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# Analysis Of Hardening Products And Micro Structure Of Steel With Carbon Equivalent Variations And Cooling Oil Viscosity

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*ABSTRACT*

The heat treatment process in metallurgy has made progress due to advancements in science and technology. It aims to modify the properties of metals according to specific objectives, such as enhancing machinability and restoring elasticity. In this study, we investigated the impact of carbon equivalent and cooling oil viscosity on the microstructure and hardness of hardened steel. Specimens were subjected to the hardening process at varying temperatures based on their thickness and composition, followed by cooling using SAE 10, SAE 40, and SAE 90 oils. Micro photo testing and Vickers hardness tests were performed. The results show that carbon equivalent has a significant effect on hardness, while oil viscosity also influences it significantly. However, the interaction between carbon equivalent and oil viscosity does not have a significant effect. The highest average hardness values were obtained with SAE 10 oil for VCN 150 steel and SAE 10 oil for S45C steel, while specimens with a dominant martensitic structure had the highest hardness values compared to those with a ferrite structure, which had the lowest hardness values.

Keywords: hardening, carbon equivalent, oil viscosity, hardness, microstructure

## 1. INTRODUCTION

Today the metal industry is growing quite rapidly. Some manufacturers use steel as a raw material for their production. Carbon steel is also being widely used as machine components such as gears, shafts and other components that require hardness [1].

Hardening and microstructure of steel are two important factors that affect machine performance and reliability. At present, technological developments have made it possible to use various types of coolant oils in engine lubrication systems. Carbon equivalent and quenching oil viscosity are two parameters that have a significant influence on the hardening characteristics and microstructure of steel in machining [2].

Research on the analysis of hardening products and steel microstructure with variations in carbon equivalent and coolant oil viscosity is an important research area to study. Deep understanding of the relationship between carbon equivalents and coolant viscosity with hardening and microstructure of steel in engines will provide valuable insights in improving engine performance and reliability [3].

Through the analysis of hardening products, we can study the level of surface hardness of steel formed due to the lubrication process using coolant oil. Meanwhile, the analysis of the microstructure of steel will provide information about the crystal structure and microcomposition formed in the steel [4].

At present, the hardening and microstructure of steel in the context of the use of engine coolant oil has become the main focus of research in the field of mechanical engineering. Several previous studies have been carried out to explore the relationship between carbon equivalents and coolant oil viscosity with the hardening characteristics and microstructure of steel [5].

In a study by [6], they carried out an analysis of the effect of carbon equivalent on the hardening and microstructure of steel at different operating temperatures. The results of this study indicate that an increase in the carbon equivalent in the cooling oil causes an increase in the surface hardness of the steel. In addition, it was found that changes in the steel microstructure occur at higher levels of carbon equivalents.

Another study conducted by [7] focused on the effect of cooling oil viscosity on hardening and steel microstructure. They found that increasing the viscosity of the cooling oil resulted in a decrease in the surface hardness of the steel. In addition, the results of microstructural analysis show that high viscosity can affect the crystal growth and grain distribution of the steel.

Related research has also been conducted [8], who analyzed the effect of variations in carbon equivalent and coolant viscosity on the tensile strength of steel. The results of these studies indicate that increasing the carbon equivalent and cooling oil viscosity significantly increases the tensile strength of steel. However, the effect of the combination of these two parameters on the mechanical properties of steel still needs to be studied further.

In addition, several studies have also revealed that changes in the hardening and microstructure of steel can have an impact on the service life of the machine. For example, the study by [9] revealed that variations in carbon equivalent and coolant oil viscosity can affect the level of wear and deformation of the engine surface.

In addition to the studies previously mentioned, there are several other studies which provide important insights into the effect of carbon equivalents and coolant oil viscosity on hardening and microstructure of steel in machining.

In a study by [10], they investigated the effect of carbon equivalent content in cooling oil on steel strength and wear resistance. The results showed that an increase in the carbon equivalent content resulted in an increase in the hardness and strength of the steel. In addition, the wear resistance of steel also increases with an increase in the carbon equivalent content. These findings suggest that carbon equivalents can play a key role in improving the mechanical performance of steel in machines.

