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MECHANICAL STUDY OF 9CR-SS316L-1MO MATERIAL FOR CLADDING NUCLEAR FUEL POWER REACTORS

M. Purnama and U. Sudjadi

Universitas Mercu Buana, Jakarta 11650, INDONESIA

Abstract

In this research, SS316 steel and modified 9Cr-1Mo steel were developed. The aim is to analyze the results of the hardness test, impact test, bending test, and microstructure. The Mo element was chosen because it has a relatively small microscopic cross-section of the neutron, which is 2.6 barn. The element Mo is in the same periodic period as Zr and Nb, so that the mechanical properties and so on are not much different. In this study, samples of SS316L steel and modified 9Cr-1Mo steel were made. Samples material of 90% SS316L + 9% Cr + 1% Mo were melted by electric arc melting. Tempering was carried out after the smelting process was completed. The sample consisted of 6 pieces, 1 sample did not receive tempering treatment while the other 5 samples received tempering treatment at 100°C, 200°C, 300°C, 400°C, and 500°C. The samples were tested using various methods including Rockwell hardness test, impact test, microstructure test, bending test, and examination of other properties of the material samples. Hardness, impact, and bending test results as well as the samples microstructure were analyzed. The highest decrease in hardness value was in specimen 1 (non-treatment) which was 21.33 HRc and the lowest decrease was in specimen 6 (heat treatment at 500°C) which was 16.66 HRc. For the results of the impact energy test (EI) with an average value, there was not too much difference, namely the highest value was 1.0034 joules/mm^2 in specimen 2 (heat treatment at 100°C) and the lowest value was 1.0020 joules/mm^2 in specimen 6 (heat treatment at 500°C). The results of the microstructure test showed that the ferrite and pearlite content is still present in the test object. The highest bending test result in sample 6 with 500°C tempering had a maximum load-bearing strength of 1050 Newton so that the bending strength was 7875 kgf/cm^2 and the lowest result was in sample 1 without tempering having a maximum load-bearing strength of 670 Newton so that the bending strength was 5025 kgf/ cm^2.

Keywords: Mechanical Properties, Physical Properties, 9Cr-SS316L-1Mo, Nuclear Fuel Cladding, Power Reactor

*Corresponding author: Tel. +62 852 1616 9062
E-mail address: maydamedi76@gmail.com

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1. Introduction

As is known, nuclear actually has benefits for human life in various fields. As in agriculture, nuclear energy can help agriculture through genetic engineering and mutations in plants, nuclear benefits in the health sector are carried out through the use of radioisotopes that can be made with high quality. These good quality radioisotopes can then be used for the treatment of various diagnoses of internal medicine to chronic diseases such as cancer. Nuclear is also useful in the development of the energy sector and there are many more benefits of nuclear in human life. However, the stigma about nuclear hazards is still very large in society, especially related to the danger of nuclear reactor explosions which are indeed classified as types of explosions with a high risk, in contrast to explosions at petrol stations, for example, which have an intermediate level of risk[1]. So, educating people about the benefits of nuclear is slowly showing the benefits of nuclear. And also, the next generation of nuclear systems for sustainable development must be a safer technology.

