling media such as SAE40 and palm oil provide a better defense against the reduction of strength during the time as compared to water, which may be attributed to their higher capacity to inhibit corrosion or degradation through fluid penetration. Waste palm oil and water, on the other hand, accelerate the decay of strength, perhaps due to the leaching out of certain compounds or moisture that speed up the degradation of the material's microstructure.

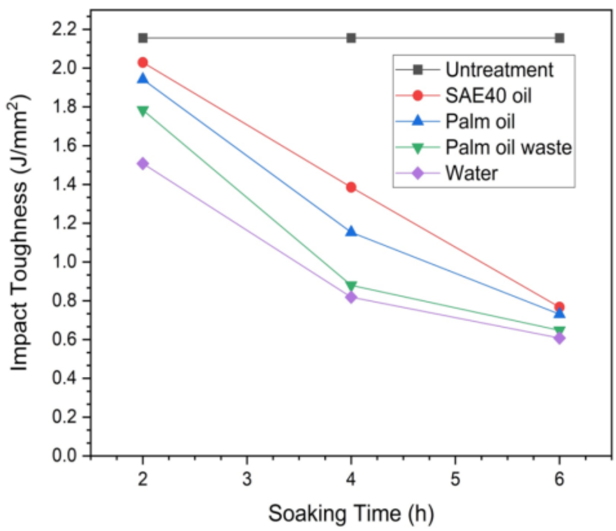


Fig. 6. The effect of cooling media on impact toughness in specimens.

Impact toughness is a measure of the capacity of a material to take in impact energy through its cross-sectional area. For all the media, except the untreated one, impact toughness values go down with increasing carburizing time (soaking time) of 2 h → 4 h → 6 h, with the untreated one staying stable at about 2.1 J/mm^2. The drop in values points out the deterioration of mechanical properties as a result of the interaction between the cooling medium and the material, which can lead to microstructural changes like corrosion or fluid penetration.

The inverse correlation between hardness and impact toughness observed in this study can be explained by the microstructural evolution during carburizing and quenching. Rapid cooling promotes the formation of a martensitic surface layer with high carbon content, high dislocation density, and substantial residual stresses. This microstructure exhibits excellent resistance to indentation, resulting in high hardness values; however, it lacks the ability to undergo plastic deformation, making the material more susceptible to crack initiation and propagation under impact loading. Consequently, specimens quenched in more severe media such as water display the highest hardness but the lowest toughness, whereas milder cooling media such as SAE 40 oil produce a softer but more ductile microstructure with superior impact performance.

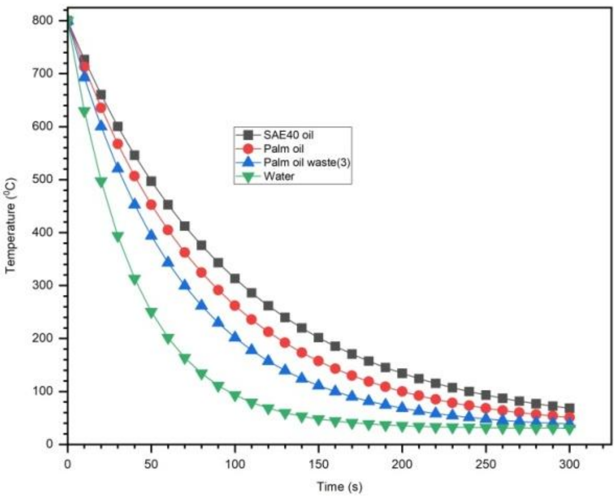


Fig. 7. The cooling rate of water, palm oil, palm oil waste and SAE 40 oil

The cooling behaviour of SAE40 oil, fresh palm oil, waste palm oil, and water was experimentally measured using a K-type thermocouple attached to a steel specimen heated to approximately 800 °C. All quenching tests were conducted under identical bath conditions to ensure valid comparison. The recorded temperature–time data are now presented in the Figure 7.

The analysis of water cooling media showed that it produced the highest cooling rate, thus more martensite content and the maximum surface hardness. Still, higher risk of distortion or cracking, too. Waste palm oil may be the fastest cooling medium since it has the chemical composition that has a better influence on viscosity and heat transfer. On the contrary, palm oil cools slower than waste palm oil, hence the hardness is slightly lower. SAE40 oil has a high viscosity and cooling rate is slow, hence there is less formation of martensite and the cooling media have the lowest hardness. The effect of soaking time, longer the soaking time (2–6 h) the higher the hardness for all cooling media. This is because, during heating, there is more uniform and extensive carbon diffusion to the steel surface that occurs which leads to a thicker and harder martensite layer being formed after quenching.

It is the cooling media that have the strongest influence on the surface hardness and impact toughness properties of specimens submitted to pack carburizing quenching treatment. The cooling rate correlatively dictates the amount of martensite produced, thus hardness is increased. However, the opposite is the case for impact toughness. Waste palm oil and palm oil yields medium hardness values 470 and 400 HV representing a structure of martensite + bainite. Waste palm oil was found to be more advantageous than pure palm oil because of the faster cooling rate. All of the cooling mediums were responsible for the significant declining of toughness approximately 60-64% after 6 h of soaking time. Waste palm oil experienced the most severe reduction (64%).

