MECHTA
International Journal Of Mechanical Engineering Technologies & Applications
ISSN 2722-3213 articles 4, pp. 34 – 47, 2025

V06 N.1

INFLUENCE OF LORJUK MUSSEL SHELLS AND PEANUT SHELLS AS CARBURIZER MEDIA IN THE PACK CARBURIZING PROCESS OF AISI 1020

Achmadi [1] ✉, Teguh Dwi Widodo [1], Yudy Surya Irawan [1]

[1] **Mechanical Engineering Department**
Brawijaya University
MT. Haryono, 167
Malang, Jawa-Timur, INDONESIA.
Achmadibbec99@gmail.com

Abstract

AISI 1020 steel is low-carbon steel with a carbon content of 0.20% and good ductility but low hardness. One of the methods to increase the hardness is by infusing carbon. The addition of carbon, called carburizing, was done by heating at a high enough temperature, namely at austenite temperature, in an environment containing active carbon atoms so that the active carbon atoms would diffuse into the steel surface and reach a certain depth. After the diffusion process, a rapid cooling treatment (quenching) is followed to obtain a harder surface, but the center is ductile. The carburizing process requires activation energy to diffuse carbon in the material. Catalysts are one solution to increase activation energy so that the time required during the carburization process is less. The study used carburizer from Lorjuk mussel shells as a catalyst and peanut shell charcoal as a source of activated carbon. The variations used were 0% catalyst/100% charcoal, 10% catalyst/90% charcoal, 20% catalyst/80% charcoal, and 30% catalyst/70%. The results of the study obtained the highest hardness and carbon diffusion values, the smallest corrosion rate obtained in the addition of 30% catalyst, and the lowest hardness in specimens without catalyst.

***Keywords**: Pack Carburizing, Peanut Shell Charcoal, Lorjuk Clam Shell, Surface Hardening, Corrosion Rate.*

1. INTRODUCTION

Steel is a typical material often used in various industrial applications, such as manufacturing machine components, construction, and work materials such as sheets, pipes, profile bars, and plates. These different forms of steel are commonly found in various projects due to their wide variety of applications. One widely used type of steel is low-carbon steel, known for its good ductility. However, the hardness of this steel tends to be low, due to the lower carbon content. The hardness of steel is greatly influenced by its chemical composition, especially the carbon content [1]. The higher the carbon content in the steel, the higher the hardness of the steel, which increases the carbon content, one of which is diffusing by carbon through the carburizing process. The carburizing process requires activation energy to diffuse carbon into the steel surface to increase activation energy by adding catalysts, so that the activation energy is higher, causing carbon to diffuse more quickly [2].

A catalyst is a substance or several substances that can accelerate a reaction without being consumed by the reaction, but not without reacting. The catalyst affects the speed of the reaction without undergoing chemical changes at the end of the reaction [3]. The process carried out by the catalyst is called catalysis. Negative catalyst (inhibitor) refers to a

Corresponding Author:
✉ **Achmadi**
Achmadibbec99@gmail.com
Received on: 2024-04-02
Revised on: 2024-06-13
Accepted on: 2024-06-18

https://mechta.ub.ac.id/
DOI: 10.21776/MECHTA.2025.006.01.4

substance that plays a role in inhibiting or slowing down a reaction [3]. Catalysts accelerate reactions by reducing the activation energy of the reaction. The activation energy of a reaction is the minimum amount of energy required by a reaction for the reaction to take place.

Adedipe *et al*.[4]] conducted a study entitled Explicit microstructural and electrochemical study of value-added carburized mild steel with coconut shell ash and $CaCO_3$ nanoparticles derived from the periwinkle shell, in this study using calcium carbonate from the periwinkle shell. The results obtained after the carburization process are increasing hardness value, more carbon diffusion, more carbon distribution on the surface of the material, and reduced corrosion rate, and this study provides the conclusion that periwinkle shell and coconut shell waste can be used for surface hardening of mild steel.

Hefni *et al*. [5] in the presence of a $CaCO_3$ catalyst, indicating better carbon diffusion into the carbon steel. This can be seen from the shape of the martensite structure after the cooling process, which means an increase or addition of carbon in the specimen. As a result, a martensite structure is formed on the hard surface; with the presence of a catalyst, carbon diffusion increases by increasing the activation energy so that processing time decreases; the higher the activation energy, the easier the carbon diffusion process to the steel surface [5].

Thammachot *et al*. [6] conducted carburization research on carbon steel knives using an additional catalyst from $CaCO_3$. The research results showed that the hardness value was higher than without a catalyst, which shows that more carbon diffuses into the steel undergoing carburization. The higher the hardness value, the higher the wear resistance value of the steel. Thus, the $CaCO_3$ catalyst strongly influences the high hardness value and the formation of martensite structure resulting from the carburization process.

Calcium carbonate, as a catalyst mixed with activated carbon sources into the furnace during the carburization process, has the characteristic of easily decomposing to produce CO2 gas compared to other types of catalysts; with more catalysts added, more CO_2 gas is available, resulting in more activation energy [5]. One of the marine wastes that can be used as a catalyst is lorjuk shells, which have high calcium carbonate ($CaCO_3$) content (around 96%), so the $CaCO_3$ content can be used as an alternative catalyst. The following reaction that occurs in $CaCO_3$ when heated above 700ºC is $CaCO_{3\ (s)} \rightarrow CaO\ (s) + CO_{2\ (g)}$ [7]. The more CO_2 that is formed, the faster the diffusion of carbon atoms on the steel surface.

The catalyst works in the pack carburizing process as a catalytic agent that increases the reaction speed between the carbon in the carburized packaging material and the metal surface, helping to accelerate the carbon absorption process into the steel surface [6]. The catalyst plays a role in enhancing the penetration of carbon into the metal surface. The pack carburizing process requires carbon to penetrate the crystal structure of the steel surface, thereby increasing the carbon content on the surface and forming a hard coating [8]. The reduced temperature required for pack carburizing can be reduced by adding a catalyst, thereby reducing energy costs and allowing processing at lower temperatures, reducing the risk of deformation or distortion at high temperatures [9].

