

THE EFFECT OF QUENCHING WITH OIL ON ANNEALING TEMPERATURE VARIATIONS ON THE HARDNESS OF ST 37 EQUIVALENT STEEL

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ABSTRACT

ST37 equivalent steel is widely used in engineering applications due to its high ductility; however, its relatively low hardness limits its performance in wear-related components. This study investigates the effect of annealing temperature variations and different oil quenching media on the hardness of ST37 equivalent steel. Specimens were annealed at 750°C, 850°C, and 950°C with a holding time of 10 minutes, followed by quenching in three types of oil: SAE 15W-40 mineral oil, SAE 10W-40 semi-synthetic oil, and SAE 10W-40 fully synthetic oil. Hardness measurements were conducted using the Rockwell B scale (HRB) at five different points on each specimen. The results indicate a consistent increase in hardness with increasing annealing temperature for all quenching media. The highest hardness value, 43.4 HRB, was obtained at 950°C using fully synthetic oil, representing an improvement of approximately 4.58% compared to the untreated material. Among the tested media, fully synthetic oil exhibited the most effective cooling performance. These findings demonstrate that both annealing temperature and oil type significantly influence the hardness characteristics of ST37 equivalent steel.

Keywords : ST 37 Steel, Heat Treatment, Annealing, Quenching, Oil Cooling Medium

1. Introduction

A commonly applied method to increase the hardness and tensile strength of metallic materials is heat treatment. Heat treatment is a process involving the controlled heating and cooling of metals to modify their mechanical properties and microstructure (Sultan et al., 2024a). This technique utilizes the manipulation of temperature and time to alter the metal's microstructure, thereby producing enhanced mechanical properties (Mudda et al., n.d.; Ali et al., 2019)). In steel, the heat treatment process generally consists of hardening, tempering, holding time, and quenching stages. The cooling medium is one of the crucial factors determining the rate and stability of the cooling process and significantly influences microstructural formation, where water and oil cooling typically produce martensitic structures, while air cooling results in ferrite and pearlite structures (Septianto, 2013; Elmaryami et al., 2021; Pamungkas et al., 2025; Arabaci, 2024)) (Sang et al., 2023). The hardness values of the raw material were 63 and 60.6 HRC, whereas the quenched specimens exhibited hardness values of 64 and 61.5 HRC; 64.6 and 62.7 HRC; and 68.5 and 63.6 HRC. The average HRC values increased at each heating temperature (Purwanto, 2011).

Previous research on the heating effects on microstructure and mechanical properties of medium carbon low alloy steel D-6A AISI examined various heat treatment processes, including initial condition treatment, normalizing, annealing, water quenching, and tempering, accompanied by microstructure analysis, hardness testing, flexibility coefficient measurement, and cold working ratio evaluation. The mechanical properties were obtained by placing all selected samples into an electric furnace and heating them to 850°C, followed by tempering at temperatures of 200°C, 400°C, and 600°C (Almula et al., 2023; Sultan et al., 2022). The process of the quenching heat treatment of AISI 4340 steel, using geometrically complex components, was undertaken with the objective of studying and understanding the effect of quenching process parameters on distortion, stress generation, and mechanical properties. A model that applied the finite element method (FEM) (Lopez-Garcia et al., 2022). The study concluded that differences in hardness values occurred for each heat treatment condition through heating processes with

temperature variations. Heat treatment is a process of heating and cooling metals to modify their mechanical properties and microstructure, utilizing controlled manipulation of temperature and time to produce superior mechanical characteristics. In steel materials, the heat treatment process generally consists of hardening, tempering, holding time, and quenching stages. A double-quenching procedure has also been investigated and compared with the conventional single-quenching process, using various cooling media during quenching treatments. The results indicate that distilled water is the most effective cooling medium for medium carbon steel heat treatment due to the absence of salts, suspended particles, and metallic contaminants (Sultan et al., 2024b). The cooling medium is a crucial factor that determines the rate and stability of the cooling process and significantly influences microstructural formation, where water and oil cooling typically produce martensitic structures, while air cooling results in ferrite and pearlite structures (Septianto, 2013). As stated by Muh Anhar, welding is an inseparable part of industrial development because it plays a leading role in engineering and metal repair processes; therefore, understanding the influence of cooling media on the hardness of weld metal and the heat-affected zone (HAZ) is essential. A study conducted on ST37 low carbon steel evaluated hardness using the Rockwell method to determine the effect of cooling media on both weld metal and HAZ regions (Anhar & Ruchiyat, 2020).