The importance of fast reactors and the associated fuel cycle in ensuring the long-term sustainability of nuclear power has been largely held by the nuclear community for a long time. In the field of structural materials for core materials, fracture toughness and austenitic fracture strain are important performance properties, which controls the serviceability of components for fast reactors including fuel assemblies. It is known that the above properties decrease under irradiation and thermal swelling, especially the strong decrease of fracture toughness under irradiation is accompanied by swelling[2]. Austenitic stainless steel 316 has very high mechanical properties and is corrosion resistant. This type of steel is widely used in both nuclear and non-nuclear industries. In the nuclear industry, austenitic stainless steel 316 is widely used in applications such as materials for primary and secondary pipes in pressurized water reactors (PWR). In the primary circuit, 316 steel is used as a structural material for steam dryers, vessels, piping systems, reactor cores, and reactor pumps, while in the secondary circuit, it is used as a preheater pipe material and considers the pipe because of its high mechanical properties and good corrosion resistance. 316 steel is widely designed as a component material for high temperature applications, such as components for nuclear power plants, super heaters, and thermal power plants[3]. T. Asayama and S. Ohtsuka from Japan Atomic Energy Agency has developed 316 steel into Oxide Dispersion Strengthened (ODS) steel. 9Cr Steel, 11Cr-ODS has been extensively developed for structural materials and will be applied to fuel pin cladding, for sodium-cooled fast reactors [4]. A. A. Sorokin et al have also reported on an austenitic study with the theme: Prediction of fracture strain and fracture toughness for irradiated austenitic steels over a temperature range taking into account the effects of swelling and thermal aging. They concluded that the fracture toughness can decrease in a dozen times due to neutron irradiation and swelling even for ductile fractures. The research was applied to a fast reactor, in the field of materials engineering (A. A. Sorokin, 2017). Sorokin et al have also reported on austenitic studies with the theme: Prediction of fracture strain and fracture toughness for irradiated austenitic steels over a temperature range taking into account the effects of swelling and thermal aging. They concluded that the fracture toughness can decrease in a dozen times due to neutron irradiation and swelling even for ductile fractures. The research was applied to a fast reactor, in the field of materials engineering (A. A. Sorokin, 2017). Sorokin et al have also reported on austenitic studies with the theme: Prediction of fracture strain and fracture toughness for irradiated austenitic steels over a temperature range taking into account the effects of swelling and thermal aging. They concluded that the fracture toughness can decrease in a dozen times due to neutron irradiation and swelling even for ductile fractures. The research was applied to a fast reactor, in the field of materials engineering (AA Sorokin, 2017).

The sample 9Cr-316steel-1Mo were investigated in this research. 1Mo was used based on many desirable properties such as high thermal conductivity, high creep and fatigue strength due to microstructural stability, resistance to decarburization as well as chloride and caustic stress corrosion cracking[5]. And characterize the mechanical properties (i.e., stress and strain test, hardness test, etc.), micro properties and physical properties. It is known that the element Mo has a small microscopic cross-section of neutrons. Thus, physically, the fission reaction will be good if using the element Molybdenum (Mo), with a cross section a = 2.6 Mo is still relevant for use. The research, sampling, and characterization of the samples will be carried out at the Center for Nuclear Fuel Technology (PTBBN-Serpong), National Nuclear Energy Agency (BATAN), Indonesia [6].

2. Experimental and Procedures

2.1 Material Samples

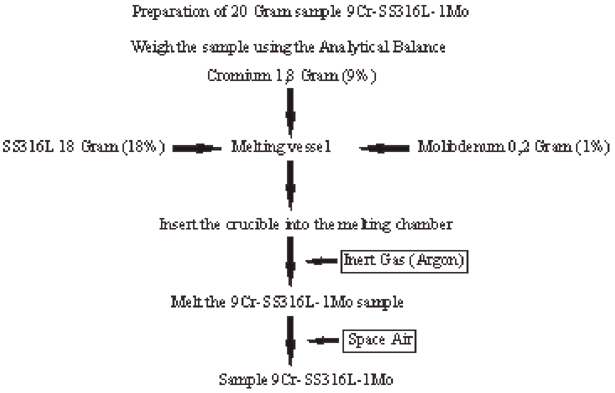

Fig. 1. Flowchart of the smelting process for 9Cr-SS316L-1Mo

Fig. 1 shows the flowchart of the smelting process for 9Cr-SS316L-1Mo. The melting procedure is as follows:

1. The material sample is placed in a copper vessel.
2. Inert gas (argon) is flowed into the melting chamber.
3. The tungsten electrode is directed into the crucible until an electric arc is emitted and the material sample melts.

The smelting process and melting test material are shown in Fig. 2 and Fig 3 respectively.