Another relevant study conducted by [11], who explored the effect of coolant oil viscosity on steel surface wear. The results showed that the proper viscosity can reduce the wear of the steel surface by reducing the friction and wear on the contact between the steel surfaces. This shows that the viscosity of the cooling oil can be an important factor in extending engine life and reducing maintenance costs.

In addition, research by [12] discussed the effect of variations in carbon equivalent and coolant viscosity on steel toughness. The results showed that the optimal combination of carbon equivalent and coolant viscosity can increase the toughness of steel, which is an important indicator in assessing the strength and reliability of the material in the machine.

In a recent study by [13], they carried out an analysis of the microstructure and mechanical properties of steel by considering the interaction between carbon equivalents, coolant oil viscosity, and engine operating temperature. Their findings show that the right combination of these three factors can result in a more homogeneous microstructure and better mechanical properties in steel.

Taken together, these studies provide a more comprehensive understanding of the effect of carbon equivalents and coolant viscosity on hardenability, microstructure, mechanical properties, and service life of steel in machines. By integrating these findings, this study aims to make additional contributions in understanding the complex interactions between carbon equivalents, coolant oil viscosity, and steel characteristics in the context of analysis of hardening products and microstructures in machining.

In this research, we will vary the carbon equivalent and engine coolant viscosity with the aim of assessing their impact on hardenability and microstructure of steel. Experimental methods will be used to obtain accurate and reliable data. In addition, microscopic analysis will be carried out to observe changes in the steel's microstructure.

The results of this study are expected to provide deeper insight into the effect of carbon equivalent and coolant oil viscosity on the hardening and microstructure of steel in engines. This information can be used as a basis for developing more effective and efficient lubrication systems, as well as for improving engine quality and reliability in various industrial applications.

Heat treatment is also progressing driven by increased science and technology. The heat treatment process has in order to shape the properties of metals with different finishes, heat treatment can also be used to change certain properties for manufacturing purposes, namely, improve machineability, improve formability, and restore elasticity after cold work operations [14].

Broadly speaking there are 2 types of steel, namely carbon steel and alloy steel. This study uses alloy steel as a specimen material. The most abundant element in use in alloy steel, namely: Cr, Mn, Si, Ni, W, Mo, Ti, Al, Cu, Nb, Zr. Alloy steel is divided into 3, namely:

1. Low alloy steel, is an alloy steel whose alloying elements are less than 2.5% wt.
2. Medium alloy steel, Medium alloy steel is an alloy steel whose alloying elements are 2.5% - 10% wt.
3. High alloy steel, is an alloy steel whose alloying elements are more than 10% wt.

The concept of carbon equivalent is used in steel and cast iron to determine alloy properties when not only carbon is used as an alloy. The principle of carbon equivalent is to change the percentage of alloying elements other than carbon to carbon equivalent in percentage, because the iron carbide phase is better understood than other alloy phases. Below is the formula for calculating carbon equivalent [15]:

$$CE = \%\mathrm{C} + \frac{\%\mathrm{Mn} + \%\mathrm{Si}}{6} + \frac{\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V}}{5} + \frac{\%\mathrm{Cu} + \%\mathrm{Ni}}{15}$$

Hardening is a heat treatment process carried out to produce hard workpieces. This treatment consists of heating the steel to its heating temperature (austenizing temperature) and holding it at this temperature for a holding time appropriate to the composition and thickness of the material and then cooling it to a very high cooling rate or quenching it to obtain the desired hardness. The main purpose of the hardening process is to increase the hardness of the workpiece and increase wear resistance. The higher the hardness, the higher the wear resistance [16].

Oil or lubricant (lubricat or often called lube) is a material that serves to reduce the wear and tear of two surfaces of moving objects that rub against each other. Microstructure is the geometric arrangement of the grains and phases in a material. The variables of these structural features include number, size, shape and distribution.

The Vickers hardness test uses a diamond pyramid indenter with a square base. The angles between the opposite faces of the pyramid are 136°. The loads normally used in the Vickers test range from 1 to 120 kg, depending on the hardness of the metal to be tested. In practice, this area is calculated from microscopic measurements of the length of the diagonals of the trail. DPH (pyramid hardness number) can be determined from the following equation:

$$VHN = \frac{2P\sin(\frac{\theta}{2})}{d^2} = \frac{(1{,}854)P}{d^2}$$

Where, P = Load applied (kg), d2 = Indented surface area (mm).

