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Analysis of Tempering Treatment after Hardening on S45C Steel Bogie Pin Materials in relation to Mechanical Strength

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ABSTRACT

S45C steel is a medium carbon steel used for railway bogie pins due to its high strength. However, this steel does not meet the minimum hardness standard for bogie pin products, requiring further processing. The specific objectives of this study are: a) to investigate the effect of tempering temperature variations on the mechanical properties of S45C steel, and b) to determine the optimal tempering temperature and time recommended for heat treatment of S45C steel. The research method applied was an experiment with hardening treatment at a temperature of 910°C for 20 minutes, followed by tempering treatment at temperatures of 175°C, 225°C, and 275°C for 20 minutes of air cooling. The testing process carried out included tensile strength testing, hardness testing, and microstructure testing. The results of this study showed that the test specimen with tempering treatment at a temperature of 175°C was the best among the other test specimens because it was more suitable for industrial needs. This test specimen had a maximum stress value of 948.6 MPa, a maximum strain value of 7.76%, a Vickers hardness value of 358.06 VHN, and a microstructure consisting of ferrite and martensite phases, making the tempering process at a temperature of 175°C almost close to the standards set by the company.

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1. Introduction

Heat treatment is a process aimed at changing the properties of metals by altering their microstructure, applying heat at specific temperatures, and controlling the cooling rate with or without changing the chemical composition of the metal [1]. In the industrial world, heat treatment is a process that has a significant impact on the physical and mechanical properties of metals. Undesirable properties in metals can be overcome by heat treatment. The heat treatment process is carried out by heating the material or metal to a certain temperature and cooling it for a certain period of time.

PT INKA is a state-owned enterprise that focuses on the production and development of trains. PT INKA strives to develop high-quality bogie pins that are made to be resilient and strong for the main connectors between train components so that the train components remain in position and do not shift. The problem encountered with S45C steel bogie pins for the 612 new generation train project is that S45C steel bogie pins from suppliers are often rejected by the company because the surface hardness of the pins does not meet the company's specifications. One alternative proposed by the author to solve this problem is to apply a heat treatment process. According to Darmawi [2] , the heat treatment process on steel materials plays a very significant role in achieving certain characteristics that are desired according to requirements. The main objectives of this process are to increase the strength, hardness, toughness, and ductility of steel. One method that can be applied to increase the strength and ductility of steel is by applying the tempering method. The tempering process involves reheating hardened steel at a temperature lower than the critical temperature of steel, followed by cooling. The purpose of tempering is to eliminate residual stress that arises in steel due to rapid cooling [3].

The role of steel in the manufacturing industry is very important, especially in the manufacture of railway-related components. Bogie pins use S45C steel to achieve the required level of toughness and hardness. S45C steel is a Japanese standard steel product commonly referred to as Japan Industrial Standard (JIS). This steel has a main content of carbon (C), iron (Fe), manganese (Mn), phosphorus (P), sulfur (S), and other supporting elements. S45C steel is classified as a medium carbon steel group that allows for improved mechanical properties [4].

Heat treatment research conducted by Zayadi [5] states that rapid cooling using oil media and tempering at a temperature of 500°C and a holding time of 1 hour results in an increase in tensile strength and yield strength. Holding time is one of the factors that affects the hardness value of S45C steel after the tempering process; the longer the holding time, the lower the hardness value produced. Research by Syamsuir [6] shows that heat treatment with quenching at a temperature of 900°C using oil quenching media can increase the hardness level of S45C steel from 185 VHN to 595 VHN. Tempering at a high temperature of 600°C causes a significant decrease in hardness level to 242 VHN. The optimal tempering temperature is in the range of 150°C to 250°C. Furthermore, research conducted by Wibowo & Samlawi [7] shows that variations in the cooling medium in the heat treatment of S45C steel affect the hardness of the material. There was an increase in material hardness of 18% with water cooling and 21% with oil cooling.