According to Muh Anhar, in the study entitled *Cooling in SMAW Welding on the Hardness of ST37 Carbon Steel Using Gray Cement Powder under a Rockwell Load of 100 kgf*, welding is an inseparable component of industrial development, as it plays a crucial role in engineering processes and the repair of metal production systems, particularly in relation to the influence of cooling media on the hardness of weld metal and the heat-affected zone (HAZ), which were evaluated using the Rockwell hardness testing method. The research was conducted on low carbon steel ST37 (Anhar, 2019). Welding is defined as the joining of metals by heat, with or without the application of pressure, resulting in metallurgical bonding due to atomic attractive forces. According to DIN (Deutsche Industrie Normen), welding refers to the metallurgical bonding of metals or metallic joints in a molten or liquid state. Furthermore, a study investigating the effect of limestone powder and gypsum as insulating media in SMAW (Shielded Metal Arc Welding) employed an experimental approach using the SMAW welding process (Anhar & Polonia, 2021). Based on these previous studies, the present research aims to examine the influence of full synthetic oil, mineral oil, and semi-synthetic oil as cooling media on the hardness of ST37 equivalent steel after heat treatment in the annealing region, to determine the annealing temperature that produces the highest hardness value, and to evaluate how the type of oil cooling medium affects the final hardness of ST37 equivalent steel following annealing heat treatment.

2. Literature Review

A cooling medium is a fluid used to reduce the temperature of heated metal at a controlled cooling rate to achieve specific mechanical properties, such as hardness, strength, or toughness (Jamhari et al., 2023). The cooling or quenching process using a cooling medium is important because it affects the metal's microstructure and its final properties. According to Nakatsukasa et al. (2025) in *Predicting the Cooling Rate in Steel-Part Heat Treatment via Random Forests*, predicting cooling rates during heat treatment is essential because the cooling behavior strongly influences phase transformation and material performance (Nakatsukasa et al., 2025). Similarly, Nitha et al. (2025), in *The Influence of Cooling Techniques on the Performance of Pack Carburized Low Carbon Steel Using Cypress Charcoal*, reported that different cooling media have a significant impact on the hardness and wear characteristics of low carbon steel (Nitha* et al., 2025).

In the heat treatment process, medium-carbon bainitic steel is designed to achieve specific mechanical properties. By combining thermal dilatometry with in-situ high-temperature metallography, the influence of continuous cooling rates on phase transformation of bainitic steel within the intermediate temperature range (500–365 °C) has been investigated (Long et al., 2024) (Guo et al., 2019). The selection of an appropriate cooling medium affects the resulting microstructure—such as martensite, bainite, or pearlite—and consequently influences the mechanical properties of steel, including hardness, strength, and toughness.

2.1 Oil

Otero (2012) reviewed published data concerning the use of triglycerides derived from various animal and vegetable sources as quenching media for steel hardening. The review particularly focused on the traditional selection and application of different vegetable and animal oils in steel hardening processes, as well as the cooling time–temperature behavior of these fluids to characterize their quenching performance. Oil used as a cooling medium may be mineral-based, synthetic, or semi-synthetic, and is specifically designed for quenching applications in heat treatment processes (Zhang et al., 2018) (Khatib Zadeh Davani et al., 2023) (Puga-Patlán et al., 2023). Oil exhibits better thermal stability, higher viscosity, and a higher flash point compared to water, resulting in slower but more uniform cooling. Pedro Brito et al. (2019) discussed the possibility of using vegetable oils as cooling media for quenching operations. Furthermore (Brito et al., 2019). Totten et al. (1999) reported in a study comparing the performance of vegetable oil with standard mineral oil that the cooling behavior of immersion-cooled workpieces is influenced by several factors, including the type of coolant used, bath temperature, stirring rate, and the physical and chemical properties of the material being cooled (Totten et al., 1999).

2.2 Heat treatment

In metals, heat treatment is essentially a combination of operations involving the heating and cooling of a metal or alloy in the solid state to obtain the desired microstructure through grain refinement and modification of various mechanical properties (Fu & Xia, 2021). Heat treatment aims to improve ductility, relieve internal stresses, refine crystal grain size, and enhance hardness or tensile strength of metals (Delhi Institute of Tool Engineering, Okhla, Delhi-110020, India et al., 2020). Heat treatment is defined as a combination of heating and cooling processes applied to a metal or its alloy in the solid state to achieve specific properties (Qasim et al., 2018).

2.3 Annealing

Various annealing processes using oil and water quenching methods have shown that the hardness of steel varies depending on the hardness testing scale used, including reductions observed in both the HRA and HRB scales. Temperature significantly influences the hardness of steel. Final dimensions were found to vary with temperature and exposure time, indicating that fiber addition had no significant effect. Although the presence of fibers affected the radius of curvature, this parameter was highly dependent on the type of fiber used. In terms of hardness, higher temperatures and longer exposure times generally resulted in higher hardness values. Regarding flexural properties, flexural strength increased with exposure time and temperature for composites. Additionally, improvements were observed in impact strength, stress relaxation, and creep behavior across all materials (Valvez et al., 2023).