This research used lorjuk shells as a catalyst and peanut shell charcoal as a source of activated carbon, which has been crushed at a size of 100 mesh; the variations used are 0% catalyst, 10% catalyst, 20% catalyst, and 30% catalyst, and for the cooling medium using water. After the carburization process was completed, hardness, microstructure, chemical composition, and corrosion rate were tested as indicators of the results of the carburization process to determine the influence of the pack carburizing process.

2. MATERIALS AND METHODS

2.1. Material

The material used is AISI 1020 low-carbon steel. AISI 1020 steel is a type of low-carbon steel that has a chemical composition with a carbon content of about 0.20% [1]. The AISI code refers to the American Iron and Steel Institute, which sets standards for most steel used in industry. AISI 1020 steel is known for its easy processing and formatting properties and relatively low production costs [1]. The manufacturing process of this steel involves normalizing or other heat treatments to improve its mechanical properties. AISI 1020 steel has several characteristics that make it widely used in various applications. Its strength, ductility, and easy machinability make it suitable for manufacturing various machine components, such as shafts, gears, and bolts. AISI 1020 steel is also applied in constructing steel structures that require strength and machinability [10]. The conceptual framework of this research is as in Figure 1. Lorjuk clams have a $CaCO_3$ content of around 98%; after undergoing heat treatment, it will react to become $CaO+CO_2$. Therefore, the CO_2 produced will become a catalyst, speeding up the carbon decomposition process on the steel surface [7].

2.2. Experimental Design

The carburizing medium used is groundnut shells that have been charred at 300°C and made into powder with a mesh size of 100, while the catalyst comes from lorjuk shells. The variations used were:

- 0% catalyst / 100% peanut shell charcoal
- 10% catalyst / 90% peanut shell charcoal
- 20% catalyst / 80% peanut shell charcoal
- 30% catalyst / 70% peanut shell charcoal

The carburization process lasted 2 hours, after which it was cooled using water. The experimental design of the carburization process is shown in Figure 2.