Based on the above issues, research is needed to improve the mechanical properties of S45C steel for bogie pin applications through heat treatment hardening followed by tempering. This study focuses on the analysis of tempering treatment after hardening on S45C steel bogie pin material in relation to mechanical properties. The results of this study are expected to provide considerations for heat treatment by industry to be more optimal in achieving the required technical standards.

2. Method

2.1. Chemical Composition Testing

The chemical composition testing process of materials is carried out to determine the elements present in a material. Chemical composition testing is a very important process to ensure that the materials used meet the established standards. This chemical composition testing was carried out on steel materials without heat treatment, commonly referred to as raw materials [8].

2.2. Specimen Preparation

2.2.1. Tensile Test Specimens

The tensile test specimen preparation process uses the ASTM E8M-13a standard with a total specimen length of 150 mm, *a gauge length* of 45 mm, an inner diameter of Ø9 mm, an outer diameter of Ø14 mm, and a radius of 8 mm with *a length of reduced section* of 54 mm. Fig. 1 shows the design and dimensions of the specimen turning process for tensile strength test specimens.

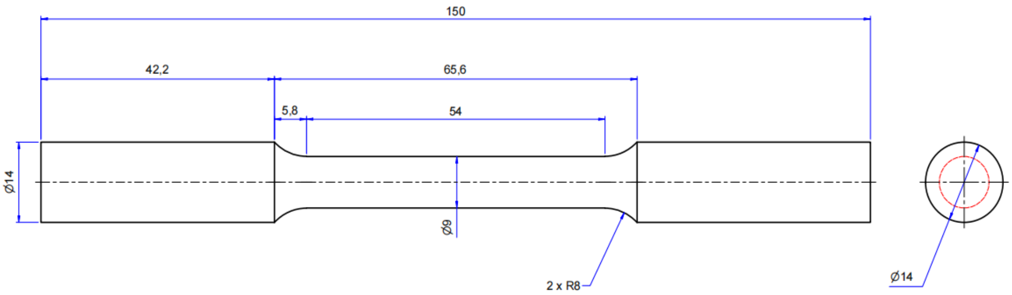


Fig. 1. Design and dimensions of tensile test specimens [9].

2.2.2. Hardness and Microstructure Test Specimens

The process of making hardness and microstructure test specimens uses the ASTM E3 standard with a specimen diameter of 24 mm and a specimen thickness of 10 mm. Fig. 2 shows the design and dimensions of the specimen turning process for hardness and microstructure testing.

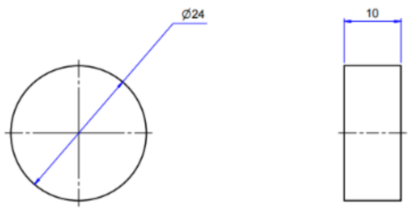


Fig. 2. Dimensions of hardness and microstructure testing specimens [10].

2.3. Heat Treatment Process

The heat treatment process is a process in which the structure and characteristics of metals are changed by heating them to a certain temperature, then cooling them using various media such as air, water, or oil to obtain the specific characteristics desired [11]. The heat treatment process of the specimens was carried out using a Nabertherm hardening machine, with details of 3 test specimens receiving heat treatment and 1 test specimen not receiving any heat treatment. For the specimens that underwent heat treatment, they were subjected to hardening at 910 °C for 20 minutes, followed by tempering at 175 °C, 225 °C, and 275 °C for 20 minutes.

2.4. Testing materials

The tensile testing process is carried out by continuously pulling the test object, causing the test object to elongate regularly until it finally breaks. The output of this tensile test is the yield stress, maximum stress, strain, and type of fracture .

Vickers hardness testing is performed using a diamond pyramid indenter with a 136-degree angle, resulting in an indentation mark. The application of the Vickers method can cover various materials, from soft metals to very hard metals. The indentation results of the Vickers test are measured with a precision measuring instrument, so they have excellent accuracy [12].