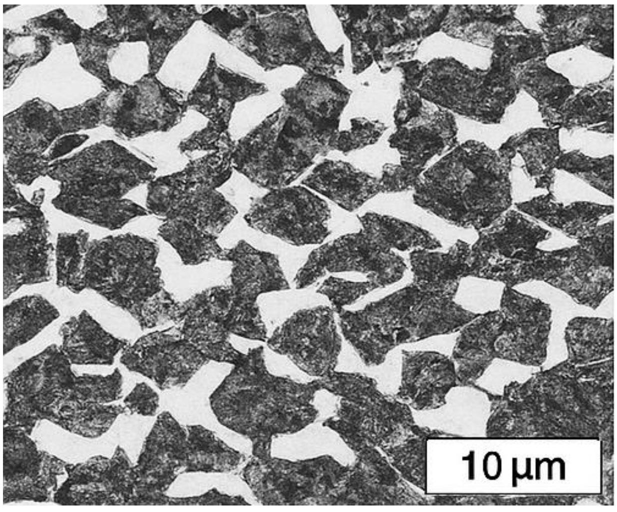
The two-way ANOVA with replication as shown in Table 3. shows that both cooling media and holding time significantly affect the measured response. The cooling media produced a significant main effect ($F = 16.83$, $p < 0.05$), indicating that each coolant provides different quenching performance due to variations in heat extraction behavior. Soaking time exhibited an even stronger influence ($F = 205.07$, $p < 0.05$), showing that longer carburizing duration leads to greater changes in the material response. A significant interaction was also identified ($F = 8.05$, $p < 0.05$), demonstrating that the effect of holding time depends on the cooling media used. In general, water cooling media at longer holding times resulted in the highest response values, consistent with its fastest cooling rate. Overall, the results confirm that both factors and their interaction play critical roles in determining pack carburizing material properties.

Table 3. The two-way ANOVA with replication.

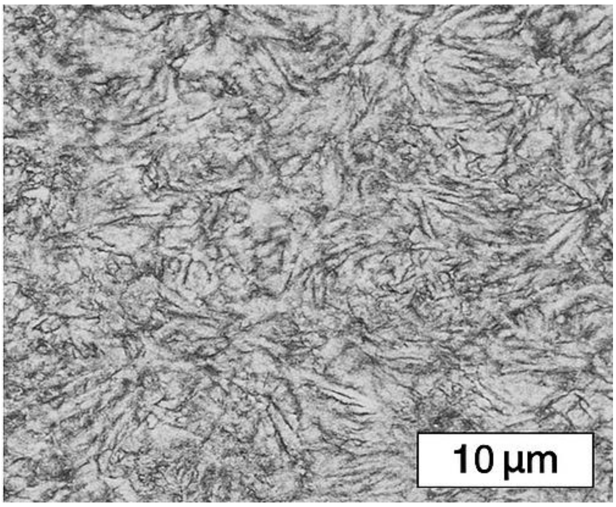
Source of Variation	SS	df	MS	F	P-value	F crit
	63727.02	3	21242.34	16.82916	4.23E-06	3.008787
Columns	517704.9	2	258852.4	205.0748	8.14E-16	3.402826
Interaction	60967.42	6	10161.24	8.050201	7.84E-05	2.508189
Within	30293.62	24	1262.234			
Total	672692.9	35				

3.3. The effect of carburizing quenching treatment on the microstructure of ASTM A36 steel

According to the analysis, the structure of the original (without treatment) microstructure mainly comprises ferrite and pearlite (the lighter areas being ferrite and the darker ones being pearlite) as depicted in the microscopic image in Figure 8a. This arrangement also gives a reason for the low and almost unchanging hardness of the surface that was not treated. The SAE40 oil cooling medium takes a longer time to cool than water; thus, the transformation is not pure martensite but it might include fractions of martensite and bainite or even some pearlite sometimes at the core/surface depending on the composition and cooling rate, as shown in Figure 8b. Palm oil and waste palm oil cooling media have apposite viscosities and surface characteristics which produce a cooling rate that is faster than that of SAE40 oil but slower than that of water. Consequently, the microstructure formed is likely to be: a matrix of martensite with little sections of bainite, as illustrated in Figures 8c and 8d.