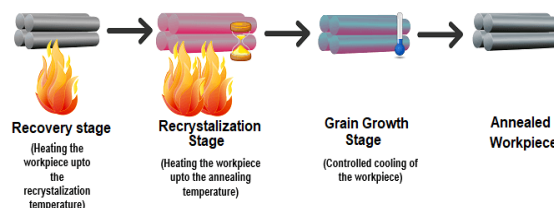


Fig. 1. Illustration of the Annealing Heat Treatment Process

Previous research has focused on the mechanical properties, impact resistance, microstructure, microhardness, and overall mechanical behavior of the material. Several test specimens for impact testing, compression testing, and microstructural analysis were prepared using CNC machining. The results showed that impact energy increased with increasing annealing temperature, while microhardness generally decreased as the annealing temperature increased. However, at 940 °C, the microhardness increased again, with the maximum reduction of 31.6% observed at 900 °C (Sharma, 2012).

2.4 Tempering

An inverse heat transfer analysis was conducted to determine the maximum magnitude of a moving Gaussian heat source corresponding to the heat load applied to the milled component. The inverse estimates were obtained from temperature measurements recorded during the processing of samples subjected to different heat treatment conditions. The estimated heat fluxes and measured temperatures were discussed in relation to metallo-thermomechanical interactions involving microstructural aspects, hardness, and thermal properties. The results indicated a substantial increase in the thermal energy transferred to the milled steel during cooling and tempering, primarily due to the increased hardness and reduced thermal conductivity of the tempered martensitic structure formed after hardening (Ramos et al., 2024; Badaruddin et al., 2023).

Through the tempering process, part of the martensitic structure transforms into a more stable microstructure, thereby reducing internal stresses within the metal. As the tempering temperature increases, hardness decreases, while ductility and toughness improve (Sutrisno et al., 2023).

2.5 Mechanical Properties of Steel

The mechanical properties of steel refer to its characteristics in responding to external loads or forces, which are essential in engineering and structural design (Murugan, 2020; Koşatepe & Yazici, 2023). The strength of steel includes tensile strength, which is its ability to withstand tensile loads before fracture and is measured through Ultimate Tensile Strength (UTS) and Yield Strength, as well as compressive strength and shear strength (Murugan, 2020). Steel also exhibits elasticity, whereby within certain limits it follows Hooke's Law, with a modulus of elasticity (E) of approximately 200 GPa for carbon steel, indicating its stiffness (Mahendran, 1996). However, once the yield point is exceeded, steel enters the plastic phase, undergoing permanent deformation that enables forming processes and energy absorption.

Fatigue resistance determines the durability of steel under cyclic loading, with the fatigue limit representing the maximum stress that can be sustained without failure (Çiuplys et al., 2010). At elevated temperatures, steel may experience creep, which is slow deformation under constant load. This behavior is influenced by factors such as carbon content, heat treatment, alloying elements, and manufacturing processes (Khamas & Lafta, 2023).

3. Research Methods

The study employed a quantitative experimental method on ST37 equivalent steel using different cooling media. The primary objective was to examine the effect of the combination of temperature and cooling media on the hardness of ST37 equivalent steel, which served as the dependent variable. All data were collected in numerical form from Rockwell Hardness Test measurements and were analyzed statistically. The hardness values were obtained using standardized testing equipment and expressed numerically, ensuring that the results were objective, measurable, and reproducible. A comparative analysis was conducted to directly evaluate the influence of temperature variations and types of oil used, and the results were presented in the form of graphs and comparative tables to clearly illustrate the differences in hardness values. The quantitative approach also enabled the findings to be structured systematically through numerical analysis and graphical representation, facilitating clearer interpretation and accountability.

Furthermore, because standardized testing procedures and calibrated measuring instruments were applied, the research results can be replicated and validated by other researchers, thereby strengthening the scientific reliability of the study.

4. Results and Discussions

Hardness testing was performed on ST37 steel specimens following heat treatment using synthetic oil, mineral oil, and semi-synthetic oil as quenching media, with annealing temperatures of 750°C, 850°C, and 950°C. The experimental results are presented in tabular and graphical forms to provide a clear comparison of hardness variations under different processing conditions. A detailed analysis was conducted to evaluate the influence of cooling medium type and annealing

temperature on the resulting hardness values of ST37 steel. The discussion focuses on identifying trends in hardness behavior, examining the interaction between temperature and cooling rate, and interpreting the results in relation to microstructural transformations induced by the heat treatment process.

4.1 Raw Material

Hardness testing of the raw material specimen was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement point was tested once, and the same testing procedure was consistently applied to all other specimens to ensure uniformity of experimental conditions. Based on the testing results, the hardness values of the raw material were obtained and recorded for further analysis.

Table 1. Hardness Values of Raw Material (Rockwell B Scale)

Measurement Point	Hardness (HRB)
1	41.5
2	41.5
3	41.5
4	41.5
5	41.5
Total	207.5
Average	41.5

The hardness test results of the raw material specimen are presented in Table 1, while the hardness distribution is illustrated in Figure 2.