## 2. RESEARCH SIGNIFICANCE

Until now, metal materials have not been replaced to meet the needs in the engineering field. Moreover, especially in the field of mechanical engineering, which requires approximately 70% metal from one device unit, for example, machine tools. The need for this metal must exist. Even though natural resources (metal mines) will run out more and more and it will take a long time to renew. There are many properties of metals that cannot be possessed by other engineering materials. Such as wood, plastic, rubber, ceramics and so forth. The type of composite does not necessarily arise from the inherent properties of the forming material/mixture.

Therefore it is important to make efforts in metal treatment to be able to maintain its basic properties as well as improve the quality of other properties better. for example machining properties, hardness, corrosion, elongation and so forth. The conductivity property is difficult to find in composite materials.

In relation to metal properties, research and development need to be continued to obtain better properties and quality. For this reason, researchers conducted research in the field of metal heat treatment engineering. Both in determining the composition of the alloy and the temperature of the heat treatment.

## 3. RESEARCH METHODS

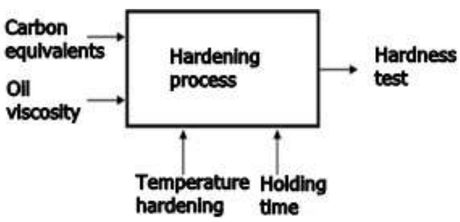


Figure 1 Research Concept Framework

The data collection method used in this study, namely:
1. Preparation of Research Specimens
2. Hardening Process
3. Cooling Process
4. Sanding
5. Polishing
6. Etching
7. Microstructure test
8. Hardness test

The data processing method used in this study was factorial anova using Minitab 18 assistance. The data obtained was then analyzed and discussed to determine the influence of the 2 independent variables that affected the results of the dependent variable. In this study, there were 2 group variations that were compared, namely carbon equivalent and cooling oil viscosity in the hardening process.

## 3. RESULTS AND DISCUSSION

The following is a chemical composition table used to calculate the carbon equivalent value for each material:

**Tabel 1** *Chemical Composition* Material

| Material | **C** | **Si** | **Mn** | **Co** | **Cr** | **Mo** | **Ni** | **V** |
|---|---|---|---|---|---|---|---|---|
| VCN 150 | 0,4 | 0 | 0,7 | - | 1.50 | 0.25 | 1.60 | - |
| SCM 440 | 0,4 | 0 | 0,8 | - | 1.05 | 0.25 | - | - |
| S45C | 0,4 | 0 | 0,7 | - | 1.50 | 0.25 | 1.60 | - |

The following is the calculation of the carbon equivalent value resulting from the chemical composition of each steel:

Calculation of carbon equivalent VCN 150

$$CE = 0{,}38 + \frac{0{,}65 + 0{,}30}{6} + \frac{1{,}50+0{,}25}{5} + 0 + \frac{0+1{,}60}{15}$$

$$CE = 0{,}38 + 0{,}16 + 0{,}35 + 0{,}11$$

$$CE = 1$$

The following is data on the effect of carbon equivalent and oil viscosity on the hardness of the results of the Vickers test:

**Table 2** Hardness Test Data

| Jenis Baja | Viskositas Oli Pendingin | | |
|---|---|---|---|
| | SAE 10 | SAE 40 | SAE 90 |
| VCN 150 | 472,9 | 461,2 | 468,4 |
| | 482,7 | 464,8 | 487,6 |
| | 504 | 426 | 502 |
| Rata - rata | 486,5 HV | 450,7 HV | 486 HV |
| SCM 440 | 263,8 | 267,4 | 311,5 |
| | 303,2 | 270,8 | 272,2 |
| | 250,1 | 258,8 | 283,6 |
| Rata - rata | 272,4 HV | 265,7 HV | 289,1 HV |
| S45C | 286,7 | 250,1 | 256,1 |
| | 286,4 | 238,3 | 279,6 |
| | 256,3 | 260,7 | 256 |
| Rata - rata | 276,5 HV | 249,7 HV | 263,9 HV |