Metallographic testing is a testing method used to observe metal structures with the aid of a microscope. In the metallographic testing process, there are two types of testing, namely macro testing and micro testing. The macro testing process aims to see the area resulting from the welding process, including measuring the width of the weld metal and identifying defects in the welding that may occur. Meanwhile, the micro testing process aims to identify various phases in metals with specific mixtures and their forms [13]. Microstructure testing is assisted by Image J software to map the percentage of microstructure visualized in the image.

3. Results and Discussion

3.1. Chemical Composition Testing

The chemical composition testing process of the test specimens was carried out at the Indonesian Materials Laboratory using a TY-9000 *Optical Emission Spectrometer*. The chemical composition testing process in this study followed the JIS G 4051 reference standard with *round bar* specimens measuring Ø25.5 mm in diameter. The chemical composition test results can be seen in Table 1.

Table 1. Chemical composition of S45C steel

	C	Si	Mn	P	Cr	Ni	Cu	Mo	Ti	Al	Fe
Composition (%)	0.402	0.182	0.649	0.022	0.059	0.084	0.050	<0.001	0.005	0.022	98.456

Based on Table 1, it is known that the material used in this study has a carbon (C) content of 0.402%. Thus, the material used in this study is classified as medium carbon steel, indicating that the specimen material in this study has characteristics that allow *heat treatment* to be carried out to improve its mechanical properties.

3.2. Tensile Test

The tensile testing process was carried out at PT INKA (Persero) using a Zwick Roell machine. The data obtained from the study was grouped into 3 categories, namely: specimens without heat treatment, specimens with a tempering temperature of 175°C, and specimens with a tempering temperature of 225 °C. The tensile testing process was carried out on each category consisting of 3 specimens, and then the average value was taken. The tensile test results, illustrated by the maximum stress, can be seen in Fig. 3.

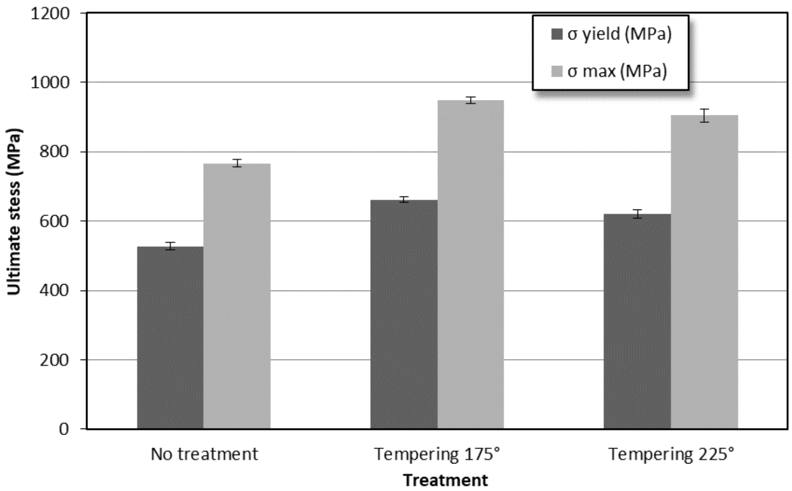


Fig. 3. Graph of maximum stress values for S45C steel

Based on the graph shown in Fig. 3, it can be seen that the highest average maximum stress value was obtained from the test specimen that had undergone heat treatment at a temperature of 175 °C. The test specimen that underwent tempering at a temperature of 175 °C had an average maximum stress value of 948.6 MPa, while the lowest average maximum stress value was found in the test specimen that did not receive any treatment, with an average maximum stress value of 767 MPa. This indicates that the tempering heat treatment process affects the maximum stress value of S45C steel. The higher the tempering temperature applied, the more significant the decrease in the maximum stress value of S45C steel.

Furthermore, from the tensile test results, strain data was obtained from the start of tensile loading until the specimen broke. The strain values for the untreated test specimen and the tempered specimen can be seen in Fig. 4.