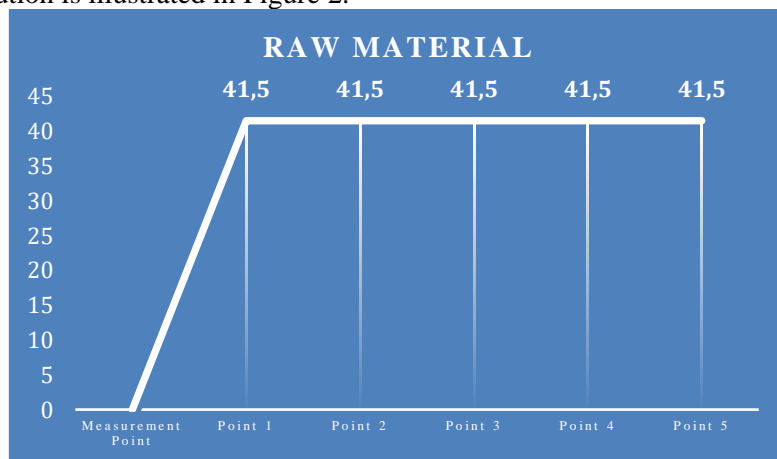


Fig. 2. Hardness Test Graph of the Raw Material

The hardness values obtained from the five measurement points were consistently 41.5 HRB, resulting in a total value of 207.5 and an average hardness of 41.5 HRB. These results represent the overall hardness values of the raw material specimen. After obtaining the hardness results of the raw material, a verification step was performed for ST37 steel. This verification involved converting the hardness test results (HRB) into tensile strength values expressed in megapascals (MPa).

Table 2 - Comparison of Vickers, Brinell, and Rockwell Hardness Values and Tensile Strength in Steel and Cast Steel

Tensile strength	Vickers strength	Brinell strength	Rockwell strength							
			HRB	HRF	HRC	HRA	HRD	HR15 N	HR30 N	HR45 N
Mpa	HV10	HB ¹⁾								
255	80	76,0	–	–	–	–	–	–	–	–
270	85	80,7	41,0	–	–	–	–	–	–	–
285	90	85,5	48,0	82,6	–	–	–	–	–	–

305	95	90,2	52,0	-	-	-	-	-	-
320	100	95,0	56,2	87,0	-	-	-	-	-
335	105	99,8	-	-	-	-	-	-	-
350	110	105	62,3	90,5	-	-	-	-	-
370	115	109	-	-	-	-	-	-	-

According to the ASM Handbook, Volume 1, low-carbon steels such as ST37 in the untreated condition typically exhibit Rockwell B hardness values ranging from 40 to 65 HRB, with corresponding tensile strengths between 250 MPa and 370 MPa. The hardness value of 41.5 HRB obtained in this study can be converted to an approximate tensile strength of 270 MPa, which remains within the characteristic range of low-carbon steel (pp. 18–19, 30–32).

4.2 Specimens Subjected to Annealing at 750°C

Specimens subjected to annealing at 750°C were quenched using three different cooling media: SAE 15W-40 mineral oil, SAE 10W-40 semi-synthetic oil, and SAE 10W-40 fully synthetic oil. The hardness test results obtained from these specimens are presented as follows:

A. SAE 15W-40 Mineral Oil as Cooling Medium

The specimen subjected to annealing at 750°C with a holding time of 10 minutes was quenched using SAE 15W-40 mineral oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 3 - Hardness Test Data of Specimens Quenched in SAE 15W-40 Mineral Oil

Measurement Point	Hardness (HRB)
1	42.5
2	42.5
3	42.5
4	43.0
5	42.5
Total	213.0
Average	42.6

The table above presents the hardness test results of specimens subjected to annealing at 750°C with a holding time of 10 minutes, followed by quenching in SAE 15W-40 mineral oil as the cooling medium. The measurements were conducted at five different testing points.

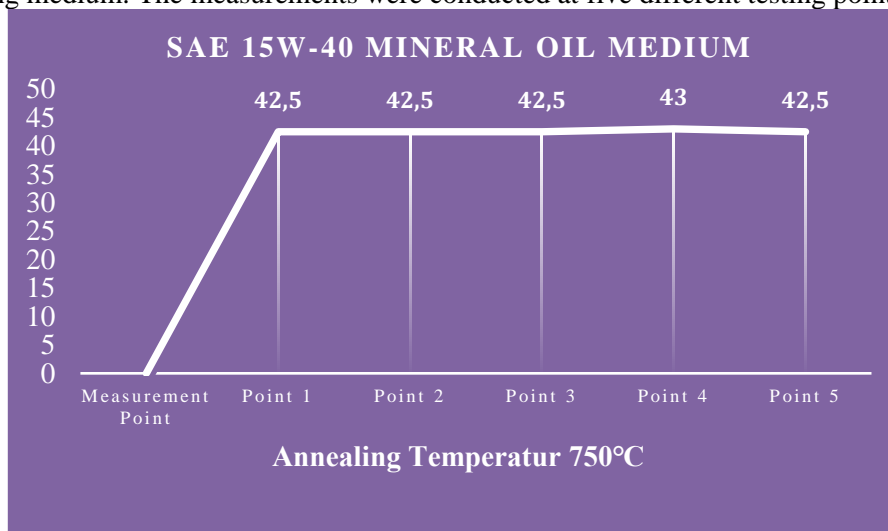


Fig. 3. Rockwell B Hardness Test Graph of Specimens Quenched in SAE 15W-40 Mineral Oil

The highest hardness value obtained from the test was 43.0 HRB, while the lowest value was 42.5 HRB. The total hardness value was 213.0, with an average hardness of 42.6 HRB. These

results represent the overall hardness values of specimens subjected to annealing at 750°C and subsequently quenched using SAE 15W-40 mineral oil as the cooling medium, with measurements taken at five different testing points.