Fig. 2. Material sample smelting process

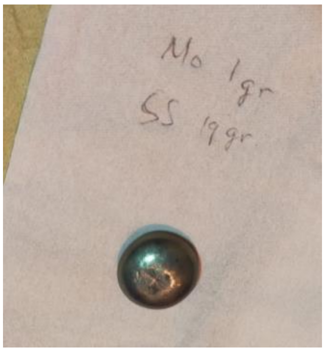

Fig. 3. Melting test material

After the smelting process is complete, then tempering is carried out. The sample consists of 6 pieces, 1 sample does not receive tempering treatment or without tempering while the other 5 samples receive tempering treatment by placing the sample into the furnace. Then, the furnace is turned on and the temperature is set to 100°C. After the digital display on the furnace shows 100°C, then the furnace is stopped and a sample is removed using tongs and then immersed in oil. Furthermore, the furnace is set at 200°C, and after the furnace temperature reach 200°C, one sample is taken out and immersed in the oil. The tempering process is continued for other samples at 300°C, 400°C, and 500°C.

2.2 Testing and Data Collection Stage

The material that is already in the form of cast material is tested, including:

Rockwell Hardness Test

Hardness testing is the ability of a material to load in a constant change. By applying pressure to the object being tested, it can be analyzed how big the level of hardness of the material is through the amount of load given to the area that receives the load.

Rockwell hardness test is one of the hardness tests that is starting to be widely used. This is because the Rockwell hardness test is simple, fast, does not require a microscope to measure traces, and is relatively non-destructive. The Rockwell hardness test is carried out by pressing the surface of the specimen (test object) with an indenter. The pressure of the indenter into the test object is carried out by applying a preliminary load (minor load), then added to the main load (major load), then the main load is released.

The hardness test using the Rockwell method is regulated according to the standard DIN 50103. The hardness standard for the Rockwell test method is shown in the table as follows: minor is still maintained.

In this Rockwell method there are two kinds of indenters that vary in size, namely:

1. A diamond cone with an angle of 120º and is known as a Rockwell cone.
2. Steel balls of various sizes and are referred to as Rockwell balls

For how to use this scale, we first determine and choose the provisions of the maximum hardness number that can be used by a particular scale. If an accurate hardness number is not reached on a certain scale, then we can determine another scale that can show a clear hardness number. Based on a certain formula, this scale has a standard or reference, where the reference in determining and selecting the hardness scale can be seen through the following table:

In the process of testing the hardness of the Rockwell method, two stages are given to the loading process, minor load and major load stage. The maximum minor load is 10 kg while the major load depends on the hardness scale used.

Rockwell hardness test method

The Rockwell method is based on pressing an indenter with a certain compressive force to a flat and clean surface of a metal being tested for hardness. After the compressive force is returned to the minor force, what will be used as the basis for calculating the Rockwell hardness value is not the result of measuring the diameter or diagonal of the indentation, but the depth of the indentation that occurred. This is how the Rockwell method differs from other hardness testing methods.

There are three types of Rockwell testing commonly used, namely HRA, HRB, and HRC. HR itself is an abbreviation for Rockwell Hardness or Rockwell Hardness Number and is sometimes abbreviated with just the letter R.

Use of Rockwell Hardness Testing Machine

The tester must first install the indenter according to the type of test required, namely a steel ball or diamond cone indenter. After the indenter is installed, the tester puts the specimen to be tested for hardness in the space provided and adjusts the load to be used for the pressing process. To find out the hardness value, the examiner can look at the needle attached to the measuring instrument in the form of a dial indicator pointer.

Errors in hardness testing are caused by several factors, namely:

a. Rockwell testing machine
b. Operator
c. Test object

Hardness testing with the Rockwell method has several advantages, including:

a. Can be used for very hard materials.
b. Can be used for grinding stones to plastic.
c. Suitable for all hard and soft materials.

In addition to having the advantages of testing the hardness of objects with the method, Rockwell has several drawbacks, including:

a. Low level of accuracy.
b. Unstable when exposed to shock.
c. Emphasizing the load is impractical.

Impact Test

Impact testing is a test that measures the resistance of materials to shock loads. This is what distinguishes impact testing from tensile and hardness tests where loading is carried out slowly. Impact testing is an attempt to simulate the operating conditions of materials that are often encountered in transportation or construction equipment where the load does not always occur slowly, but comes suddenly.

The basic principle of impact testing is the absorption of potential energy from a pendulum of a load that swings from a certain height and strikes the test load, so that the test load experiences maximum deformation to cause fracture. Charpy method for impact testing is shown in Fig.