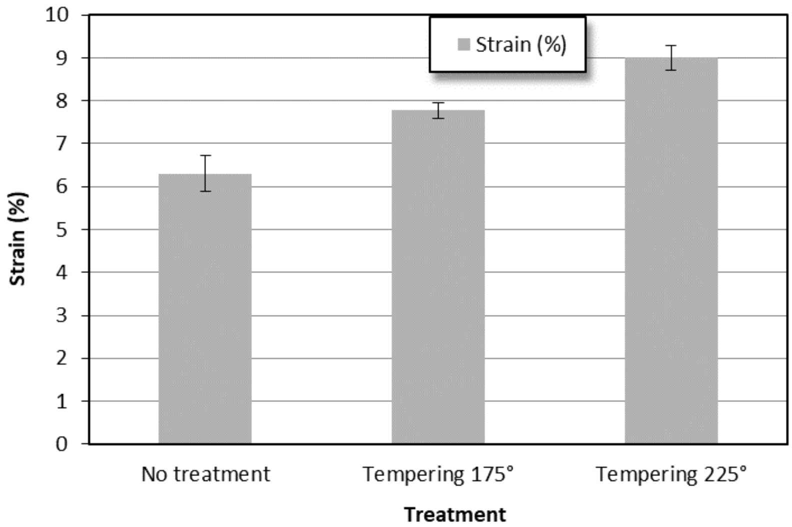


Fig. 4. Graph of maximum strain values of S45C steel

Based on the graph in Fig. 4, it can be seen that the highest average maximum strain value of the specimen was obtained from the test specimen that had undergone *heat* treatment at a temperature of 225 °C. Test specimens that underwent *tempering* at a temperature of 225 °C had an average maximum strain value of 9%, while the lowest average maximum strain value was found in test specimens without treatment, with an average maximum strain value of 6.3%. This indicates that *the tempering* heat treatment process affects the ductility of S45C steel. The higher the *tempering* temperature applied, the more significant the increase in the ductility of S45C steel. The fracture results of the tensile test were identified based on the shape of the fracture surface and necking that occurred to determine the ductility level of the material.

The fracture images of the specimens after tensile testing are shown in Fig. 5. Based on the images, it can be seen that before fracture, there was a reduction in the fracture surface area (necking) in all test specimens, both untreated and treated with tempering temperatures of 175°C and 225°C. This indicates that the material still has good ductility. Based on the strain data, it is known that the best ductility occurs at a tempering temperature of 225°C.

(Untreated) (Tempering 175 ℃) (Tempering 225 ℃)

Fig. 5. Specimen fracture results after tensile testing

3.3. *Vickers* Hardness Test

The Vickers hardness test was conducted using an MFL Pruf GMBH D-6800 type RBV machine with a load of 105 kg. The data obtained from the study were grouped into four categories, namely: specimens without tempering treatment, specimens with a tempering temperature of 175℃, specimens with a tempering temperature of 225℃, and specimens with a tempering temperature of 275℃. The hardness test results are shown in Fig. 6. Based on the graph in Fig. 6, it can be seen that the highest *Vickers* hardness value of S45C steel was obtained from test specimens that had undergone a *tempering* heat treatment process at a temperature of 175℃. The test specimen that underwent *tempering* at a temperature of 175℃ had a *Vickers* hardness value of 358.06 VHN, while the lowest *Vickers* hardness value was found in the test specimen that did not receive any treatment, with a *Vickers* hardness value of 115.86 VHN. This indicates that the *tempering* heat treatment process affects the hardness level of S45C steel. The higher the *tempering* temperature applied, the more significant the decrease in the hardness level of S45C steel.