B. SAE 10W-40 Semi-Synthetic Oil as Cooling Medium

The specimen subjected to annealing at 750°C with a holding time of 10 minutes was quenched using SAE 10W-40 semi-synthetic oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 4 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil

Measurement Point	Hardness (HRB)
1	43.0
2	43.0
3	43.0
4	42.5
5	43.0
Total	214.5
Average	42.9

The table above presents the hardness test results of specimens subjected to annealing at 750°C with a holding time of 10 minutes, followed by quenching in SAE 10W-40 semi-synthetic oil as the cooling medium. Measurements were conducted at five different testing points.

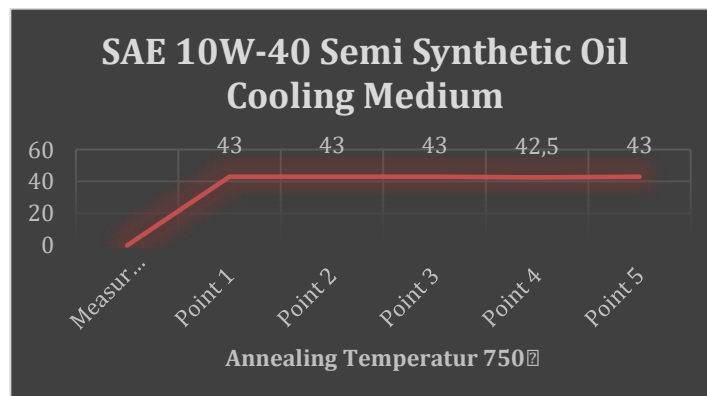


Fig. 4. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil at 750°C

The highest hardness value obtained from the test was 43.0 HRB, while the lowest value was 42.5 HRB. The total hardness value was 214.5, with an average hardness of 42.9 HRB. These results represent the overall hardness values of specimens subjected to annealing at 750°C and subsequently quenched in SAE 10W-40 semi-synthetic oil, with measurements taken at five different testing points.

C. SAE 10W-40 Fully Synthetic Oil as Cooling Medium

The specimen subjected to annealing at 750°C with a holding time of 10 minutes was quenched using SAE 10W-40 fully synthetic oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 5 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil

Measurement Point	Hardness (HRB)
1	43.5
2	43.0
3	43.0
4	42.5

Measurement Point	Hardness (HRB)
5	43.0
Total	215.0
Average	43.0

The table above presents the hardness test results of specimens subjected to annealing at 750°C with a holding time of 10 minutes, followed by quenching in SAE 10W-40 fully synthetic oil as the cooling medium. Measurements were conducted at five different testing points.

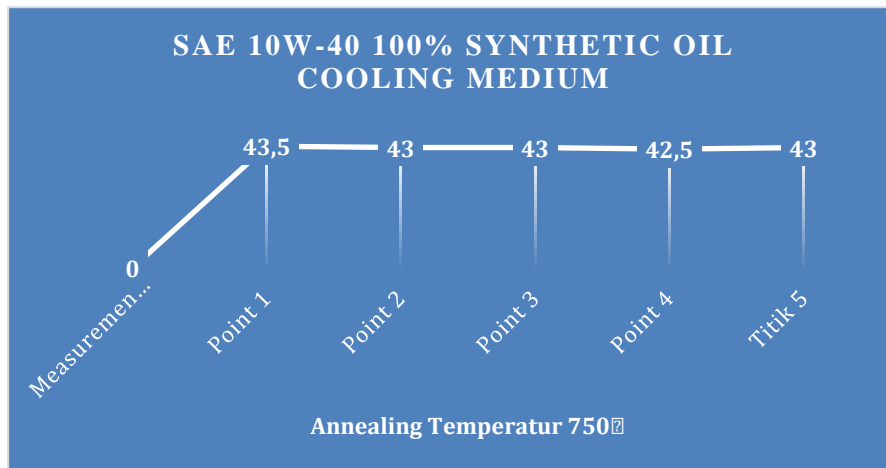


Fig. 5. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil at 750°C

The highest hardness value obtained from the test was 43.5 HRB, while the lowest value was 42.5 HRB. The total hardness value was 215.0, with an average hardness of 43.0 HRB. These results represent the overall hardness values of specimens subjected to annealing at 750°C and subsequently quenched in SAE 10W-40 fully synthetic oil as the cooling medium, with measurements taken at five different testing points.