The results from table 2 are then processed using minitab 18 to determine the effect of each variable

**Analysis of Variance**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 8 | 256994 | 32124 | 102,56 | 0,000 |
| Linear | 4 | 255891 | 63973 | 204,24 | 0,000 |
| Carbon Equivalent | 2 | 252509 | 126255 | 403,08 | 0,000 |
| Viskositas Oli | 2 | 3381 | 1691 | 5,40 | 0,015 |
| 2-Way Interactions | 4 | 1104 | 276 | 0,88 | 0,495 |
| Carbon Equivalent*Viskositas Oli | 4 | 1104 | 276 | 0,88 | 0,495 |
| Error | 18 | 5638 | 313 | | |
| Total | 26 | 262632 | | | |

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 17,6982 | 97,85% | 96,90% | 95,17% |

In this study, the alpha value was 5% or 0.05 in decimal. The meaning of the alpha value is the maximum error value allowed for the alternative hypothesis to be accepted. In this study the results were obtained from the carbon equivalent variable which had a significant effect on the dependent variable (response) because the P-value was smaller than the alpha value (0.00 <0.05) so the research hypothesis was the null hypothesis (H0) was rejected, whereas in the oil viscosity variable has a significant effect on the dependent variable (response). ) has no significant effect on the dependent variable (response) because the P-value is greater than the alpha value (0.495 > 0.05) so the research hypothesis is the null hypothesis (H0) is accepted.

For the determinant coefficient value or $R^2$ which has a value of 100%, where if the determinant coefficient value is closer to 100% then it is said to have a significant influence between the two independent variables on the dependent variable (response) otherwise the determinant coefficient value is getting further away from 100% it can be said that it has no significant effect significant difference between the two independent variables on the dependent variable (response). The results of the study above determine the coefficient of 97.85% of the two independent variables on the dependent variable (response), so this value can be said to have a significant effect on the dependent variable (response) and 2.15% due to other factors during the research.

**Effect of Carbon Equivalent on Hardness**

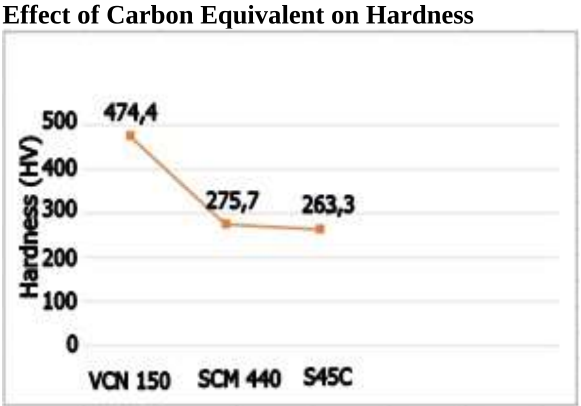

Figure 2 The Effect of Carbon Equivalent on Hardness

Figure 2 shows the effect of oil viscosity on hardness. It can be seen that SAE 10 shows an average hardness value of 345.1 HV. Meanwhile, SAE 40 has the lowest average hardness value of 322.1 HV. Then SAE 90 has the highest average hardness of 346.3 HV. Here proves that the viscosity of SAE 90 oil has the highest average value while SAE 40 oil has the lowest average hardness value.

**Effect of Oil Viscosity on Hardness**

Figure 3 shows the effect of oil viscosity on hardness. It can be seen that SAE 10 shows an average hardness value of 345.1 HV. Meanwhile, SAE 40 has the lowest average hardness value of 322.1 HV. Then SAE 90 has the highest average hardness of 346.3 HV. Here proves that the viscosity of SAE 90 oil has the highest average value while SAE 40 oil has the lowest average hardness value.

Figure 3. The Effect of Oil Viscosity on Hardness

**The Interaction Effect of Carbon Equivalent Value and Oil Viscosity on Hardness**

Figure 4 shows the results where the interaction effect of variations in carbon equivalent values and oil viscosity has an average hardness value. It can be seen that VCN 150 shows the highest average hardness value using SAE 10 oil cooling medium of 486.5 HV, while the lowest average hardness value uses SAE 40 oil cooling medium of 450.7 HV. The SCM 440 interaction shows the highest average hardness value using SAE 90 oil cooling of 289.1 HV, while the lowest average hardness value is produced with SAE 40 oil cooling of 265.7 HV. The S45C interaction produced the highest average hardness value using SAE 10 oil cooling medium of 276.5 HV, while the lowest average hardness value was shown in SAE 40 oil cooling of 249.7 HV.