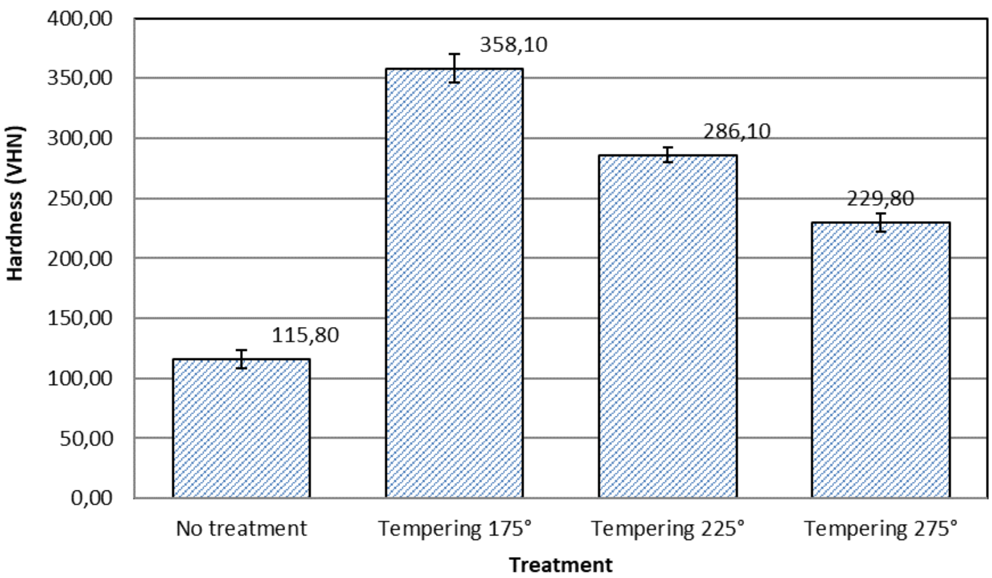
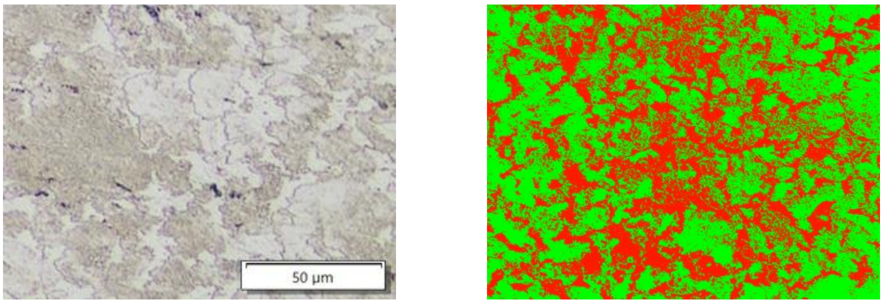


Fig 6. Graph of S45C steel hardness values.

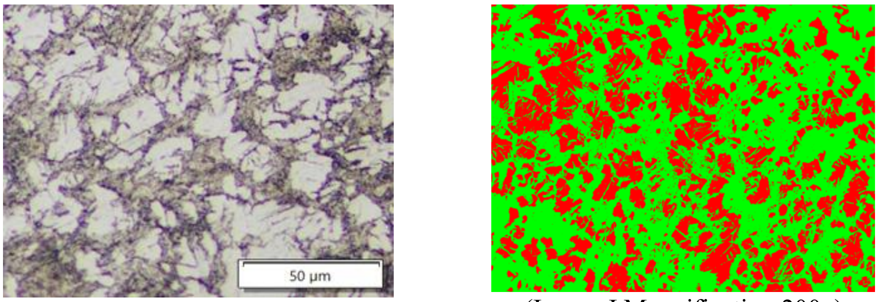
3.4. Microstructure Observation

The microstructure observation process of the test specimens in this study was carried out using an *Olympus* machine. The data obtained was then processed using Image J software to determine the percentage of microstructure displayed in the image. The microstructure observation process of the specimens was carried out on the surface of the test specimens using a microscope with a 200x eyepiece magnification. The results of the microstructure observation and interpretation using Image J are shown in Fig. 7, Fig. 8, Fig. 9, and Fig. 10. Based on the microstructure of Fig. 7, Fig. 8, Fig. 9, and Fig. 10, it can be seen that there are two types of structures, namely ferrite and pearlite/martensite. Image J, which is an interpretation of the microstructure image, is used to calculate the percentage of each type of structure in the steel material.