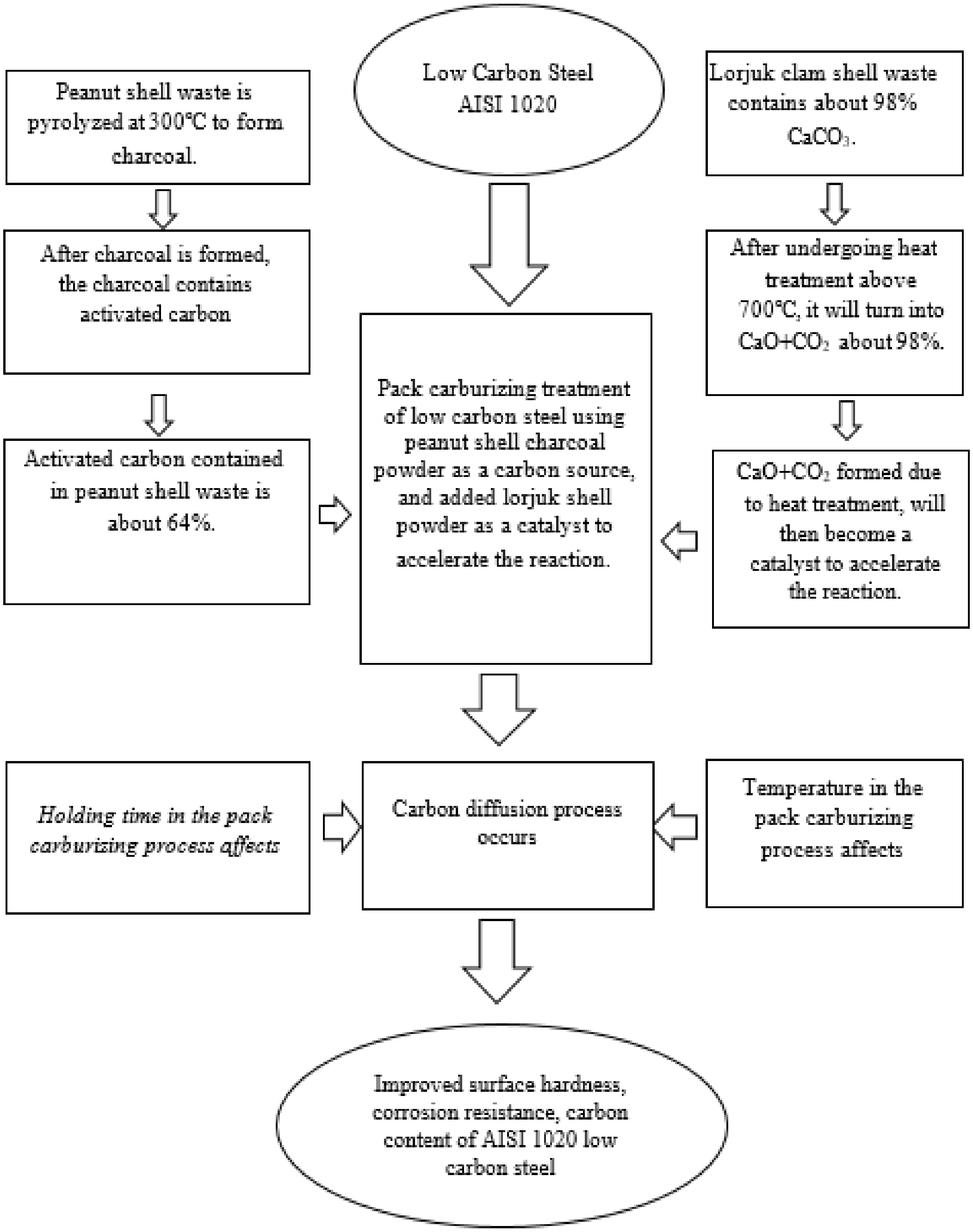

Figure 1. Conceptual framework

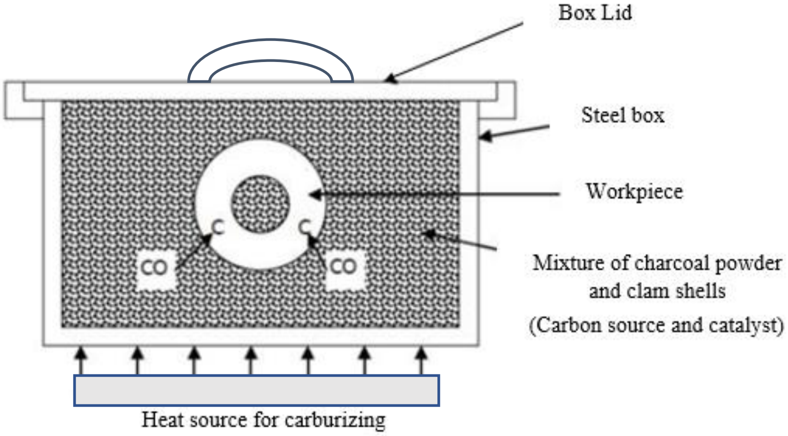

Figure 2. Pack Carburizing Process

3. RESULT AND DISCUSSION

3.1. Hardness

The hardness test used was the Micro Vickers hardness test. The hardness testing distance is 0 µm, 300 µm, 600 µm, 900 µm, or 1200 µm from the surface of each specimen. The hardness test results are presented in graphic Figure 4.

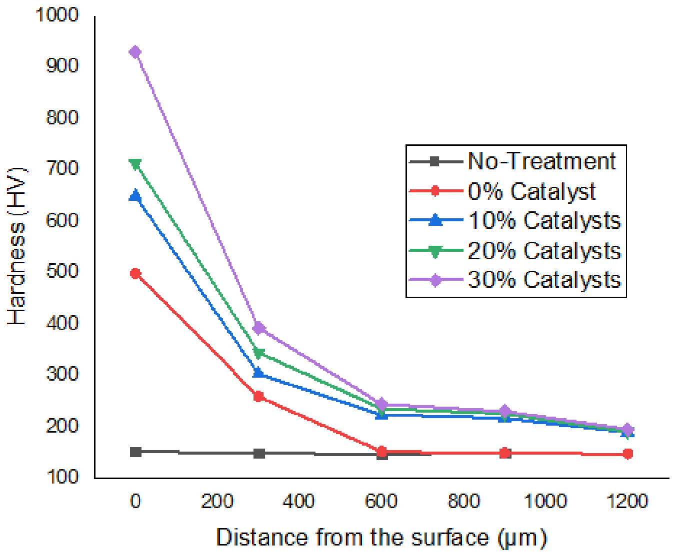

Figure 3. Graph of hardness values before and after the pack carburizing process with and without the addition of a catalyst.

Hardness testing is one of the indicators to see the effect of the pack carburizing process on the tested specimen. In this way, it can be seen whether the influence can occur due to the pack carburizing process with and without the addition of catalysts. The result of the observation was an increase in hardness value, especially on the surface of the specimen. In the observations made, it can be seen that the highest surface hardness value of all variations of catalyst addition is at 30% catalyst addition with a value of 929.8 HV, while the lowest hardness value is at 0% catalyst with a value of 498.7 HV, and for raw material hardness or without treatment around 149 HV. As the amount of catalyst increases, the hardness also increases, indicating more carbon diffusion on the metal surface. In the presence of catalysts, carbon atoms move more easily into the metal, forming a thicker and harder carburized layer [11]. Catalysts can also affect the phase transformation process on the metal surface. In pack carburizing, the metal undergoes changes in crystal structure when carbon is added [12]. Catalysts can accelerate and enhance this process, resulting in a denser and harder crystal structure [13]. Catalysts can affect the formation of carbides on metal surfaces [14]. Carbides are compounds between metal and carbon that are very hard; with the presence of catalysts, the formation of carbides can be increased, thereby significantly increasing the hardness of the metal surface. Another effect of adding catalysts was to reduce process time [15]. Catalysts can accelerate the chemical reactions involved in pack carburizing, resulting in a fairly thick carburized coating in a shorter time [16].

3.2. Micro-Structure

After the pack carburizing process was completed, SEM (Scanning Electron Microscope) testing was carried out to examine the surface microstructure of the material that had undergone the pack carburizing process. SEM testing allows researchers to examine the microstructure of the surface coating, which can affect the mechanical properties and strength of the material [17] [18].