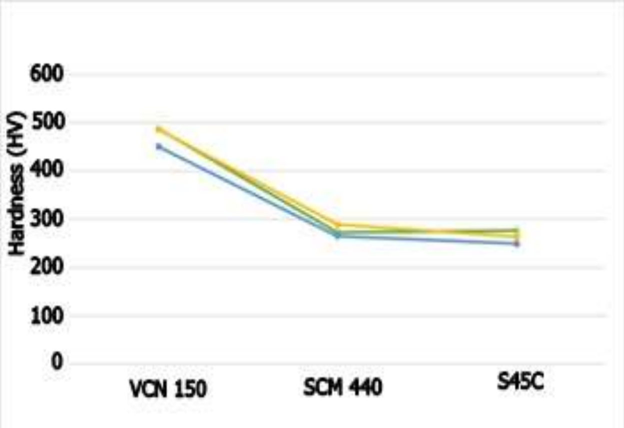


Figure 4 The Interaction Effect of Carbon Equivalent Value and Oil Viscosity to Hardness

**Analysis of the microstructure of Carbon Equivalent VCN 150 and Viscosity of Hardening Oil**

From the taking of the microstructure that was carried out, microstructure images were obtained from each VCN 150 specimen. Microstructure photos produced images like Figure 5 where the phases were the result of etching using HNO3 solution and using 500x magnification

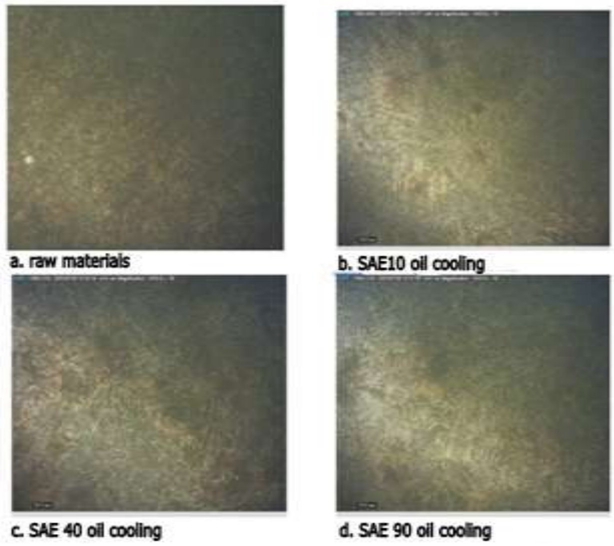


Figure 5 Microstructure of VCN 150

figure 5.a raw material has a lot of ferrite (light) microstructure, lots of pearlite (dark) and no martensite, here proves that the specimen has a low average hardness of 296.4 HV. Figure 5.b shows SAE 10 oil cooling has a little ferrite (bright) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that SAE 10 oil cooling has the highest average hardness value of 486.5 HV due to having the most martensite structure. On picture

Figure 5.c shows cooling SAE 40 oil has a lot of ferlite (bright) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that the ferrite structure still dominates over martensite so it has the lowest average hardness value. In figure d) SAE 90 oil cooling has a little ferrite (light) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that when SAE 90 oil cools it has an average value almost the same hardness as SAE 10 oil cooling of 480 HV.