4.3 Specimens Subjected to Annealing at 850°C

Specimens subjected to annealing at 850°C with a holding time of 10 minutes were quenched using three different cooling media: SAE 15W-40 mineral oil, SAE 10W-40 semi-synthetic oil, and SAE 10W-40 fully synthetic oil. The hardness test results are presented as follows.

A. SAE 15W-40 Mineral Oil as Cooling Medium

The specimen annealed at 850°C for 10 minutes was quenched in SAE 15W-40 mineral oil. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once.

Table 6 - Rockwell B Hardness Values of Specimens Quenched in SAE 15W-40 Mineral Oil at 850°C

Measurement Point	Hardness (HRB)
1	43.5
2	42.0
3	43.5
4	42.5
5	42.5
Total	214.0
Average	42.8

The table above presents the hardness values of specimens annealed at 850°C and quenched in SAE 15W-40 mineral oil.

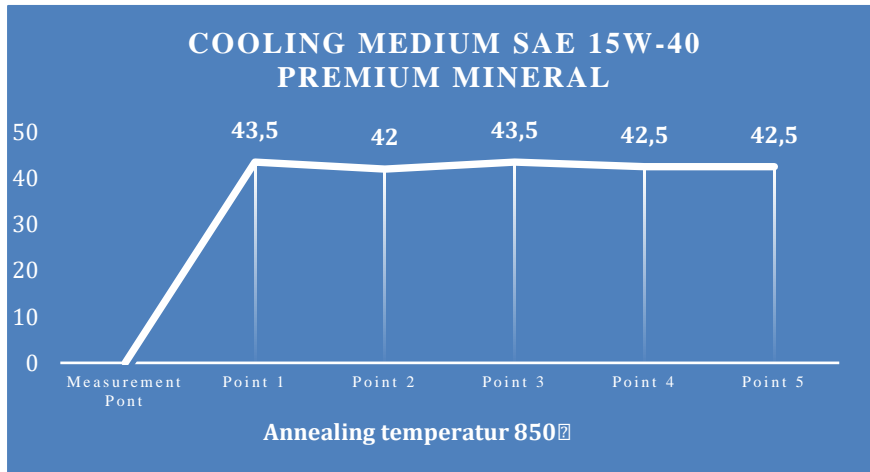


Fig. 6. Rockwell B Hardness of Specimens Quenched in SAE 15W-40 Mineral Oil at 850°C

The highest hardness value obtained was 43.5 HRB, while the lowest was 42.0 HRB. The total hardness value was 214.0, with an average of 42.8 HRB. These values represent the overall hardness characteristics of the specimen under this treatment condition.

B. SAE 10W-40 Semi-Synthetic Oil as Cooling Medium

The specimen annealed at 850°C for 10 minutes was quenched using SAE 10W-40 semi-synthetic oil. Hardness testing was performed at five different measurement points using the Rockwell B scale (100 kgf).

Table 7 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil at 850°C

Measurement Point	Hardness (HRB)
1	42.5
2	43.0
3	43.0
4	43.5
5	43.5
Total	215.5
Average	43.1

The table above presents the hardness test results of specimens subjected to annealing at 850°C with a holding time of 10 minutes, followed by quenching in SAE 10W-40 semi-synthetic oil as the cooling medium. Measurements were conducted at five different testing points.

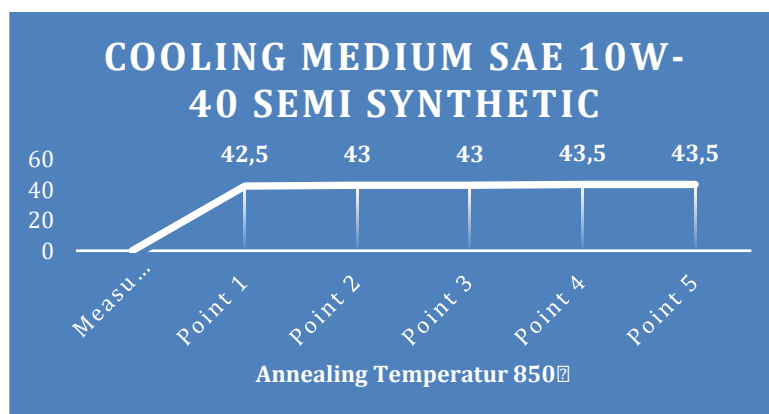


Fig. 7. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil at 850°C

The highest hardness value recorded was 43.5 HRB, and the lowest was 42.5 HRB. The total hardness value was 215.5, with an average hardness of 43.1 HRB. These results indicate a slightly higher hardness compared to mineral oil under the same annealing temperature.

C. SAE 10W-40 Fully Synthetic Oil as Cooling Medium

The specimen subjected to annealing at 850°C with a holding time of 10 minutes was quenched using SAE 10W-40 fully synthetic oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 8 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil at 850°C

Measurement Point	Hardness (HRB)
1	43.0
2	43.5
3	43.0
4	43.0
5	43.5
Total	216.0
Average	43.2

The table above presents the hardness values of specimens annealed at 850°C and subsequently quenched in SAE 10W-40 fully synthetic oil, with measurements taken at five different testing points.

