



Mechanical Property Characterization Of Carbon Steel Material Based On Rockwell Hardness Testing

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ABSTRACT

Carbon steel is one of the most widely used engineering materials in the manufacturing and construction industries due to its favorable mechanical properties, ease of fabrication, and relatively low production cost. One of the most important parameters in evaluating carbon steel quality is hardness, which reflects the material's resistance to plastic deformation. This study aims to characterize the mechanical properties of carbon steel through Rockwell hardness testing using the Jominy End Quench method, determine the hardness distribution along the specimen, and analyze the relationship between the testing position and hardness value. The research employed ST 37 carbon steel specimens with a diameter of 25 mm and a length of 100 mm. The specimens were heated to 763°C, held for 5 minutes, cooled using the Jominy End Quench method, and subsequently tested using the Rockwell hardness method at ten measurement points. The results indicate that the hardness decreased from 78.6 HRB at a distance of 4 mm to 72.1 HRB at 40 mm, reflecting the reduction in cooling rate along the specimen. The average hardness value obtained was 67.205 HRB, with a measurement accuracy of 99.91%. Regression analysis produced the equation $Y = 73.255 - 0.3025X$, indicating that every 1 mm increase in testing distance resulted in a hardness reduction of approximately 0.3025 HRB. The correlation coefficient of -0.886 demonstrates a very strong negative relationship between testing position and hardness, while the coefficient of determination of 78.53% indicates that most of the hardness variation is influenced by the testing position or cooling rate. The findings confirm that the combination of the Jominy End Quench method and Rockwell hardness testing is effective for evaluating the hardenability and hardness distribution of carbon steel.

Keywords: carbon steel, Rockwell hardness, Jominy End Quench, hardenability, mechanical properties

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1. Introduction

Metals, particularly steel, can be hardened by modifying their microstructure without adding alloying elements. Carbon steel is widely used because of its favorable mechanical properties, ease of processing, availability in various specifications, and relatively low production cost compared with other materials [1]. Carbon steel must possess mechanical characteristics that enable it to withstand the loading conditions encountered

during its operational service life [2]. The mechanical properties of a material include strength, hardness, ductility, toughness, and wear resistance. One of the most important parameters commonly used to evaluate material quality is hardness [3].

Hardness testing is widely employed in material evaluation because it is relatively simple to perform, requires a short testing period, and provides useful information regarding the mechanical characteristics of a

material [4]. This method offers several advantages, including rapid testing, direct readings from the testing instrument, and reasonably good measurement accuracy for various metallic materials [5].

Material characterization is the process of identifying and analyzing the properties of a material to obtain comprehensive information about its characteristics. Therefore, characterizing the mechanical properties of carbon steel through Rockwell hardness testing is essential to obtain data that can serve as a reference for material selection and the development of engineering materials.

This study employed an experimental research design with a quantitative approach. The experiments were conducted at the Fluid Mechanics Laboratory, Campus 3, Universitas Widya Gama Malang, from May to July 2026

2. Methodology of Research

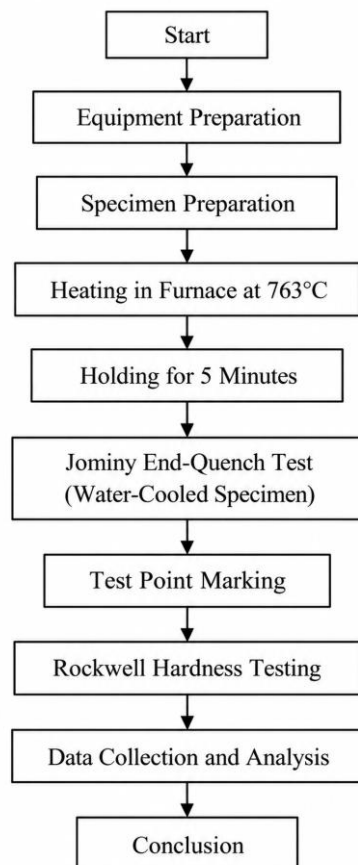


Figure 1. Research Flowchart

The materials and equipment used in this study are described as follows. The test material was ST37 steel with a diameter of 25 mm and a length of 100 mm. The experiments were conducted in May at the Metal Testing Laboratory, Faculty of Engineering, Universitas Yudharta Pasuruan. The specimen dimensions are illustrated in the following figure

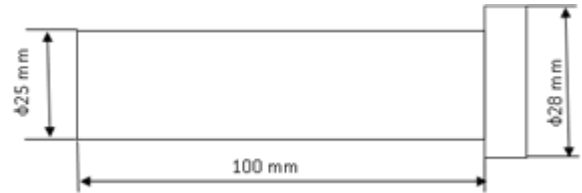


Figure 2. Shape and Dimensions of the Jominy Specimen (mm)

3. Result and Discussion

This study evaluated the hardness of a Jominy specimen made of cylindrical steel using the Rockwell Hardness Number method. The test was performed using a 1/16-inch-diameter spherical indenter with a test load of 100 kgf [8]. A total of 10 hardness measurements were performed on the specimen. The results of the hardness testing are presented in Table 1.