**Analysis of the microstructure of Carbon Equivalent SCM 440 and Hardening Oil Viscosity**

From taking the microstructure carried out, obtained microstructural images from each SCM 440 specimen. Microstructure photos produce images like Figure 4.4 where the phase results from etching using HNO3 solution and using 500x magnification

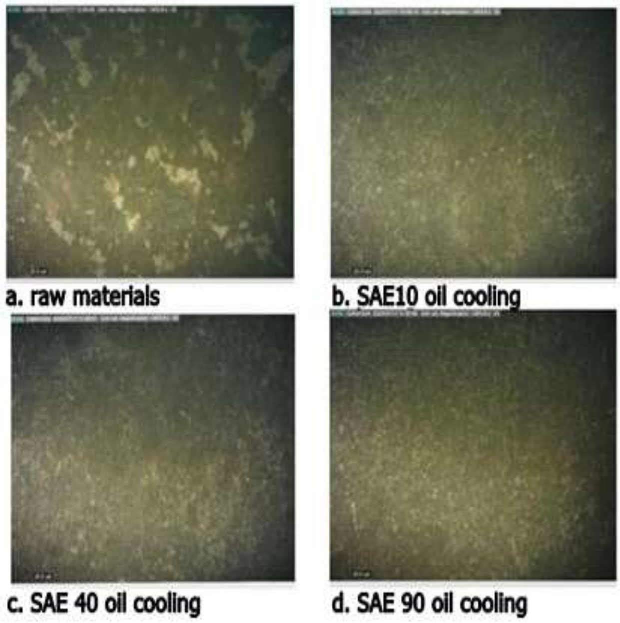


Figure 6 SCM 440 Microstructure

Figure 6. a shows the raw material has a lot of ferrite (light) microstructure, lots of pearlite (dark) and no martensite, here proves that the specimen has a low average hardness of 250.5 HV. In figure b) SAE 10 oil cooling has a little ferrite (light) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that when SAE 10 oil cools it has an average hardness value of 272, 4 H.V. In figure c) SAE 40 oil cooler has a little ferlite (light) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), but has a lower average hardness value than SAE 10 and SAE 90 oil coolers of 265.7 HV. In figure d) SAE 90 oil cooling has a little ferrite (light) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that the martensite structure predominates in SAE 90 oil cooling so it has an average value the highest hardness of 289.1 HV.

**Analysis of the microstructure of Carbon Equivalent S45C and Hardening Oil Viscosity**

From the taking of the microstructure that was carried out, microstructure images were obtained from each S45C specimen. Photo microstructure produces images like Figure 7. where the phase results from etching using $HNO_3$ solution and using 500x magnification.

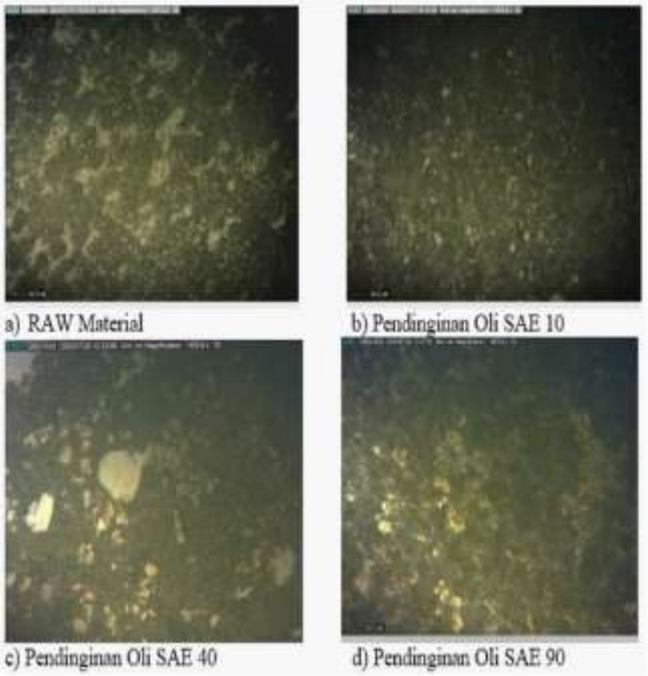


Figure 7. The S45C Microstructure

Figure 7.a shows the raw material has a lot of ferrite (light) microstructure, lots of pearlite (dark) and no martensite, here proves that the specimen has a low average hardness of 199.4 HV. Figure 5.b shows the SAE 10 oil cooling has a little ferrite (bright) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that SAE 10 oil cooling has the highest average hardness value of 276.5 HV due to having the most martensite structure compared to other specimens. Figure 5.c shows the SAE 40 oil cooling has a lot of ferlite (bright) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that the ferrite structure dominates the same as the martensite structure so it has an average hardness value lower than SAE 10 oil cooler and SAE 90 oil of 249.7 HV. Figure 5.d shows the SAE 90 oil cooling has a lot of ferrite (bright) microstructure, a little pearlite (dark), and a lot of martensite (slightly dark/scale), here proves that the martensite structure dominates over the ferrite structure so that SAE 90 oil cooling has the average value of hardness is higher than that of SAE 40 oil cooling of 263.9 HV.