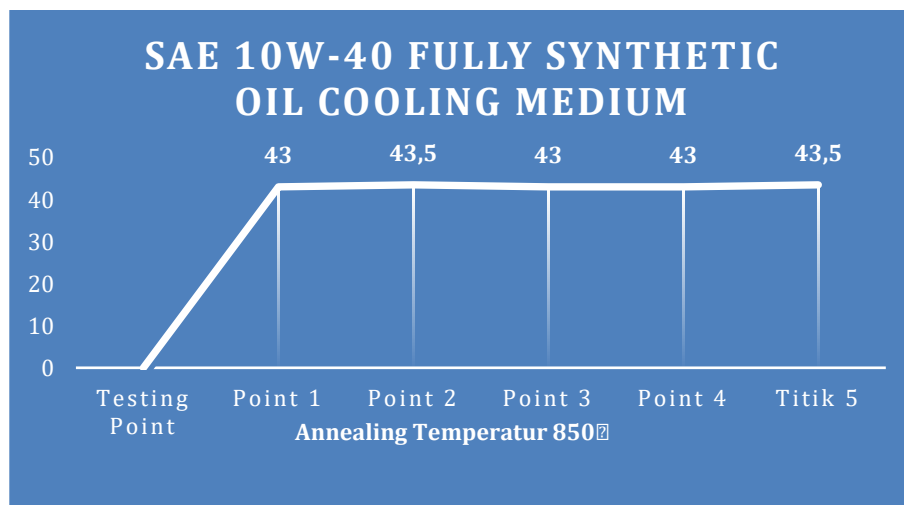


Fig. 8. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil at 850°C

The highest hardness value obtained was 43.5 HRB, while the lowest value was 43.0 HRB. The total hardness value was 216.0, with an average hardness of 43.2 HRB. These values represent the overall hardness characteristics of the specimens subjected to annealing at 850°C and quenched in SAE 10W-40 fully synthetic oil.

4.4 Specimens Subjected to Annealing at 950°C

Specimens subjected to annealing at 950°C with a holding time of 10 minutes were quenched using three different cooling media: SAE 15W-40 mineral oil, SAE 10W-40 semi-synthetic oil, and SAE 10W-40 fully synthetic oil. The hardness test results are presented as follows.

A. SAE 15W-40 Mineral Oil as Cooling Medium

The specimen annealed at 950°C for 10 minutes was quenched using SAE 15W-40 mineral oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 9 - Rockwell B Hardness Values of Specimens Quenched in SAE 15W-40 Mineral Oil at 950°C

Measurement Point	Hardness (HRB)
1	42.5
2	43.0
3	43.5
4	43.0
5	43.5
Total	215.5
Average	43.1

The table above presents the hardness values of specimens annealed at 950°C and subsequently quenched in SAE 15W-40 mineral oil, with measurements taken at five different testing points.

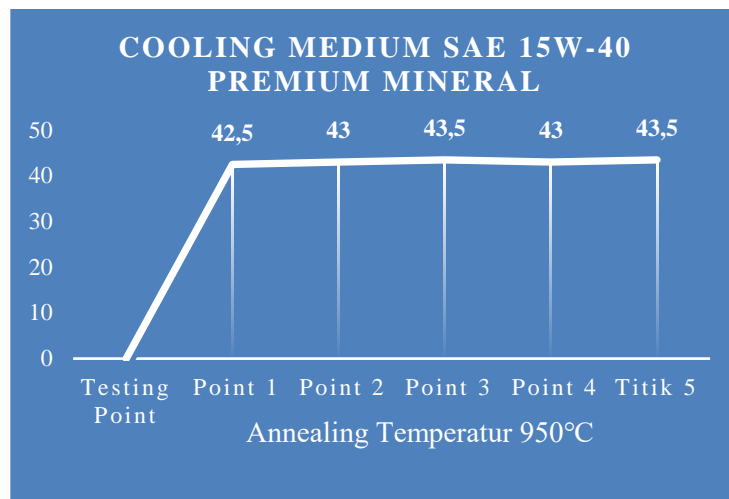


Fig. 9. Rockwell B Hardness of Specimens Quenched in SAE 15W-40 Mineral Oil at 950°C

The highest hardness value obtained was 43.5 HRB, while the lowest value was 42.5 HRB. The total hardness value was 215.5, with an average hardness of 43.1 HRB. These values represent the overall hardness characteristics of the specimens subjected to annealing at 950°C and quenched in SAE 15W-40 mineral oil.

B. SAE 10W-40 Semi-Synthetic Oil as Cooling Medium

The specimen subjected to annealing at 950°C with a holding time of 10 minutes was quenched using SAE 10W-40 semi-synthetic oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 10 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil at 950°C

Measurement Point	Hardness (HRB)
1	42.5
2	43.0
3	43.0
4	43.5

Measurement Point	Hardness (HRB)
5	43.5
Total	215.5
Average	43.1

The table above presents the hardness values of specimens annealed at 950°C and subsequently quenched in SAE 10W-40 semi-synthetic oil, with measurements taken at five different testing points.