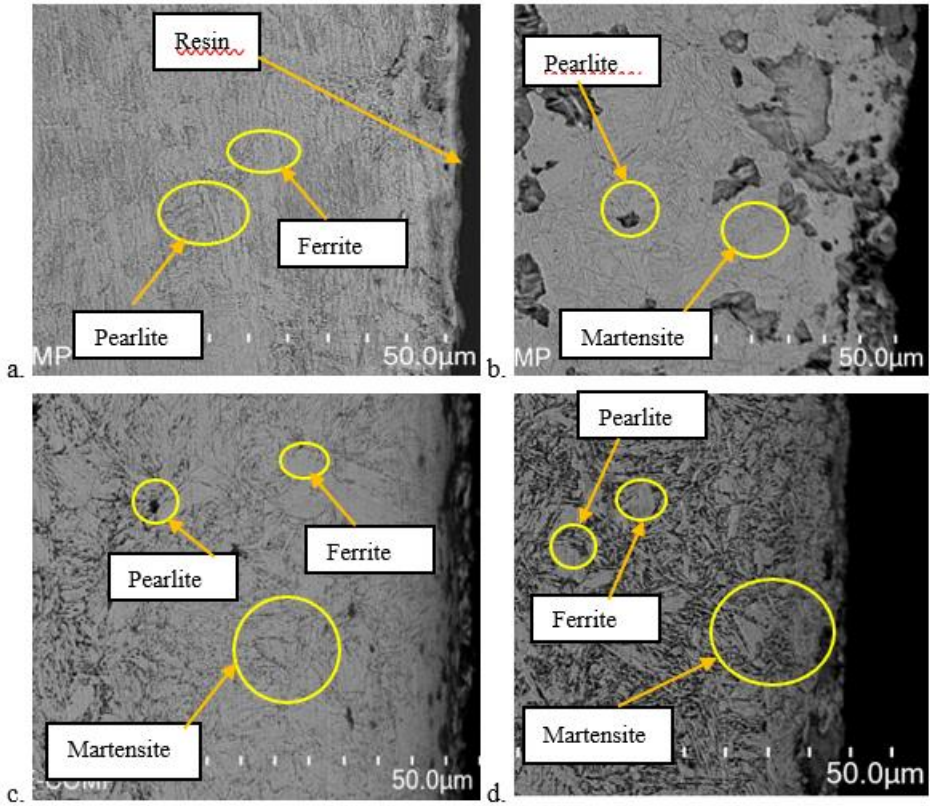

Figure 4 a. Microstructure without the addition of a catalyst. b. microstructure with an additional 10% catalyst. c. microstructure with an additional 20% catalyst. d. microstructure with an additional 30% catalyst.

The microstructure photos obtained show apparent differences in the test results of various variations of catalyst addition, especially between those without catalyst and those with catalyst added. In the specimen without catalyst addition, as shown in Figure 4. a, it can be seen that the microstructure formed mainly consisted of pearlite and ferrite. In the addition of the 10% catalyst in Figure 4.b., it can be seen that the structure formed was martensite, and there are some pearlite and ferrite. With the addition of 20% catalyst in Figure 4.c., the resulting structure was not much different from the microstructure with the addition of 10%. Still, with the addition of 10% catalyst, the pearlite formed was larger. In the test specimen with the addition of 30% catalyst, namely in Figure 4.d, it was found that most of the martensite structure formed was martensite, although some pearlite and ferrite formed. The formation of pearlite was caused by several factors. The first was due to insufficient carbon diffusing into the test piece. The cause is the limited holding time, so the time for carbon to diffuse was insufficient. The activation energy was lacking, causing carbon not to diffuse much, and the energy required was higher. Activation makes carbon easier to diffuse [19]. The second cause is that the carbon content of peanut shell charcoal is not as high as teak wood charcoal, so higher activation energy is needed so that more carbon can diffuse during the decomposition process [20]. In the CCT (Continuous Cooling Transformation) diagram, the smaller or less carbon content, the more difficult it is for the austenite phase to transform into martensite in the rapid cooling process [1]. High carbon content in steel increases the likelihood of martensite formation during quenching. The higher the carbon content, the greater the possibility of austenite transforming into martensite during the rapid cooling process. However, carbon content that is too low can also inhibit martensite formation or produce undesirable structures, resulting in lower hardness [21]. Martensite formation generally occurs due to rapid cooling with sufficient carbon content [13]. In the pack carburizing process, the addition of a catalyst will increase the activation energy, making it easier for carbon to diffuse on the steel surface. Enough carbon makes it easier for austenite to transform into martensite, as shown in Figure 5.d. The more catalyst added, the more martensite was formed and the higher the hardness obtained [8], as in Figure 5.d at 30% catalyst addition.

3.3. Composition and Distribution of Elements

The composition test in this research focused on the elements carbon (C) and iron (Fe), which are the main elements in carbon steel. The test used was EDX (Energy Dispersive X-ray Spectroscopy), which was done to analyze the chemical composition of the metal surface layer that has undergone the pack carburizing process. This is important because pack carburizing involves the process of introducing carbon into the metal surface to increase its hardness and strength. The EDX test allows researchers to examine how much carbon has been distributed into the surface layer [22]. In addition, the EDX test also helps in validating the success of the pack carburizing process. By analyzing the chemical composition of the surface layer, researchers can determine if the amount of carbon-infused has met the required standards. Controlling the exact chemical composition is critical as it will directly impact the mechanical properties and strength of the material after carburizing. The EDX test can also provide additional information about other elements that may be present in the surface layer, such as nitrogen, oxygen, and other elements that can affect material properties [23]. The chemical composition test results are shown in Table 1.

Table 1. The chemical composition of the carburizing process results

Element	Weight (%)			
	0% Catalyst	**10% Catalyst**	**20% Catalyst**	**30% Catalyst**
Fe	98,49	98,10	98,06	97,46
C	1,51	1,90	1,94	2,54

Table 1 shows the results of chemical composition testing using EDX, material with no addition of catalyst or 0% catalyst obtained iron content (Fe) 98.49, carbon (C) 1.51, with the addition of 10% catalyst obtained iron content (Fe) 98.10 carbon (C) 1.90, with the addition of 20% catalyst obtained iron content (Fe) 98.06 carbon (C) 1.94, with the addition of 30% catalyst obtained iron content (Fe) 97.46 carbon (C) 2.54. From the test results, it was found that the carbon content increases with the addition of catalysts. The higher the carbon value, the more solid crystals formed in the steel structure. The more solid crystals in the steel structure cause an increase in hardness and strength [24]. Carbon can also harden steel by blocking the movement of dislocations in the crystal structure [25]. Dislocations are defects in crystals that can cause plastic deformation. The addition of carbon can inhibit the movement of these dislocations, thereby increasing the hardness and strength of the steel [26]. Carbon forms strong bonds with iron atoms in the steel structure. This increases strength and hardness due to stronger bonds between atoms in the steel structure. In addition, carbon can also form interstitial alloys with iron, where carbon atoms occupy the space between iron atoms in the crystal structure, making the steel harder [27]. The elemental distribution resulting from the pack carburizing process with the addition of catalyst and without the addition of catalyst after testing with EDX-Mapping is presented in Figure 5.

