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The Effect of Airflow Speed as Cooling Media in the Hardening Process to the Hardness, Corrosion Rate and Fatigue Life of Medium Carbon Steel

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Abstract. Carburizing is a method for obtaining a sturdy material surface. This hard surface is used for machine elements that intersect with other materials, so failure due to wear can be avoided. However, this increase in hardness has always been followed by decreased ductility. This condition certainly lowers the fatigue life of the material. For that, it is necessary to compromise between surface hardness and ductility. This study used AISI 1045 steel, which has a surface roughness of 0.4 and 4.7 μm with carburation media used, is a mixture of 80% coconut shell charcoal and 20% Barium carbonate. The sample was given the pack carburization treatment at 850^{o}C and holding time for 3 hours, and then cooled in the open air. The samples were reheated at 850^{o}C, holding time for 17 minutes, and then cooled with airflow at speeds of 10.34, 15.51, and 20.06 m/s for 30 minutes. This research shows that the surface of steel with a roughness of 0.4 μm has excellent performance with the hardness and corrosion level respectively 228.6 HV and 2.3586 mpy at cooling airflow rate of 20.06 m/s while the fatigue life of material occurs at the speed of airflow cooling 10.43 m/s.

Introduction

Carburizing is a heat treatment process to produce hard surfaces resistant to wear but have toughness and strength at the core of the material. Increased hardness and strength is caused by the diffusion of carbon atoms on the surface of the steel. Carburizing is usually applied to low-carbon steels. The quality of the galvanized steel depends mainly on its temperature and holding time. A rapid cooling process generally follows the carburizing process to obtain a carbon layer. The selection of the proper method has a significant effect on the properties of the desired material.

Carburizing usually does not stand alone, but also accompanied by other heat treatments, such as cooling, hardening and tempering. Steel with carburation process is then cooled with air and water will change the mechanical properties. The higher cooling rates during the quenching process will form smaller grain sizes, improving the hardness and strength of steel, but toughness and ductility are decreased [1]. A mixture of 80% charcoal and 20% sodium carbonate is used in carburizing on steel rod at a temperature of 930^{o}C. This treatment can change the microstructure, hardness, and tensile strength of the mild steel. This study shows that the longer the holding time will produce in the more profound the case zone and the stronger the material [2]. A critical factor in changing the properties of the material is to control the cooling rate after the carburizing or hardening process.

The cooling rate is determined by the cooling type used, e.g. water, saline solution, oil and air. Carburizing at the temperature of 900^{o}C and cooling in water will be formed martensitic microstructure so that the better mechanical properties obtained [3]. SAE 1020 steel when in contact with chloride ions can decrease ductility of the material [4]. Carburizing at 950^{o}C in the electrical muffle furnace and followed by the forging process will have different properties when cooled with normal air, compressed air or oil. Yield strength, ultimate tensile strength, and hardness are increase while the cooling rate after hot forging is increased.

When the steel is cooled in the oil will form a microstructure of fine ferrite and pearlite, the elongation of the material drastically decrease [5]. Carbide type and mechanical properties in carburized steel have a robust correlation. The distribution of spherical carbide uniformly enhances tensile and bending strength due to the suppression of initial and crack propagation [6]. The St 37 carbon steel is heated at a temperature of 850°C for one hour and then cooled with water, air and holds in the furnace until cold can improve its mechanical properties [7].

Quenching can form a martensitic microstructure. Martensitic causes the hardness to increase, but the material becomes brittle. Therefore, a tempering process is needed to enhance the ductility and toughness of martensitic. At a high-temperature tempering of 600°C, the microstructure changes from martensitic to tempered martensitic and ferrite grain. Tempering for medium carbon steel can change material properties [8]. The cooling rate in the quenching process affects the hardness of oxide dispersion strengthened steel. The higher the cooling rate and normalizing without tempering, its hardness is higher when compared to normalizing with tempering. The greater the number of dissolved carbides in the oxide dispersion strengthened steel matrix as a solid solution will generate higher hardness [9].