(a)



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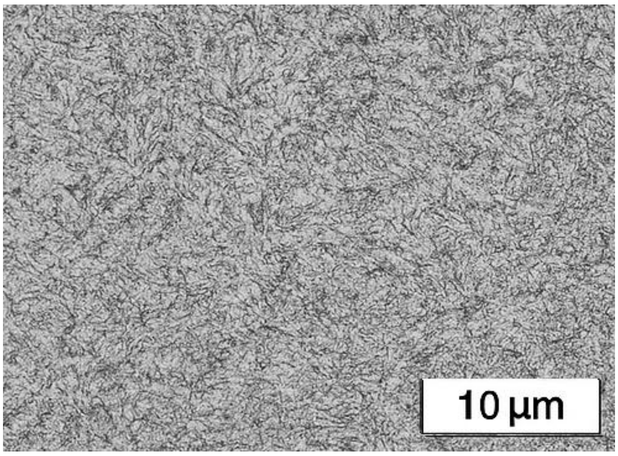

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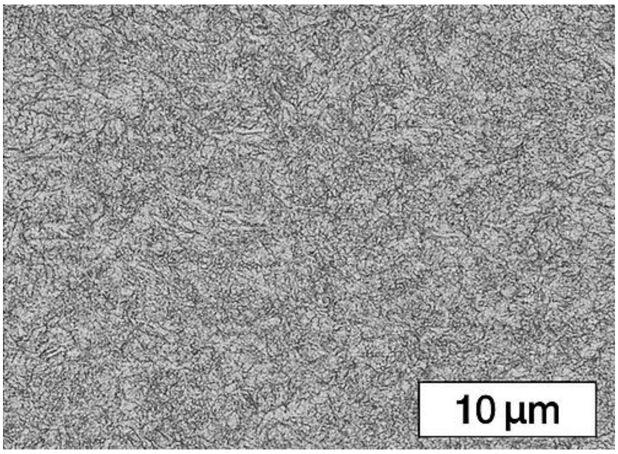

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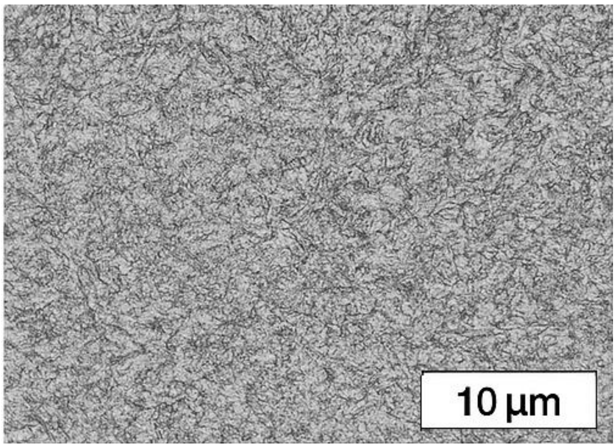

(e)

Fig. 8. The effect of cooling media on the microstructure of specimens, b. Ferrite, b.Upper bainite, c. Lower bainite, d. Martensite, e. Fine ferrite-pearlite.

The waste palm oil has a larger martensite surface fraction compared to palm oil which is why the hardness is higher (near the value in between oil and water). The water as a cooling medium causes very high cooling rates to be achieved on the surface. As illustrated in Figure 8e, the austenite is converted into fine-lath-martensite and martensite. The hardness at the surface is highest due to the martensite (the graph shows the water to have the highest value). However, such rapid cooling can lead to the formation of cracks and deformation. The micrograph of water-quenched samples produces evidence that martensite is the main phase at the surface.

4. CONCLUSION

1. Surface hardness increased with longer soaking time and was governed by the cooling severity of the quenching media. The maximum hardness was obtained in water-quenched specimens at 6 h soaking time (616 HV), while the lowest value occurred in SAE40 oil (190 HV at 2 h). Waste palm oil consistently produced high hardness values (473–493 HV), slightly below water but higher than palm oil and SAE40 oil.
2. Carbon Content Distribution. Carbon diffusion depth increased with soaking time for all conditions. Faster quenching media such as water and waste palm oil promoted higher carbon gradients and limited back-diffusion, resulting in stronger surface hardening.
3. Impact Energy and Toughness. An inverse relationship between hardness and toughness was observed. Water-quenched specimens exhibited the lowest toughness at 6 h (48–49 J), while SAE40 oil produced the highest (61–62 J). All media experienced a significant reduction in toughness of approximately 60–64% after 6 h, with waste palm oil showing the greatest reduction (64%).
4. Microstructural Evolution. The untreated steel consisted of ferrite and pearlite. Water quenching produced predominantly martensite due to the highest cooling rate. Waste palm oil generated a martensitic matrix with minor bainite, attributed to its lower viscosity and efficient heat transfer. Palm oil yielded a martensite–bainite structure of lower hardness, whereas SAE40 oil produced a mixture of bainite, martensite, and residual pearlite due to its slow cooling rate.
5. Recommendation for Engineering Application. Considering hardness, toughness, carbon penetration, and microstructural stability, waste palm oil provides the most balanced performance. It yields high hardness while retaining moderate toughness and forms a predominantly martensitic microstructure without the brittleness associated with water quenching. Accordingly, waste palm oil is recommended as the optimal cooling media for carburized ASTM A36 steel components requiring a balance of wear resistance and structural integrity.

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