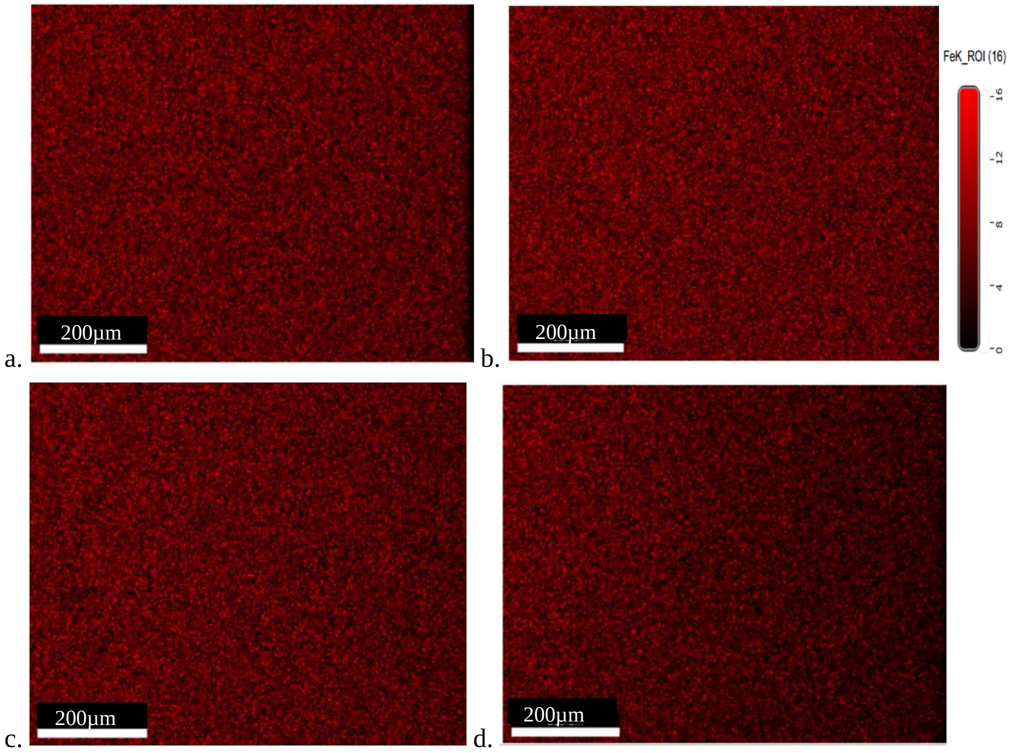

Figure 5 a. Distribution of Fe elements without the addition of catalysts. b. 10% catalyst. c. 20% catalyst. d. 30% catalyst.

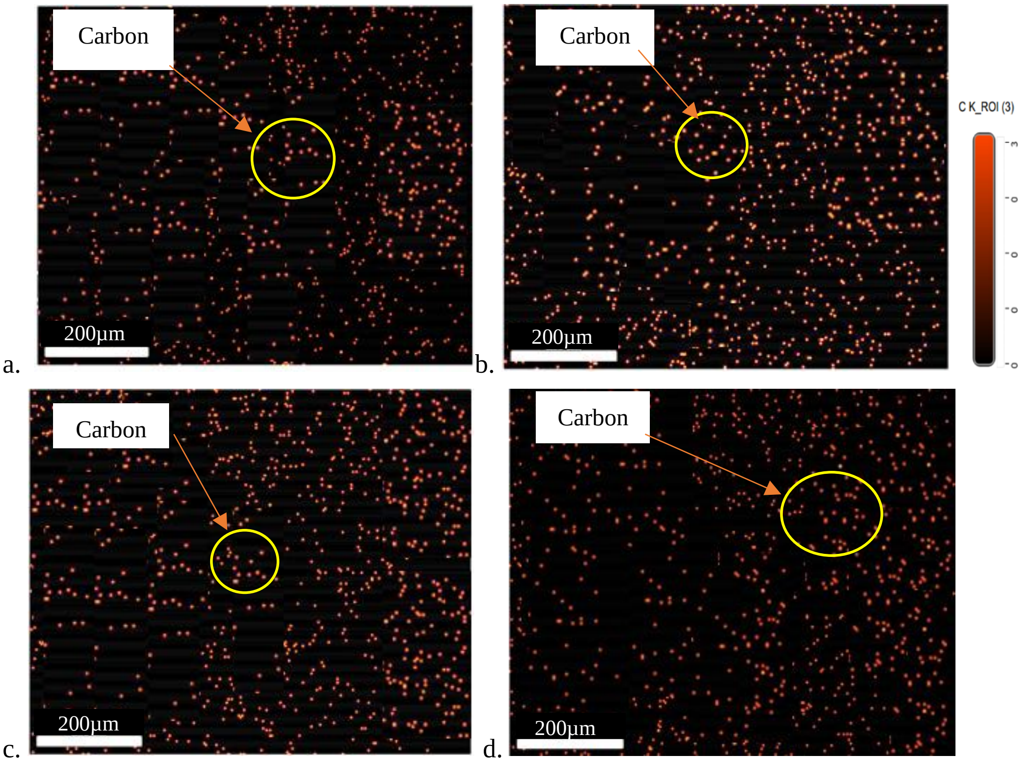

Figure 6 a. Distribution of C elements without the addition of catalyst. b. distribution of C elements with the addition of 10% catalyst. c. distribution of C elements with the addition of 20% catalyst. d. distribution of C elements with the addition of 30% catalyst.

EDX-Mapping testing was carried out to determine the distribution or distribution of elements, such as iron and carbon elements; in this study, testing was carried out with a magnification of 1000x with a scale of 200 microns in the Cross-Section area resulting from the pack carburizing process with the addition of catalysts and without the addition of catalysts as in Figures 6, and 7 showing the distribution pattern of elements. The test results show that the distribution of carbon elements is more widely spread in the surface area of the material, it was because the surface of the material was in direct contact with the carbon source, causing carbon atoms from the carburizing material to seep into the steel surface more easily than into the material [28]. Due to the difference in partial pressure of carbon on the surface and inside the material, it causes a greater flux of carbon to the surface [29]. In addition, due to the influence of a relatively fast holding time, carbon absorption is more dominant on the surface [8].