Table 1. Hardness Testing Results

No	Posisi (mm)	Kekerasan (HRB)
1	4	78,6
2	8	76,3
3	12	75,1
4	16	74
5	20	73
6	24	72,8
7	28	71,9
8	32	73,1
9	36	71,9
10	40	72,1

After obtaining the test results, the accuracy of the Jominy hardness testing was evaluated as follows.:

- Mean value ($\bar{X}$) = $\frac{\sum X}{n} = \frac{672,05}{10} = 67,205$
- Standard deviation (SD) = $\sqrt{\frac{[X - \bar{X}]^2}{n - 1}} = \sqrt{\frac{354,4548}{10 - 1}} = 6,2756$
- Standard error of the mean ($\bar{SD}$) = $\frac{SD}{n} = \frac{6,2756}{10} = 0,62756$
- Measurement result (MR) = $\bar{X} \pm \bar{SD} = 672,05 \pm 0,62756 = 672,67$
 $= 672,05 - 0,62756 = 671,42$
- Relative error (RE) = $\frac{\bar{SD}}{\bar{X}} \times 100\% = \frac{0,62756}{672,05} \times 100\% = 0,09\%$
- Measurement accuracy (MA) = $100\% - RE = 100\% - 0,09\% = 99,91\%$

The test results indicate that the hardness of the steel generally decreased from 78.6 HRB at a distance of 4 mm to approximately 72 HRB at a distance of 40 mm. This phenomenon is consistent with the principles of the Jominy End-Quench Test, in which the region closest to the quenched end experiences the highest cooling rate, promoting the formation of martensite, a microstructure characterized by high hardness. As the distance from the quenched end increases, the cooling rate decreases, resulting in the formation of a greater proportion of bainite or pearlite, which generally exhibit lower hardness than martensite. Therefore, the obtained Jominy hardness curve demonstrates a typical hardness distribution that can be used to evaluate the hardenability of the tested steel material [7].

The accuracy of the Jominy hardness testing results is presented in Table 2.

Table 2. Jominy hardness testing results

No	x	$ X - \bar{X} $	$ X - \bar{X} ^2$
1	74.35	7.145	51.05
2	73.45	6.245	39
3	68.3	1.095	1,119
4	68.75	1.545	2.387
5	65.1	2.105	4.431
6	64.7	2.505	6.275
7	67.82	0.62	0.3844
8	63.325	3.88	15.05
9	62.3	14.905	224.16
10	63.95	3.225	10.59
Σ	672.045		1472.327

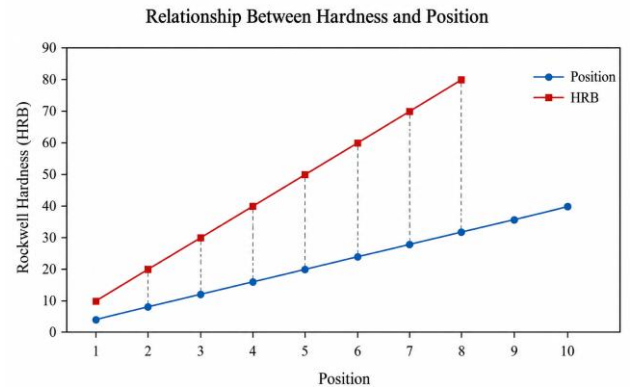


Figure 3. Relationship Between Hardness and Position

Figure 3 illustrates the relationship between measurement position and Rockwell hardness in the Jominy End-Quench Test. The plotted hardness values increase from approximately 10 HRB at position 1 to 80 HRB at position 8, indicating an upward trend in the presented data. However, this trend should be verified against the original experimental measurements, as hardness in a Jominy end-quench specimen generally decreases with increasing distance from the quenched end due to a reduction in cooling rate. Therefore, the measurement positions, data series, and hardness values should be checked to ensure that the graph accurately represents the experimental results.

Based on the data presented in Table 1, the Jominy test results show variations in the measured values at each observation point, with a total sum of measurements of 672.045 and a sum of squared deviations of 1,472.327. The average test result can be calculated as follows:

$$\bar{X} = \frac{\sum X}{n} = \frac{672,045}{10} = 67,205$$

The average value of 67.205 represents the mean hardness of the specimen after the cooling process in the Jominy test. The Jominy test is used to determine the hardenability of steel by examining the hardness

distribution from the rapidly quenched end to regions farther away from the cooling source.

The data show that the highest measured value was 74.35, whereas the lowest was 62.30. This relatively wide range indicates variations in the material properties associated with differences in cooling rates at each measurement position.