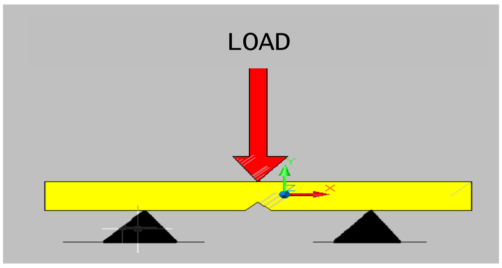

Fig. 4 Impact Charpy method

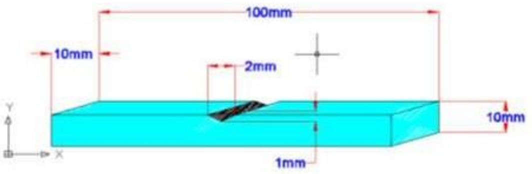

Fig. 5 Dimension of the test sample

The energy parameters of a material tested by the impact Charpy method is calculated using the following formulas:

a. Impact potential energy

$$E_P = m.g.L\,(1 - \cos\alpha) \qquad (1)$$

where:
Ep : potential energy (joule)
m : weight of pendulum (kg)
L : swing arm distance (m)
g : earth's gravity (m/s^2)
α : initial angle of the pendulum (°)

b. Energy absorbed

$$W = m.g.L\,(\cos\beta - \cos\alpha) \qquad (2)$$

where:
W : energy absorbed (joule)
β : pendulum end angle (°)

c. Impact energy

$$EI = \frac{W}{A} \qquad (3)$$

where:
EI : impact energy (joule/mm^2)
A : cross-sectional area under the notch 90 (mm^2)

Bending Test

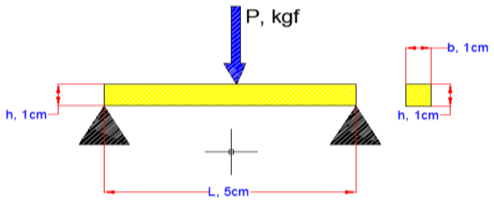

Fig. 6. The shape and dimension of the bending test sample

The bending strength of the sample in Fig. 4 can be calculated using the following formula:

$$\text{Bending strength} = \frac{3\,PL}{2\,bh^2} \qquad (4)$$

Microstructural Testing using SEM (Scanning Electron Microscope)

Before carrying out the microstructure test, one end of the specimen should be first cut into a 2 cm long sample and then flattened and smoothed its surface until meets the requirements using sandpaper sizes of 60, 240, and 1000. Then, it is cleaned with a soft cloth and given H_2SO_4 solution which has been dissolved with aquadest to make it shiny. Next, it is viewed with a SEM microscope to get an image of the structure of the specimen.

Microstructure testing aims to determine the microstructure of the casting results and observe the defects of the casting results microscopically with a microscope magnification. The micro-photo test equipment consists of a microscope for observing specimens and a computer screen for displaying micro-photo images and then storing them. Micro photo magnification with a microscope is done using magnifications of 50 x, 100 x, or 200 x.

3. Results and Discussion

3.1 Impact Test

The impact testing machine specifications are:

a. Pendulum mass: 12.3 kg
b. Earth's gravitational force: 9.8 m/s^2
c. Pendulum arm length: 0.75 m

Impact measurement data for the 6 samples is listed in Table 1.