The catalyst plays a very important role in the spread of carbon elements. It can be seen from the test in Figure 6 that the more catalyst added, the more carbon spread on the surface of the material. The first reason was that catalysts in pack carburizing often increase the reaction rate between carbon and the surface of steel materials [11]. When more catalysts are added, the reaction between carbon and the material surface can occur more quickly and efficiently. This results in more even carbon uptake across the surface of the material rather than just in certain areas [4]. Secondly, catalysts can also increase the ability of carbon atoms to permeate the material [30]. In the presence of a catalyst, the activation energy for the carbon diffusion process into the material can be reduced, allowing carbon atoms to penetrate deeper into the material more effectively. As a result, the spread of carbon can be more even throughout the thickness of the carburizing coating [14]. The catalyst can also reduce the effect of excessive carbon deposition on the surface of the material [13]. When a catalyst is present, carbon tends to be more absorbed into the material than deposited on the surface, resulting in a more homogeneous carburizing coating. The more catalysts added in the pack carburizing process, the more even and more carbon spreading that occurs on the surface of the material [15].

3.4. Corrosion

Corrosion testing of metals is a process to evaluate the resistance of metals to damage caused by chemical reactions with the environment, such as oxygen, water, or other chemicals. The purpose of corrosion testing is to measure how well metals can resist corrosion processes that can reduce the life and performance of metals [24]. The data obtained was presented in the form of Figure 7. It was used to measure the corrosion rate of materials that have undergone the pack carburizing process or before experiencing pack carburizing treatment, as well as to compare the corrosion resistance of materials that undergo carburizing with and without the addition of catalysts.

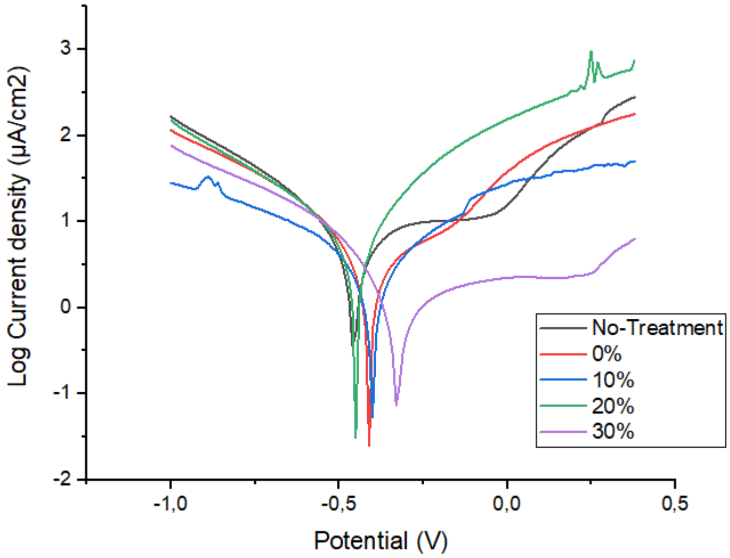

Figure 7. Corrosion stain of specimens subjected to carburizing and without carburizing.

The results of the corrosion rate of each treatment are different. After undergoing treatment, the corrosion resistance tends to be better. The following was the corrosion rate data, both test objects that do not undergo carburizing and those that experience carburizing. The corrosion rate of specimens without treatment or carburizing was 0.075. For test specimens with treatment without the addition of catalyst (0%), the corrosion rate was 0.067; for test specimens with an additional 10% catalyst, the corrosion rate was 0.054; for test specimens with an additional 20% catalyst, the corrosion rate was 0.021, and for test specimens with 30% catalyst is 0.016. The data obtained showed that the lowest corrosion rate was on objects that experienced carburizing with the addition of 30% catalyst, and the highest corrosion rate was found in the test specimen without treatment.

Table 2. Corrosion test results data

Variation	βa (V/decade)	βc (V/decade)	E Corr (V)	I Corr (μA)	CR (mm/year)
No-Treatment	1.388	0.262	0.460	6.658	0.075
0% Catalyst	0.486	0.433	-0.410	5.977	0.067
10% Catalysts	0.458	0.217	-0.580	4.589	0.051
20% Catalysts	0.940	0.257	-0.340	1.812	0.021
30% Catalysts	2.009	0.177	-0.330	1.395	0.016

With the increase in carbon after undergoing the carburizing process, the corrosion rate decreases, and the higher the carbon value due to the influence of the catalyst, the corrosion rate decreases. Here, the role of carbon-on-carbon corrosion was prominent. Carbon was able to reduce the corrosion rate of the material. Carbon plays a role in increasing the resistance value of the material, and the higher the resistance value, the lower the corrosion rate [31]. This increase in carbon content significantly increases the resistance value of the material, which in turn can reduce the corrosion rate [32].

Carbon has a vital role in reducing the corrosion rate of low-carbon steel that has undergone pack carburizing. First, the addition of carbon through the carburizing process can increase the hardness and strength of the material, which makes the steel surface more resistant to deformation and wear [33]. This reduces the possibility of damage to the surface, which can be the starting point for corrosion formation [4]. Secondly, carbon can also form carbides with other metallic elements in the material structure. These carbides are more inert or less susceptible to corrosive environments than the base metal, thus protecting the steel surface from chemical reactions that cause corrosion [34]. Carburizing can also block the access of corrosive substances to the metal surface, reducing the overall corrosion rate [35]. Lastly, the increased hardness and strength of the material after carburizing can reduce the susceptibility of steel to galvanic corrosion [36]. This occurs when two metals with different electrochemical potentials come into contact in an electrolyte-containing environment, which can accelerate corrosion. With increased hardness, low-carbon steel that has been carburized becomes more resistant to galvanic corrosion, maintaining the structural integrity of the material over a longer period [13].