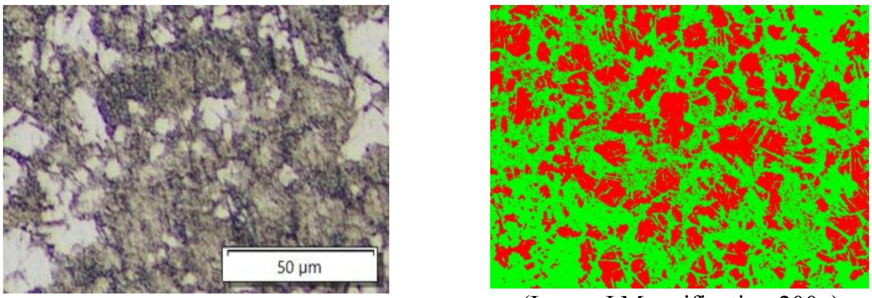
(200x magnification) (Image J Magnification 200x)

Fig. 7. Microstructure of untreated specimens



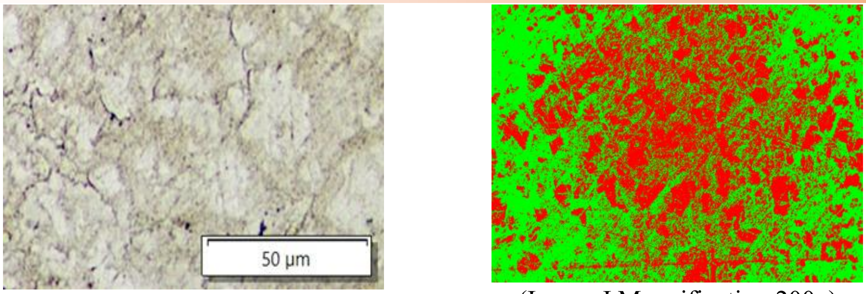
(200x magnification) (Image J Magnification 200x)

Fig. 8. Microstructure of specimen with *tempering* at 175°C



(200x magnification) (Image J Magnification 200x)

Fig. 9. Microstructure of test specimen with *tempering* temperature of 225 °C



(200x magnification) (Image J Magnification 200x)

Fig. 10. Microstructure of test specimen with *tempering* temperature of 275 °C

Fig. 11 shows a graph of the Image J calculation results for the ferrite structure in each specimen, which serves as a quantitative comparison reference. Furthermore, Fig. 12 shows a graph of the Image J calculation results for the pearlite/martensite structure in each specimen. Based on the graph shown in Fig. 11, it is known that the highest ferrite percentage value was obtained from the test specimen that had undergone tempering at a temperature of 275 °C. The test specimen that underwent tempering at a temperature of 275 °C had a ferrite percentage value of 45.868%, while the lowest ferrite percentage value was found in the test specimen that underwent heat treatment tempering at a temperature of 175 °C with a ferrite percentage value of 37.360%. This indicates that the tempering heat treatment process affects the ferrite percentage value of S45C steel. The higher the tempering temperature applied, the more significant the increase in the ferrite percentage value of S45C steel.