Austenization of CA-15 3Mo-3Ni steel at 1100°C for 3 hours and followed by air cooling. Then the samples were given a tempering treatment of temperature variations of 300°C, 400°C, 600°C, and 700°C with holding times of 1 hour, 3 hours, and 5 hours. It is known that there is a reduction in hardness at a tempering temperature of 400-700°C with all holding time [10]. The stainless steel 13Cr3Mo3Ni ingot was given hot forging at temperature 900-1100°C and austenized at 1050°C for 1 hour, followed by oil quenched. The austenized stainless steels were tempered at a temperature of 600°C, 650°C, and 700°C with holding time 1 hour, 3 hours, and 6 hours. The corrosion rate increases with increasing tempering temperatures, as the diffusion of oxygen atoms depends on the tempering temperature [11]. The higher the holding time and temperature of tempering tend to decrease the hardness and tensile strength of 410 martensites stainless steel [12].

Fatigue is the main factor that causes the mechanical structure to fail, about 85% [13]. Heat treatment processes can improve the fatigue strength of 316-austenitic steel by forming the carburized smooth surface. This research used a mixture of CO and H2. Carburizing at a temperature of 773K for 15 and 35 hours increases the carburized case's high corrosion resistance. Soaking media is a solution of 3%NaCl [14]. The fatigue strength can be improved by the plasma carburizing process up to 25%. Whereas, the lower carbide film compound will reduce the limit fatigue of material significantly [15]. Two types of steel, 16MNCR5 and 17CRNI6-6, are given a carburizing process and then followed high-pressure gas cooling has a difference in fatigue behavior. The growth of austenite grains size of both types of steel can decrease its fatigue strength, although the 17CrNi6-6 steel is still performing better when compared with 16MNCR5 [16].

A mixture of 150 g of charcoal, 15 g of sodium chloride, and 30 g of barium carbonate as a carburizing medium significantly increases fatigue resistance SAAB 709 material. The combination of a carburization temperature of 900°C and an immersion time of 4 hours provides a substantial increase in fatigue strength. This condition is caused by the depth of the carbon layer that forms on the shaft surface [17]. Double tempering is another method for increased fatigue resistance. Martensitic structures increase the hardness of the material. For this reason, it is necessary to reduce hardness by decarburization. Shot peening followed by heat treatment causes residual compressive stress on the steel surface. This residual stress increases the fatigue life of the 56SiCr7 spring steel [18].

The fatigue strength can be increased by flame hardening using an oxy-acetylene torch. Medium carbon steel with 0.39%C is hardened with an oxy-acetylene torch followed by rapid cooling with water after hardening. This study's hardening temperature was 750°C with a holding time of 5, 10, and 15 seconds. The speed of hardening used is 3.5, 1.75, and 1,165 mm/s. From this study, it is known that the higher the flame hardening speed, the fatigue strength of the material decreases [19]. Carburizing media of pomace canaliculated Lamarck (PCL) shell was used in pack carburizing of steel SS400. The temperature pack carburizing is 950°C for 5 hours with a variation of 10%, 20%, and 30% of PCL shell powder. This research shows that the higher PCL shell powder, the hardness increase, and fatigue strength decrease. The pearlite structures increase during the tempering process so that the ductility and fatigue strength increase [20]. Shot peening (SP) and cavitation peening (CP) are methods to increase the fatigue strength of aluminum alloy 7075. SP and CP treatments can improve the life of fatigue by about 23%. The compressive residual stress caused by SP and CP is a major factor of increased fatigue strength [21].

Previous literature shows that the rate of cooling significantly affects the mechanical properties of the material. Different cooling media also have different cooling rates. This study's new method was to use airflow at a certain speed as a cooling medium. The selection of air as a cooling medium is based on literature that researchers understand that air can provide better mechanical properties. Besides, the amount of air is very abundant, and it is easy to control its cooling rate so that a compromise between hardness and toughness can be achieved.

Experiment Method

Material and Instrument. The material used in this study is AISI 1045 Steel from PT. Bhinneka Bajanas. After conducting tests at PT. Krakatau Steel obtained composition 0.98.46%Fe, 0.4679%C, 0.2529%Si, 0.6050MN, 0.1340Cr, 0.0109%P and 0.0070%S. Coconut shell charcoal powder (80%) and barium carbonate powder (20%) were used as an activator. This steel includes medium carbon steel, thereby increasing the carbon content on the sample surface because the diffusion process is not very significant.