The deviation column indicates how far each measurement deviates from the mean value. Some measurements exhibit relatively small deviations, such as the value of 67.82, with a deviation of 0.62 and a squared deviation of 0.3844. This indicates that the measurement is close to the mean and may represent the general condition of the material. In contrast, the value of 62.30 exhibits a relatively large deviation, contributing substantially to the overall data variation.

Based on the sum of squared deviations of 1,472.327, the standard deviation can be calculated as follows:

$$S = \sqrt{\frac{\sum (X - \bar{X})^2}{n-1}} = \sqrt{\frac{1472,327}{9}} \approx 12,79$$

Result A relatively large standard deviation indicates substantial data dispersion. This condition suggests that the cooling process may have produced variations in the microstructure at different testing locations. Regions subjected to faster cooling rates are expected to develop a higher proportion of martensite, resulting in greater hardness, whereas regions cooled more slowly may form pearlite or bainite, which generally exhibit lower hardness values. Overall, the Jominy test results indicate that the specimen exhibits variations in hardenability along its length. The observed differences in hardness are characteristic of the Jominy End-Quench Test and demonstrate the influence of cooling rate on microstructural development and the mechanical properties of steel.

Based on the observed data, a regression analysis was subsequently performed to determine the Jominy regression model. The results of the regression analysis are presented in the following table 3.

Table 3 results of the regression

No	X	Y	X ²	Y ²	XY
1	2	74.35	4	5527.923	148.7
2	6	73.45	16	5394.903	440.7
3	10	68.3	100	4664.89	683
4	14	68.75	196	4726.563	962.5
5	18	65.1	324	4238.01	1171.8
6	22	64.7	484	4186.09	1423.4
7	26	67.82	676	4600.23	1763.45
8	30	63.32	900	4010.055	1899.75
9	34	62.3	1156	4881.29	2118.2
10	38	63.95	1444	4089.603	2430.1
Σ	200	672.04	5300	46319.56	13041.6

Where:

- (X) represents the temperature.
- (Y) represents the hardness value.

Using the linear regression equation:

$$Y = a + bX$$

the regression coefficients can be determined as follows.:

$$(a) \quad a = \frac{\sum Y - b(\sum X)}{n} = \frac{672,05 - (-0,3025 \times 200)}{10} = \frac{732,55}{10} = 73,255$$

$$(b) \quad b = \frac{n(\sum XY) - (\sum X)(\sum Y)}{n(\sum X^2) - (\sum X)^2} = \frac{(10 \times 13041,6) - (200)(672,5)}{(10 \times 5320) - (200)^2} = \frac{-3994}{13200} = -0,3025$$

Thus, the regression equation is obtained as follows:

$$Y = 73.255 + (-0.3025)X$$

Or equivalently,

$$Y = 73.255 - 0.3025X$$

This equation indicates that for every 1 mm increase in the measurement position along the specimen, the predicted hardness decreases by approximately 0.3025 HRB.

Based on the linear regression model ($Y = a + bX$), the resulting regression equation is presented as follows.

Table 4. linear regression model

No	X	Y = a + b . X
1	2	72,65
2	6	71,84
3	10	70,23
4	14	69,02
5	18	67,81
6	22	66,6
7	26	65,39
8	30	64,18
9	34	62,97
10	38	61,76

4. Conclusions

Based on the characterization of the mechanical properties of carbon steel using Rockwell hardness testing combined with the Jominy End-Quench method, the following conclusions can be drawn:

1. The test results indicate that hardness is not uniform along the specimen. The highest hardness value was

obtained in the region closest to the quenched end, while hardness decreased at positions farther from the cooling source. This condition demonstrates that the cooling rate has a significant influence on the hardenability of the steel material.

2. The hardness of the carbon steel decreased from 78.6 HRB at a position of 4 mm to approximately 72.1 HRB at a position of 40 mm. The average hardness value was approximately 67.205 HRB, while the measurement accuracy reached 99.91%, indicating a high level of measurement consistency. The decrease in hardness occurred because the cooling rate decreased with increasing distance from the quenched end, resulting in a microstructural transition from a predominantly martensitic structure toward bainite and pearlite, which generally exhibit lower hardness.
3. The relationship between the measurement position and hardness value exhibited a strong negative correlation. Regression analysis yielded the equation ($Y=73.255-0.3025X$), indicating that each 1 mm increase in measurement distance was associated with a predicted decrease in hardness of approximately 0.3025 HRB. The correlation coefficient of -0.886 indicates a strong negative relationship, while the coefficient of determination of 78.53% indicates that approximately 78.53% of the observed variation in hardness can be explained by the measurement position in the fitted regression model. Therefore, combining the Jominy End-Quench method with Rockwell hardness testing provides an effective approach for evaluating the hardenability of carbon steel and predicting hardness distribution along the specimen.

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