Carbon resulting from the pack carburizing process can form inhibitors in low-carbon steel that can reduce the corrosion rate. This happens because the carbon added through the carburizing process can form carbides with other metal elements in the material structure [4]. These carbides are more inert to corrosive environments and can act as corrosion inhibitors. The formed carbides can form a protective film on the steel surface, blocking direct contact between the base metal and corrosive substances such as water or oxygen. This reduces the possibility of chemical reactions causing corrosion so that the corrosion rate can be significantly reduced. Carbides can also reduce the diffusion speed of corrosive substances into the steel material structure by hindering the entry of corrosive substances, carbides can reduce the corrosion rate by slowing down the corrosion process occurring on the steel surface [35]. The carbon resulting from the pack carburizing process not only improves the hardness and strength of the material, but also can form an effective corrosion inhibitor in low-carbon steel, which in turn can significantly reduce the corrosion rate [24].

4. CONCLUSION

This research is focused on the effect of catalysts in the pack carburizing process on hardness, carbon diffusion, microstructure, and corrosion rate of AISI 1020 low carbon steel, after undergoing a pack carburizing process for 2 hours and cooled with water. The following conclusions are obtained from the research that has been done:

1. The catalyst affects the hardness value. The more catalyst added, the higher the hardness due to the addition of more carbon diffusion.
2. The catalyst also affects the formation of microstructure. The more catalyst added, the more martensite structure was formed. The less added the formation of pearlite was greater, the more carbon content, the easier it was to form a martensite structure.
3. Carbon diffuses more and more as the catalyst is added, indicating the catalyst can reduce the carbon content.
4. The corrosion rate decreases after carburizing due to the added carbon.

ACKNOWLEDGMENTS

The authors would like to thank the colleagues and academic staff of the Mechanical Engineering Postgraduate Program at Brawijaya University. This research did not use financial assistance from any organization. Therefore, no liability of interest can be stated by the authors.

REFERENCES

[1] W. D. Callister Jr and D. G. Rethwisch, Characteristics, Application, and Processing of Polymers. 2018.

[2] G. Parrish, Carburizing:Microstructures and Properties. 1999. [Online]. Available: http://link.springer.com/10.1007/BF02646170

[3] I. Mon, Yerimadesi, and Hardeli, “Kimia Fisika (Kinetika Kimia).” p. 32, 2012. [Online]. Available: http://repository.unp.ac.id/26756/1/2012-Buku kinetika kimia %28Yerimadesi%2C dkk%29 1.pdf

[4] O. Adedipe *et al.*, “Explicit microstructural and electrochemical study of value-added carburized mild steel with coconut shell ash and CaCO 3 nanoparticles derived from periwinkle shell,” Chem. Data Collect., vol. 45, no. March, p. 101028, 2023, doi: 10.1016/j.cdc.2023.101028.

[5] H. Hafni, S. Hadi, and E. Edison, “The Influence of Calcium Carbonate Composition and Activated Carbon in Pack Carburizing Low Carbon Steel Process in the Review of Hardness and Micro Structure,” IOP Conf. Ser. Earth Environ. Sci., vol. 97, no. 1, 2017, doi: 10.1088/1755-1315/97/1/012037.

[6] P. A. Ihom, “Case hardening of mild steel using cowbone as Energiser,” African J. Eng. Res., vol. 1, no. October, pp. 97–101, 2013.

[7] N. Thammachot, P. Nachaisit, W. Homjabok, C. Peeratatsuwan, and A. Mayai, “The Effects of Energizer, Carburizing Temperature and Time on the Mechanical Properties of Hardened Big Knives in a Pack Carburizing process,” KKU Eng. J., vol. 43, no. December, pp. 172–177, 2016, doi: 10.14456/kkuenj.2016.33.

[8] Ramli, C. C. Wu, and A. Shaaban, “Mechanical properties of pack carburized scm 420 steel processed using natural shell powders and extended carburization time,” Crystals, vol. 11, no. 9, 2021, doi: 10.3390/cryst11091136.

[9] A. González-Angeles, J. López-Cuevas, and N. Pitalúa-Díaz, “Comparison of CaCO3 from natural sources and artificial carbonates as activators of solid-phase carburizing of low-carbon steel,” Met. Sci. Heat Treat., vol. 55, no. 7–8, pp. 355–357, 2013, doi: 10.1007/s11041-013-9634-4.

[10] “Ilmu Logam II - Ir. Wahid Suherman. Surabaya, 1998.”

[11] T. Dwi Susanto, N. Rekto Prabowo, and B. Darmawan, “Intuisi Teknik dan Seni Efektifitas Katalis Proses Pack Carburizing Terhadap Kekerasan Permukaan dan Struktur Mikro Baja ST 42 The Effectiveness of Pack Carburizing Catalyst Against Surface Hardness and Microstructure of ST 42,” vol. 12, no. 2, pp. 29–39, 2020.

[12] O. Adedipe *et al*., “Unveiling high-performance carburized mild steel using coconut shell ash and CaCO3 nanoparticles derived from periwinkle shell,” Int. J. Adv. Manuf. Technol., vol. 126, no. 9–10, pp. 4711–4721, 2023, doi: 10.1007/s00170-023-11399-w.

[13] N. Shell, W. Powders, and C. Duration, “Effective Case Depth and Wear Resistance of Pack Carburized,” 2022.

[14] S. Dampang, E. Purwanti, F. Destyorini, S. B. Kurniawan, S. R. S. Abdullah, and M. F. Imron, “Analysis of Optimum Temperature and Calcination Time in the Production of CaO Using Seashells Waste as CaCO3 Source,” J. Ecol. Eng., vol. 22, no. 5, pp. 221–228, 2021, doi: 10.12911/22998993/135316.

[15] I. Jamal, M. Rahman, and A. Abdullah, “Pengaruh Karburisasi Padat dengan Katalisator Cangkang Kerang Darah (CaCO 2) Terhadap Sifat Mekanik dan Keausan Baja St . 37,” no. Snttm Xiii, pp. 15–16, 2014.