The equipment used for this research is a digital perthometer with the brand Mahr Perthern for measuring surface roughness. Vickers Hardness Tester with Brand Wolpert dia-2-RC for testing surface hardness with JIZ Z 2244 Standard. Nikkon Metallurgical Microscope to observe microstructure. Electrochemical equipment made at the EG&G of Princeton Applied Research to measure the corrosion level of product tempering. Rotary bending machine with Shimadzu brand to measure fatigue durability of materials with standard test ASTM E466-07.

(a) (b) (c)

Fig. 1. Instrument for material characterization: (a) – vickers hardness tester, (b) – corrosion tester equipment, (c) – rotary bending testing machine

Method and Procedure. AISI 1045 Steel is made specimen for fatigue test under ASTM E466-07 standard with different surface roughness, namely nine samples (4.25-4.73 μm), nine samples (0.40-0.43 μm) and three samples (1.92 μm) (Fig. 2). The samples were given a pack carburizing treatment in the box with 80% coconut shell charcoal and 20% barium carbonate was then heated in the furnace at a temperature of 850^{o}C for 3 hours. And then, the samples were cooled in the open space. Samples were reheated gradually until 850^{o}C and held for 17 minutes. After that, airflow with a speed of 10.34, 15.51 and 20.06 m/s was used to cool samples for 30 minutes.

Coconut Shell charcoal powder is mashed and sifted to obtain a smooth size. In this research, the size of coconut charcoal powder is not regarded as a research variable. The test material is inserted into the Carburation box, where there is a mixture of coconut shell charcoal and Barium carbonate.

The samples are stacked neatly in a box and covered with coconut shell charcoal powder in the carburation box.

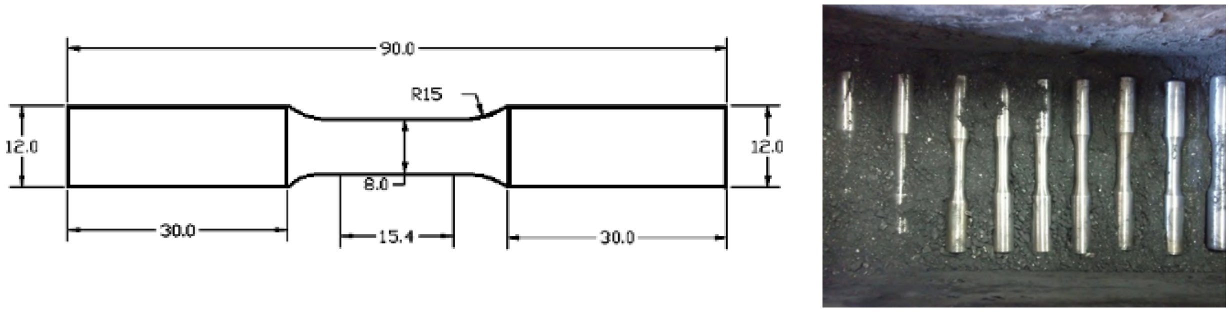

Fig. 2. ASTM E-466 standard test samples

The carburation box was heated in a furnace at a temperature of 850°C with a holding time of 3 hours. After 3 hours, the furnace is turned off, and the sample lets cool in it. Hardening is done by heating the sample at a temperature of 850°C and holding time of 17 minutes according to the sample's thickness. This process aims to improve the core part of the workpiece that is overheating during the carburizing process. The cooling process is carried out using air cooling media, spraying into specimens with airflow speed of 20.06 m/s, 15.51 m/s, and 10.34 m/s for 30 minutes.

Result and Discussion

Chemical Composition. Chemical composition testing was conducted in the chemical laboratory of PT. Krakatau Steel. Pack carburizing with coconut shell charcoal and barium carbonate ($BaCO_3$) as an activator can change chemical composition. There are differences between before and after carburizing treatment. Changes in chemical structure can be shown in Table 1.

Table 1. Chemical composition before and after carburizing.