## 4. RESULTS AND DISCUSSION

The following is a chemical composition table used to calculate the carbon equivalent value for each material:

Only those manuscripts that meet the standards of the journal, and fit within its aims and scope, will be sent to expert reviewers. Deadline from 2 weeks till 2 months. After the article has passed the priority check, it is necessary to provide a package of documents and pay an advance payment after which your article is sent for processing to the editor. Get the answer from the editors of the magazine. If there are adjustments that need to take them into account and send the article back by e-mail. If no adjustments or fixed all the comments made by the editor, you will need to prepare a package of documents

**Table 1.** Biogas composition

| Components | Value (%) |
|---|---|
| $CH_4$ | 42,37 |
| $CO_2$ | 48,97 |
| CO | 1,92 |
| The others | 6,74 |

Source: laboratorium analysis

## 5. CONCLUSIONS

1) Based on the results of the research above, the variation of carbon equivalent to hardness results where the carbon equivalent value of VCN 150 produces the highest average hardness value of 474.4 HV. Meanwhile, the carbon equivalent value of S45C resulted in the lowest average hardness value of 263.4 HV. In processing ANOVA data, the carbon equivalent variation has a significant effect on the response because the P-value is smaller than alpha (P-value $<\alpha$).
2) In the results of the study of variations in the viscosity of the cooling oil on hardness, it was found that SAE 90 oil produced the highest average hardness value of 346.3. Whereas in SAE 40 oil the lowest average hardness value was 322 HV for each type of steel used. In processing ANOVA data variations oil viscosity has a significant effect on the response because the P-value is smaller than alpha (P-value $<\alpha$).
3) Based on the research above, the effect of the interaction between carbon equivalent variations and cooling oil viscosity on hardness shows that the VCN 150 carbon equivalent value using SAE 10 oil cooler produces the highest hardness of 486.5 HV, while the lowest hardness is the S45C carbon equivalent value interaction using oil cooler SAE 40 of 249.7 HV. In processing ANOVA data, the interaction between carbon equivalent variations and oil viscosity did not have a significant effect on response because the P-value was greater than alpha (P-value $> \alpha$).
4) In the analysis of the Carbon Equivalent microstructure and the viscosity of the oil which has the highest average hardness value because it has a dominant martensite structure. Meanwhile, specimens with ferrite structure still predominate compared to martensite with the lowest average hardness value.

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## 7. AUTHOR CONTRIBUTIONS

Conception and design: Listiyono
Methodology: Subagijo
Data acquisition: Sugeng Hadi Susilo
Analysis and interpretation of data: Sugeng Hadi Susilo
Writing publication: Subagijo, Sugeng Hadi Susilo
Approval of final publication: Listiyono.
Resources, technical and material supports: Listiyono,
Supervision: Subagijo

## 6. REFFERENCES

[1] S. B. Zaman, J. Hazrati, M. B. de Rooij, and A. H. van den Boogaard, "Effect of heating temperatures on AlSi coating microstructure and fracture during hot-tensile tests," *IOP Conf.*

*Ser. Mater. Sci. Eng.*, vol. 1157, no. 1, 2021, doi: 10.1088/1757-899x/1157/1/012018.

[2] W. Guo *et al.*, "Microstructure characteristics and mechanical properties of a laser cladded Fe-based martensitic stainless steel coating," *Surf. Coatings Technol.*, vol. 408, 2021, doi: 10.1016/j.surfcoat.2020.126795.

[3] N. Diakonenko, N. Khatsko, and K. Khatsko, "Studying the values of distribution of chromium-nickel steel microhardness using statistical methods," *Bull. Kharkov Natl. Automob. Highw. Univ.*, no. 97, 2022, doi: 10.30977/bul.2219-5548.2022.97.0.58.