[16] D. N. K. Putra Negara, I. D. M. K. Muku, I. K. G. Sugita, I. M. Astika, I. W. Mustika, and D. G. R. Prasetya, “Hardness Distribution and Effective Case Depth of Low Carbon Steel after Pack Carburizing Process under Different Carburizer,” Appl. Mech. Mater., vol. 776, pp. 201–207, 2015, doi: 10.4028/www.scientific.net/amm.776.201.

[17] P. I. Purboputro and R. Ekaputra, “Analysis of Carburizing Effect Due to Hardness and Microstructure on ST 60 Steel Using Carbon Particle with 80 Mesh,” Urecol Journal. Part E …. 2022. [Online]. Available: http://e-journal.urecol.org/index.php/uje/article/view/176%0Ahttp://e-journal.urecol.org/index.php/uje/article/download/176/192

[18] T. D. Widodo, R. Raharjo, H. Kusumaningsih, R. Bintarto, R. C. Siswoyo, and M. N. Sasongko, “Pengaruh Tegangan dan Waktu pada Proses Elektropolishing terhadap Surface Roghness Material Stainless Steel AISI 316L,” J. Rekayasa Mesin, vol. 10, no. 3, pp. 309–316, 2019, doi: 10.21776/ub.jrm.2019.010.03.11.

[19] S. Nasional, T. Riset, I. P. Series, and S. Vol, “ANALISA PROSES CARBURIZING BAJA AISI 4140 TERHADAP SIFAT MEKANIK DAN MIKROSTRUKTUR YN Rohmat,” vol. 8, no. 1, pp. 319–326, 2022.

[20] A. Tempurung, K. Di, T. Dari, and S. Micro, “KARBON RENDAH DENGAN MENGGUNAKAN CALCIUM CARBONAT DAN,” vol. 5, no. 1, pp. 6–11, 2015.

[21] D. H. fig. Si. and M. P. Drs. Syukri S, “Kesetimbangan Fasa,” Univ. negeri Padang, 2013.

[22] Abdillah and & Hartono, Analisis Sem. 2015.

[23] A. Al-Jauhari, “Kata Pengantar,” Dialog, vol. 44, no. 2, pp. i–Vi, 2021, doi: 10.47655/dialog.v44i2.507.

[24] L. Joska, J. Fojt, M. Hradilova, F. Hnilica, and L. Cvrcek, “Corrosion behaviour of TiN and ZrN in the environment containing fluoride ions,” Biomed. Mater., vol. 5, no. 5, 2010, doi: 10.1088/1748-6041/5/5/054108.

[25] T. J. Irwanto and A. Irmawan, “Pengaruh Pemanfaatan Limbah Kulit Kerang Bambu Sebagai Pengganti Sebagian Semen Terhadap Kuat Tekan Beton dengan Penggunaan Agregat Kasar Madura,” Ge-STRAM J. Perenc. dan Rekayasa Sipil, vol. 4, no. 1, pp. 21–26, 2021, doi: 10.25139/jprs.v4i1.3360.

[26] A. Srivastava, H. Kumar, M. Z. Khan Yusufzai, and M. Vashista, “Microstructural characterization of pack carburized is-2062 low carbon steel using magnetic barkhausen noise,” Mater. Today Proc., vol. 16, pp. 439–443, 2019, doi: 10.1016/j.matpr.2019.05.112.

[27] “edited by German S. Fox-Rabinovich, George E. Totten. - Steel Heat Treatment Metallurgy and Technologies (2007, Taylor & Francis) - libgen.li.pdf.”

[28] R. J. Bishop and R. E. Smallman, “Modern Physic Metallurgy & Materials Engineering,” Butterworth-Heinemann, p. 256, 1962.

[29] O. Adedipe *et al.*, “Sustainable carburization of low carbon steel using organic additives: A review,” Sustain. Mater. Technol., vol. 38, no. September, 2023, doi: 10.1016/j.susmat.2023.e00723.

[30] R. Umunakwe, O. C. Okoye, C. I. Madueke, and D. O. Komolafe, “Effects of Carburization with Palm Kernel Shell/Coconut Shell Mixture on the Tensile Properties and Case Hardness of Low Carbon Steel,” FUOYE J. Eng. Technol., vol. 2, no. 1, 2017, doi: 10.46792/fuoyejet.v2i1.83.

[31] D. A. K. Hussein, D. L. K. Abbas, and A. K. Hameed, “Investigation Corrosion and Mechanical ةسارد لكأتلا صاوخلاو ةيكيواكيملا ذلاوفلل ضخنملا نوبراكلا هبركملا,” J. Eng. Sustain. Dev., vol. 22, no. 2, pp. 8–17, 2018.

[32] H. Ameen and K. Hassan, “Effect of nitrocarburizing on corrosion resistance of carbon steel,” Am. J. Sci. Ind. Res., vol. 1, no. 2, pp. 320–325, 2010, doi: 10.5251/ajsir.2010.1.2.320.325.

[33] M. F. Sidiq, Soebyakto, G. R. Willis, and M. A. Shidik, “The effect of coffee powder as a carburizing agent and preventing corrosion,” IOP Conf. Ser. Mater. Sci. Eng., vol. 1088, no. 1, p. 012084, 2021, doi: 10.1088/1757-899x/1088/1/012084.

[34] “Pengaruh Variasi Temperatur Proses Pack Carburizing Terhadap Laju Korosi Material Baja Karbon ASTM A36.pdf.”

[35] K. S. Hassan, A. I. Razooqi, and M. H. Ridha, “Mechanical, Pure Fatigue and Corrosion Fatigue Properties of Pack Carburizing Low Carbon Steel Aisi 1020 by Using Waste Organic Materials in 3.5% Nacl,” pp. 1–15, 2020.

[36] I. K. Suarsana, I. M. Astika, and I. G. P. Agus Suryawan, “Efek perlakuan pack carburizing dan media korosif pada baja AISI 1045 terhadap laju korosi,” J. Energi Dan Manufaktur, vol. 14, no. 2, p. 37, 2022, doi: 10.24843/jem.2021.v14.i02.p01.