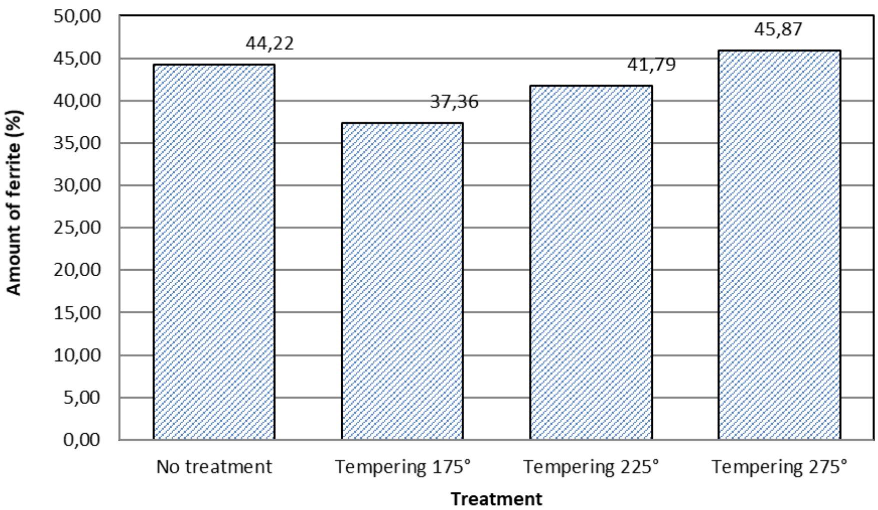


Fig. 11. Graph of the percentage of *ferrite in* S45C steel

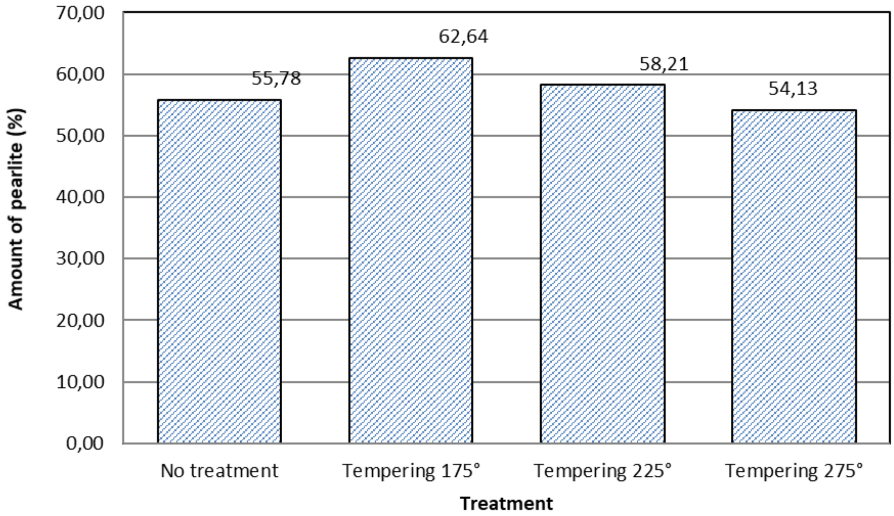


Fig. 12. Graph of *pearlite/martensite* percentage values of S45C steel

Furthermore, Fig. 12 shows that the highest *pearlite* or *martensite* percentage values were obtained from test specimens that had undergone a *tempering* process at a temperature of 175 °C. Test specimens that underwent *tempering* at a temperature of 175 °C had a *martensite* percentage value of 62.64%, while the lowest *pearlite* or *martensite* percentage value was found in test specimen s that underwent *tempering* at a temperature of 275 °C with a *martensite* percentage value of 54.13%. This indicates that the *tempering* heat treatment process affects the *pearlite* or *martensite* percentage value of S45C steel. The higher the *tempering* temperature applied, the more significant the decrease in the *pearlite* or *martensite* percentage value of S45C steel.

2. Conclusion

Based on the discussion, the following conclusions can be drawn:

S45C steel without treatment has the lowest maximum stress with a value of 767 MPa and a maximum strain of 6.3%. Meanwhile, specimens that have undergone a *tempering* process at a temperature of 175°C have the highest maximum stress with a value of 948.6 MPa and a maximum strain of 7.76%.

The highest hardness of S45C steel was obtained from specimens that had undergone a *tempering* process at a temperature of 175°C with a value of 358.06 VHN. Meanwhile, the lowest hardness value was found in untreated specimens with a value of 115.86 VHN.

Untreated S45C steel has a dominant *ferrite* and *pearlite* phase content in its microstructure. Meanwhile, specimens that have undergone *tempering* at temperatures of 175°C, 225°C, and 275°C have a dominant *ferrite* and *martensite* phase content in their microstructure.

S45C steel with a *tempering* process at a temperature of 175°C is considered more suitable for meeting industrial needs because it has a hardness value that is close to the industry standard for bogie pin materials, which is 370 VHN.

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