Table 1. Impact measurement data

Sample	Starting angle, α (°)	Final angle, β (°)	Pendulum weight, m (kg)	Swing arm distance, L (m)
1	90	4	12.3	0.75
	90	2	12.3	0.75
	90	4	12.3	0.75
	270/3 = 90	**10/3 = 3.3**	**36.9/3 = 12.3**	**2.25/3 = 0.75**
2	90°	3	12.3	0.75
	90°	3	12.3	0.75
	90°	2	12.3	0.75
	270/3 = 90	**8/3 = 2.6**	**36.9/3 = 12.3**	**2.25/3 = 0.75**
3	90	4	12.3	0.75
	90	3	12.3	0.75
	90	4	12.3	0.75
	270/3 = 90	**11/3 =3.6**	**36.9/3 = 12.3**	**2.25/3 = 0.75**
4	90	40	12.3	0.75
	90	20	12.3	0.75
	90	30	12.3	0.75
	270/3 = 90	**9/3 = 3**	**36.9/3 = 12.3**	**2.25/3 = 0.75**
5	90	3	12.3	0.75
	90	4	12.3	0.75
	90	4	12.3	0.75
	270/3 = 90	**11/3 = 3.6**	**36.9/3 = 12.3**	**2.25/3 = 0.75**
6	90	5	12.3	0.75
	90	3	12.3	0.75
	90	4	12.3	0.75
	270/3 = 90	**12/3 = 4**	**36.9/3 = 12.3**	**2.25/3 = 0.75**

The potential energy, absorbed energy, and impact energy for the 6 samples are calculated from the impact testing machine specification and measurement data in Table 1 using Eq. (1), Eq. (2), and Eq. (3). The results are listed in Table 2.

Table 2. Impact test results

Sample	Lift angle, α (°) Average flat	Final angle, β (°) Average flat	Potential Energy (joule) Average	Absorbed Energy (joule) Average	Impact Energy (joule/ mm^2) Average
1	90	3.3	90.4	90.251	1.0027
2	90	2.6	90.4	90.3055	1.0034
3	90	3.6	90.4	90.2241	1.0025
4	90	3	90.4	90.2784	1.0031
5	90	3.6	90.4	90,2241	1.0025
6	90	4	90.4	90.1789	1.0020

The potential energy of the impact test is illustrated in the graph in Fig. 7: The average potential energy for sample 1 (without tempering) and samples 2, 3, 4, 5, and 6 (tempered at 100°C, 200°C, 300°C, 400°C, and 500°C) have the same value i.e. 90.40 joules.

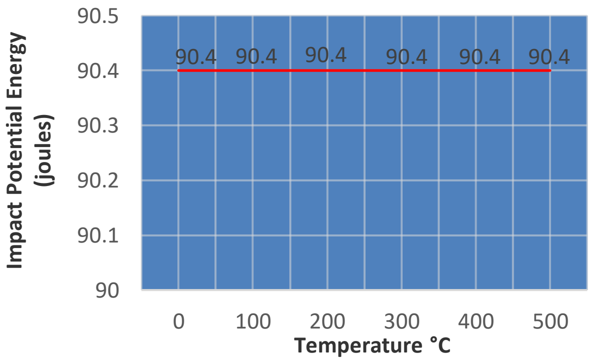

Fig. 7. Impact potential energy

The absorbed energy of the impact test is illustrated in the graph in Fig. 8. The data from the impact test results show that the average absorbed energy increase from Sample 1 to Sample 2, decrease in Sample 3, increase again in Sample 4, and then decrease in Sample 5 and Sample 6.

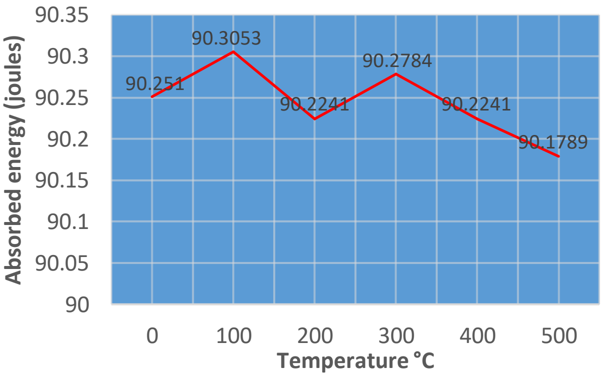

Fig. 8. Absorbed energy

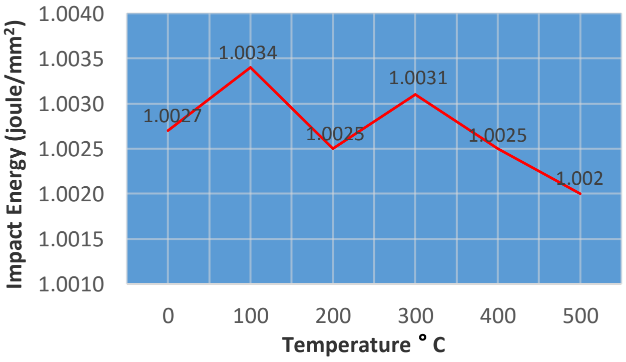

Fig. 9. Impact energy

The impact energy of the impact test is illustrated in the graph in Fig. 9. The data from the impact test results show that the average impact energy increase from Sample 1 to Sample 2, decrease in Sample 3, increase again in Sample 4, and then decrease in Sample 5 and Sample 6.