Chemical Element	Raw Material (%)	Carburizing (%)
C	0.4679	1.0266
Si	0.2529	0.2501
P	0.0109	0.0067
S	0.0070	0.0056
Ni	0.0166	0.0068
V	0.0010	0.0014
Mo	0.0020	0.0006
W	0.0025	0.0023

The five chemical elements that have undergone significant changes are carbon elements, phosphorus, sulphur, nickel, vanadium, and molybdenum. The increase in carbon content reaches 119.41%. This increase in carbon atoms that caused the hardness of steel surface AISI 1045 has also increased. The content of wolfram, tungsten, molybdenum, nickel, and tungsten decreased significantly. At the same time, those elements are responsible for preventing the rate of corrosion. By reducing the content of these elements automatically leads to the speed of corrosion of this steel material has increased.

Surface Hardness. The diffusion depth of carbon atoms depends on the carburizing temperature and holding time during heat treatment running. The higher the temperature and holding time, the deeper carbon atoms diffuse. The smooth steel surfaces produce a more equitable distribution of carbon atoms. The diffusion of atoms moves evenly onto the steel surface and forms a carbon layer. This event will affect the increased hardness of steel surfaces more significantly. The depth of diffusions of carbon atoms on smooth surfaces is deeper than rough surfaces. Figure 3 shows that the higher the hardening treatment's airflow speed, the higher the hardness is produced. This phenomenon suggests that the velocity of airflow significantly affects the cooling rate of steel. The higher the airflow speed, the higher the cooling rate.

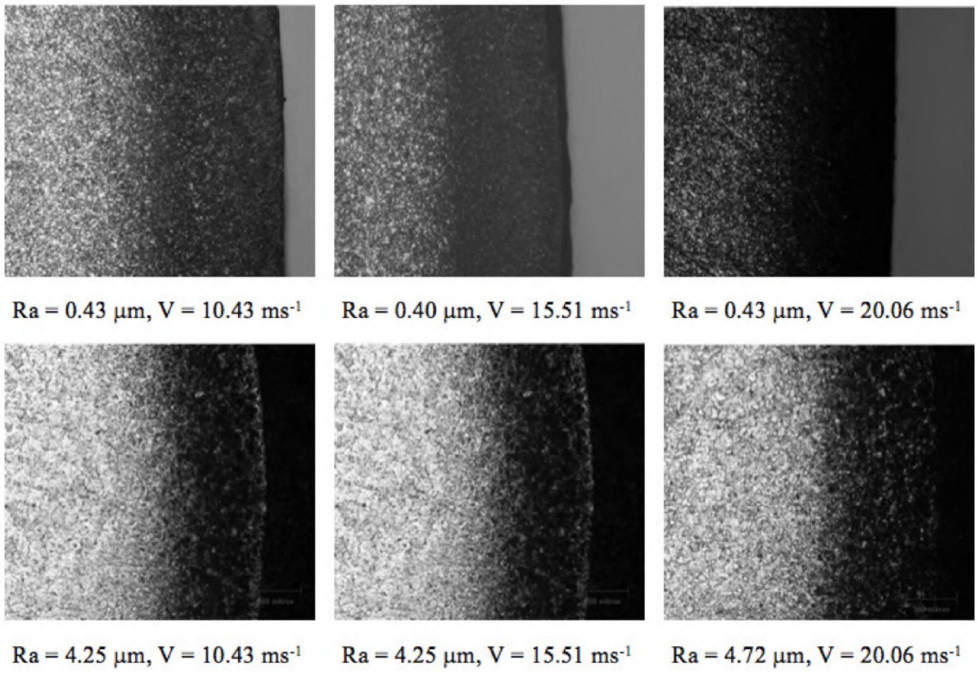

Fig. 3. Diffusion of carbon atoms to the surface

The diffusion of carbon atoms on rough surfaces resulted in a random distribution. The diffusion of atoms follows the phenomenon of surface roughness. At peak, surface roughness occurs the buildup of carbon atoms in certain areas. This condition causes non-uniform surface hardness. While on a smooth surface, the carbon diffusion is formed more evenly and densely.