[4] E. SALUR, "Structural evolution of mechanically alloyed ODS steel powders during ball milling and subsequent annealing treatment," *Int. Adv. Res. Eng. J.*, vol. 6, no. 2 (under construction), 2022, doi: 10.35860/iarej.1075508.

[5] B. B. Sherpa, P. D. Kumar, A. Upadhyay, S. Kumar, A. Agarwal, and S. Tyagi, "Effect of explosive welding parameters on Al/LCS interface cladded by low velocity of detonation explosive welding (LVEW) process," *Int. J. Adv. Manuf. Technol.*, vol. 113, no. 11–12, 2021, doi: 10.1007/s00170-021-06800-5.

[6] V. I. Alekseev, B. K. Barahtin, A. S. Zhukov, G. A. Panova, S. G. Petrova, and E. A. Shirokina, "Probable Ways of Hardening in the Metal Structure Obtained by Selective Laser Melting Technology," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1079, no. 3, 2021, doi: 10.1088/1757-899x/1079/3/032042.

[7] H. Xiao, P. Xu, Z. Qi, Z. Wu, and Y. Zhao, "Preparation of Steel/Aluminum Laminated Composites by Differential Temperature Rolling with Induction Heating," *Jinshu Xuebao/Acta Metall. Sin.*, vol. 56, no. 2, 2020, doi: 10.11900/0412.1961.2019.00150.

[8] M. Einolghozati and A. Assempour, "A micro mechanical study on tensile behavior of steel sheets with spheroidal cementite using crystal plasticity finite element method," *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 236, no. 12, 2022, doi: 10.1177/14644207221078990.

[9] F. Borchers *et al.*, "The influence of former process steps on changes in hardness, lattice and micro structure of aisi 4140 due to manufacturing processes," *Metals (Basel).*, vol. 11, no. 7, 2021, doi: 10.3390/met11071102.

[10] M. H. Park, Y. Tagusari, and N. Tsuji, "Characterization of local deformation and fracture behavior in ferrite + martensite dual-phase steels having different grain sizes," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1249, no. 1, 2022, doi: 10.1088/1757-899x/1249/1/012041.

[11] Z. C. Zhuo, Q. Y. Zhang, and J. C. Wang, "Fracture behavior of welded joints of ship steel plates and numerical analysis with GTN model," *Gongcheng Lixue/Engineering Mech.*, vol. 37, no. 11, 2020, doi: 10.6052/j.issn.1000-4750.2019.12.0746.

[12] E. F. Talantsev, M. V. Degtyarev, T. I. Chashchukhina, L. M. Voronova, and V. P. Pilyugin, "Piecewise Model with Two Overlapped Stages for Structure Formation and Hardening upon High-Pressure Torsion," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 52, no. 10, 2021, doi: 10.1007/s11661-021-06403-5.

[13] D. Chatterjee, "Effect of Cryorolling–Annealing and Bake-Hardening on the Microstructure and Mechanical Properties of AISI 301LN Grade Austenitic Stainless Steel," *Metallogr. Microstruct. Anal.*, vol. 9, no. 5, 2020, doi: 10.1007/s13632-020-00677-8.

[14] V. E. Gromov, Y. F. Ivanov, V. E. Kormyshev, A. A. Yuriev, A. P. Semin, and Y. A. Rubannikova, "Change in structural-phase states and properties of lengthy rails during extremely long-term operation," *Prog. Phys. Met.*, vol. 21, no. 4, 2020, doi: 10.15407/ufm.21.04.527.

[15] T. Allam, P. Ostermayer, B. Blinn, T. Beck, and W. Bleck, "Influence of the Inherited Structure Induced by Al and Si Alloying on Microstructure Evolution and Mechanical Properties of 100Cr6 Steels," *steel Res. Int.*, 2023, doi: 10.1002/srin.202200804.

[16] Z. Yang, J. Bai, and X. Zhang, "Effect of heat treatment on microstructure and mechanical property of selective laser melted high speed steel," *Cailiao Gongcheng/Journal Mater. Eng.*, vol. 50, no. 12, 2022, doi: 10.11868/j.issn.1001-4381.2022.000530.