3.2 *Rockwell Hardness Test*

The scale used in the tst is type C with a mass weight of 150 kg, applied using a diamond cone with an angle of 120°, superficial (E) of 100, and penetration (e) of h/0.002. Table 5 shows the results of the Rockwell hardness testing.

Table 5 Rockwell hardness test results

Sample	Rockwell Test Results 1 (Load 150 kg)	Rockwell Test Results 2 (Load 150 kg)	Rockwell Test Results 3 (Load 150 kg)	Total Hardness Test Results (HRc)	Average Hardness (HRc)
1	22	21	21	64	21.333
2	21	22	21	64	21.333
3	20	21	20	61	20.333
4	19	20	19	58	19.333
5	19	18	18	55	18.333
6	17	17	16	50	16,667

The average hardness of the Rockwell hardness test for the 6 samples is illustrated in the graph in Fig. 10. The highest hardness value is shown by samples that have not experienced tempering, which is 21.333 HRc, while the lowest hardness value lies in samples that have undergone heat treatment/tempering at 500°C, which has a hardness value of 16.667 HRc. It can be concluded that the hardness of 9Cr-SS316-1Mo metal will decrease if it is given heat treatment with high temperature.

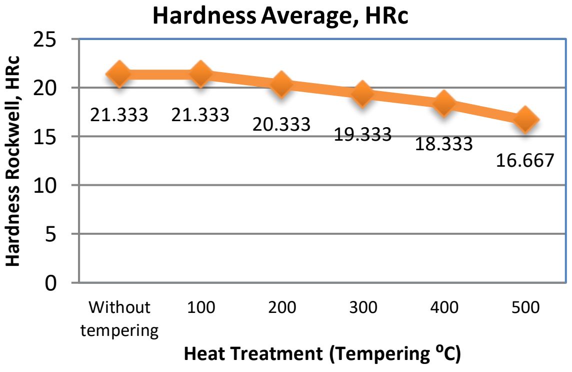

Fig. 10. Average Rockwell hardness

3.3 *Bending Test*

The following are the specifications for the specimens tested, namely the 9Cr-SS316L-1Mo alloy sample with the following dimensions:

a. Length of the supported sample (L) = 5 cm
b. Sample width (b) = 1 cm
c. Sample thickness (h) = 1 cm

The bending strength is calculated for various load using Eq. 4. The results are shown in Table 6. The 9Cr-SS316L-1Mo alloy test sample has varying bending strength even though it comes from the same product/formula plus 1Mo.

Table 6. Results of bending strength calculation

Sample	P kgf	Bending strength kgf/cm^2
1	670	5025
2	725	5437.5
3	770	5775
4	845	6337.5
5	910	6825
6	1050	7875

3.4 *Microstructure Test*

In microstructure testing, the sample is alternately tested and measured by placing the test object on a table located on the machine, after which the metal structure of the test material can be seen directly on the monitor screen. Magnification was carried out 200x using a Leco microscope as shown in Fig. 11.

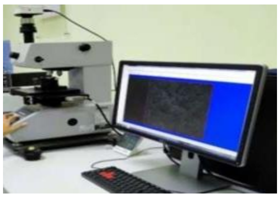

Fig. 11. Microstructure testing tool/Scaning Electron Microscope (SEM)

a. Sample 9Cr-SS316-1Mo without tempering

In the image of the microstructure of 9Cr-SS316-1Mo without tempering as shown in Fig. 12, the ferrite form is thick white like cotton, while the pearlite is fine black like powder.