The speed of airflow cooling after the hardening process has a different influence on surface hardness (Fig. 4). The higher the airflow rate cools the steel surface, the higher the hardness of the material. This condition is due to the high flow rate, which causes a high cooling rate as well. This condition applies to both rough and smooth surfaces. The difference is that the hardness on the smoother steel surface is higher compared to the uneven surface.

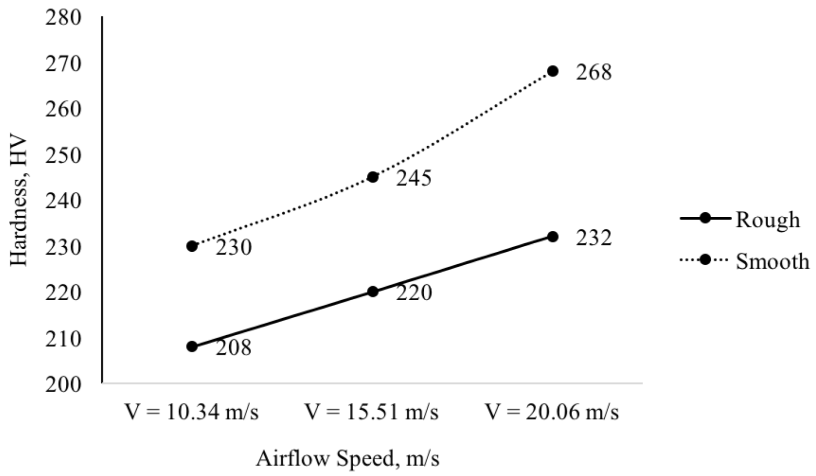

Fig. 4. Correlation between tempering airflow speed and surface hardness

The speed of air flowing has a significant effect on the heat taken from the cooling chamber. The higher the airflow rate, the greater the amount of heat incurred from the specimen. This amount of heat can affect the cooling rate of the sample. The higher the cooling rate, the higher the value of material hardness. This condition is in line with previous research using cooling media in water, oil, and air. From this research, it is known that cooling with water will produce the highest surface hardness. Water, oil, and air have different capabilities in the cooling of materials.

On rough surfaces indicates that the diffusion of carbon atoms is insufficient in reaching the physical core. From Figure 5, it can be seen that the 1-3 point has almost the same hardness on all airflow speeds. The hardness increased sharply from point 4 to the material surface. While on a smooth surface, the difference in hardness has occurred starting at position one then gradually rising to the 4th point (Fig. 6).

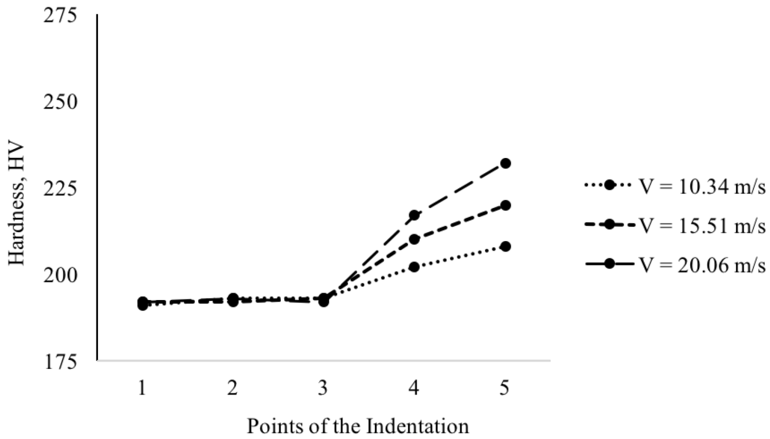

Fig. 5. Transverse hardness on material's rough surface

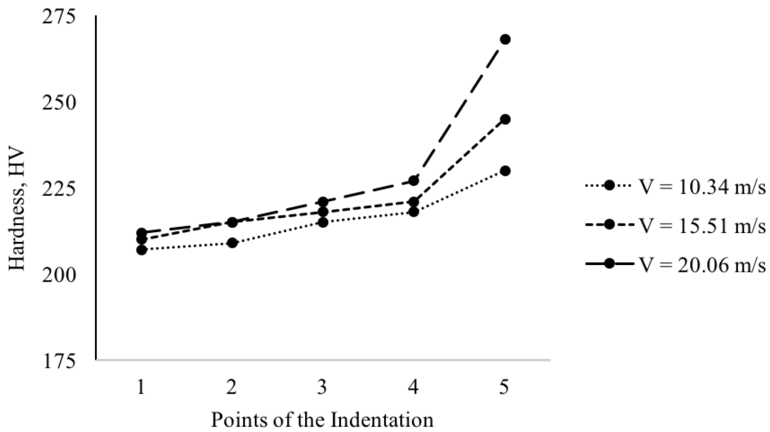

Fig. 6. Transverse hardness on material's smooth surface

A sharp increase occurred at the 5th point. This phenomenon becomes attractive due to increased hardness at point 1 to point 4, having a percentage change almost the same on both rugged and smooth surfaces. Increased hardness occurred very sharply from point 4 to point 5. Increased hardness on the flat surface reaches more than two times on rough surfaces. This hardness indicates that the second range of these points has a significant carbon content.

Corrosion Rate. Corrosion is one of the factors that cause material failure. Corrosion is the chemical reaction between the material and the surrounding conditions. Many studies have been conducted to reduce the material corrosion rate. Heat treatment is the method to reduce the occurrence of corrosion, in addition to other surface treatments. Figure 7 shows that the airflow speed in the cooling process significantly affects the corrosion rate. If the higher the airflow speed, the lower the corrosion rate. The high cooling rate was resulting in the accumulation of carbon atoms on the material surface. Carbon accumulation on surfaces is caused by limited time for carbon atoms to diffuse deeper. The corrosion rate is also influenced by surface roughness. The smooth surface of the material can withstand corrosion attacks. There are two reasons why the better corrosion rate on the smooth surface. Firstly, the smooth surface has an evenly distributed carbon atom setting to withstand corrosion attacks together. Secondly, the smooth surface has a contact area with less outside air so that the corrosion rate becomes obstructed.

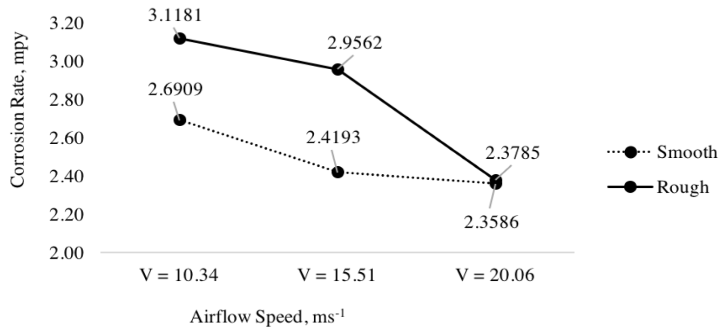

Fig. 7. Correlation between tempering airflow speed and corrosion rate

This corrosion rate is inversely proportional to material surface hardness. From this research, it is known that the higher the hardness of the steel surface, the lower the corrosion rate. This phenomenon is caused by the layer of carbon atoms formed on the surface of the material that can withstand the rate of corrosion. The carbon atom layer can protect the surface of steel reacts with the environment. This research is in line with Tokaji conducted that specimens undergoing carburizing treatment have excellent corrosion resistance [15]. While this study precisely shows that the corrosion rate is higher than the untreated material. The carbon layer can also cause the material surface to more brittle and easily crack. It is necessary to determine the compromise between hardness, corrosion rate, and fatigue life of the material.

The corrosion rate increases higher on the material subjected to heat treatment than the untreated material. The unprocessed material corrosion rate is 1,7915 mpy, while heat treatment materials have increased the corrosion rate to 3.1181 mpy or about 174.05%. This increase is caused by the residual stress generated by the carbon atom layer. Other causes are the content of W, Ni, and Mo that descend during the carburizing process, as it is known that these three chemical elements play a significant role in preventing corrosion.

Fatigue Resistance. Fatigue resistance is the material's ability to receive repeated loading and fluctuate over a certain period until failure. In this study, it is known that the velocity of airflow in the cooling process after hardening has a significant effect on the fatigue life of steel. The higher the airflow speed, the lower its fatigue resistance. However, in general, the material's fatigue life increases if exposed to heat treatment, compared with the materials without heat treatment.