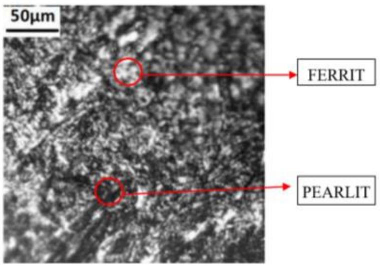

Fig. 12. Microstructure shape of 9Cr-SS316L-1Mo without tempering

b. Sample 9Cr-SS316L-1Mo tempered at 300°C

In the image of the microstructure of 9Cr-SS316-1Mo tempered at 300°C as shown in Fig. 13, ferrite is black as fine as powder, while pearlite is white as fine as powder.

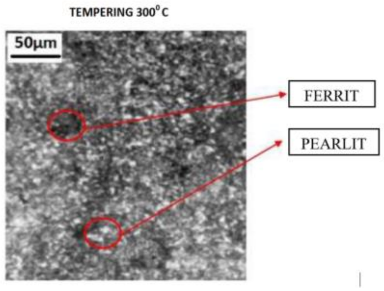

Fig. 13 Microstructure of 9Cr-SS316-1Mo tempered at 300°C for 1 hour

c. Sample 9Cr-SS316L-1Mo tempered at 400°C

In the image of the microstructure of 9Cr-SS316-1Mo with a tempering temperature of 400°C as shown in Fig. 14, the ferrite form is thick white like cotton, while the pearlite is fine black like powder.

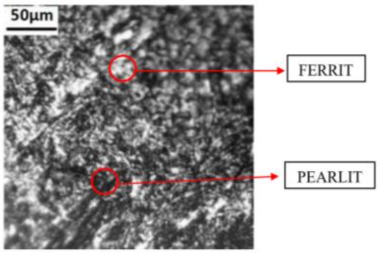

Fig. 14. Microstructure of 9Cr-SS316-1Mo tempered at 400°C for 1 hour

d. Sample 9Cr-SS316L-1Mo tempered at 500°C

In the image of the microstructure of 9Cr-SS316-1Mo tempered at 500°C as shown in Fig. 15, ferrite is black as fine as powder, while pearlite is finely white like powder.

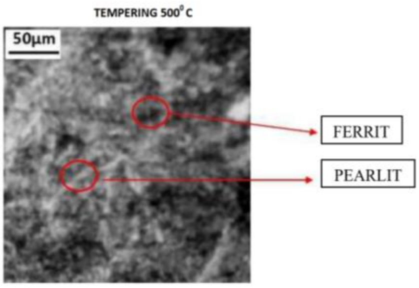

Fig. 15. Microstructure of 9Cr-SS316L-1Mo tempered at 500°C for 1 hour

4. Conclusions

Based on the results of the research that have been carried out, the conclusions are:

1. The impact test with 6 test samples produced the following results:
   - Impact potential energy with all average values of 90.4 joules.
   - Absorbed energy with the highest value in sample 2 (heat treated at 100°C) i.e., 90.3055 joules and the lowest decrease in sample 6 (heat treated at 500°C) i.e., 90.1789 joules.
   - Impact energy with not too significantly different average values, i.e., the highest value of 1.0034 joules/mm^2 in sample 2 (heat treated at 100°C) and the lowest value of 1.0020 joules/mm^2 in sample 6 (heat treated at 500°C).
2. The Rockwell hardness test produced the highest decrease in hardness value in sample 1 (non-treated) i.e., 21.333 HRc and the lowest decrease at sample 6 (heat treated at 500°C) i.e., 16.667 HRc.
3. The highest bending test result is in sample 6 (heat treated at 500°C) which has a maximum load-bearing strength of 1050 Newton so that the bending strength is 7875 kgf/cm^2 and the lowest result is in sample 1 (without tempering) which has a maximum load-bearing strength of 670 Newton, so that the bending strength is 5025 kgf/cm^2.
4. The results of the microstructure test shows that the ferrite and pearlite content is still present in the test object. Ferrite is formed due to an unstable cooling process. Ferrite is very soft, ductile, and has high conductivity. While the relatively less pearlite content is formed due to the relatively smaller content of carbon alloy elements in steel.

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