Fig. 8 and 9 show that surface roughness affects the strength of material fatigue. This condition can be seen in the S-N diagram. The durability of excellent surface fatigue material increased by 6-27% compared to rough surfaces. Surface roughness is formed during the manufacturing process in grooves or scratches, which can be stress concentration points. In these areas, material stress is increased. This condition can trigger the occurrence of new cracks so that objects become broken.

The fatigue resistance of AISI 1045 steel is also affected by surface hardness. This research suggests that the more brittle surface will decrease the elasticity – a reduced number of cycles characterizes this phenomenon. The increased property fragility is caused by the carbon layer formed during the carburizing process. The high concentration of carbon can cause residual stress on the surface so that the material is broken when subjected to external force.

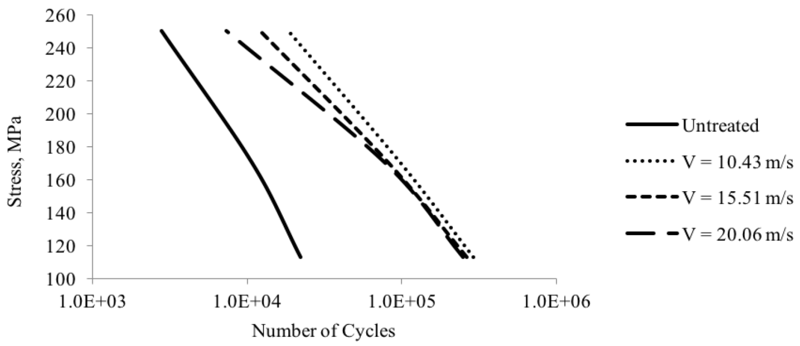

Fig. 8. Correlation between airflow speed and fatigue resistance on rough surface

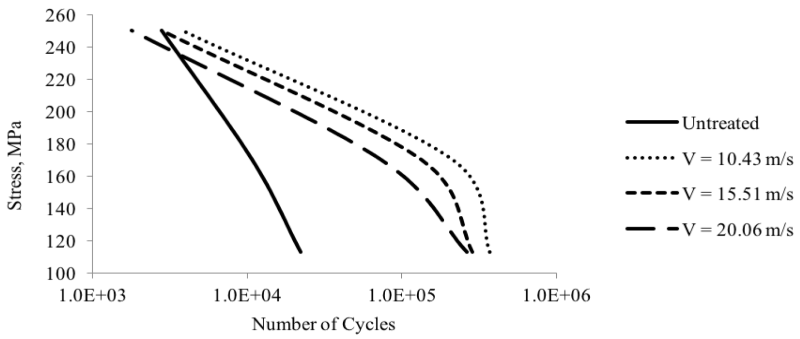

Fig. 9. Correlation between airflow speed and fatigue resistance on smooth surface

The steel provided by pack carburizing and followed hardening can significantly improve material fatigue life, both on the material with rough and smooth surfaces. The results of this research are in line with previous research. By carburizing, the fatigue strength is increased [14-15], [17]. Materials that receive preheating, austenitizing, quenching, and tempering can improve the fatigue strength of the material [22]. Ideally, the carburation process is followed by another method to lower the material's brittleness so it is not quickly broken. To increase the toughness and tensile strength can be followed by other processes such as tempering, shot peening, or hardening to relieve residual stress.

Conclusion

Carburizing and hardening are heat treatment processes to change the material to have the desired properties. There are several conclusions obtained from this research:

1. Carburizing and hardening on AISI 1045 steel followed by airflow cooling affect the hardness, corrosion rate, and fatigue life of the material.
2. Air cooling on the hardening process can increase the lifetime of material fatigue. This condition is inversely proportional to water and oil cooling media.
3. The flowing airspeed is related to the amount of heat taken from the sample during the hardening process. Airspeed directly affects the rate of cooling. The cooling rate affects the distribution of carbon atoms and phase-forming materials.
4. The higher airflow speed, the surface hardness is increased, but the corrosion rate and fatigue life are decreases.
5. The air can be an exciting cooling medium in the future by doing engineering at speed, temperature, cooling length, and other variables. Air does not significantly affect the change in material toughness drastically.

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