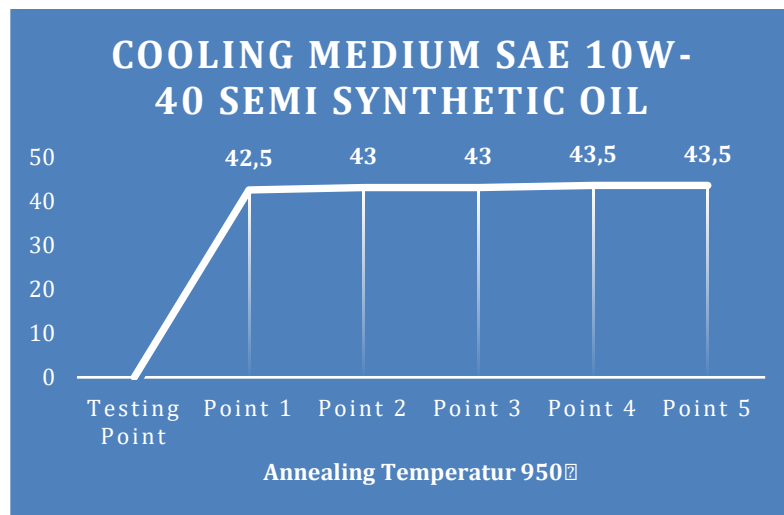


Fig. 10. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Semi-Synthetic Oil at 950°C

The highest hardness value obtained was 43.5 HRB, while the lowest value was 42.5 HRB. The total hardness value was 215.5, with an average hardness of 43.1 HRB. These values represent the overall hardness characteristics of specimens subjected to annealing at 950°C and quenched in SAE 10W-40 semi-synthetic oil.

C. SAE 10W-40 Fully Synthetic Oil as Cooling Medium

The specimen subjected to annealing at 950°C with a holding time of 10 minutes was quenched using SAE 10W-40 fully synthetic oil as the cooling medium. Hardness testing was conducted at five different measurement points using the Rockwell B scale with a total load of 100 kgf. Each measurement was performed once at each testing point.

Table 11 - Rockwell B Hardness Values of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil at 950°C

Measurement Point	Hardness (HRB)
1	43.0
2	43.5
3	43.0
4	43.0
5	43.5
Total	216.0
Average	43.2

The table above presents the hardness values of specimens annealed at 950°C and subsequently quenched in SAE 10W-40 fully synthetic oil, with measurements taken at five different testing points.

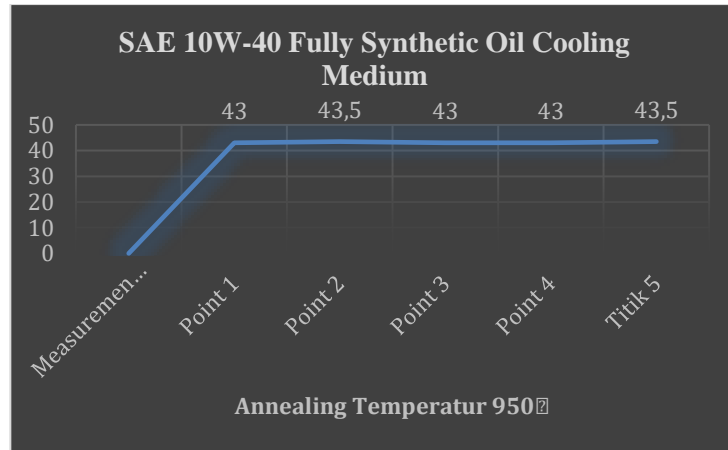


Fig. 11. Rockwell B Hardness of Specimens Quenched in SAE 10W-40 Fully Synthetic Oil at 950°C

The highest hardness value obtained was 43.5 HRB, while the lowest value was 43.0 HRB. The total hardness value was 216.0, with an average hardness of 43.2 HRB. These values represent the overall hardness characteristics of specimens subjected to annealing at 950°C and quenched in SAE 10W-40 fully synthetic oil.

4.5 Comparative Analysis of Hardness Values for All Specimens

The following section presents the overall hardness test results, which were verified and approved by the head of the laboratory. The data include the hardness values of the raw material and all specimens subjected to heat treatment at different annealing temperatures and cooling media variations.

Table 12 - Overall Hardness Values of ST37 Steel

Steel Hardness Value ST 37 (HRB)										
Testing Point	No Heat Treatment	(Heat treatment)								
	Raw Material	Annealing 750°C			Annealing 850°C			Annealing 950°C		
		Cooling Media								
		M	S.S	F.S	M	S.S	F.S	M	S.S	F.S
1	41,5	42,5	43	43,5	43,5	42,5	43	42,5	43	43,5
2	41,5	42,5	43	43	42	43	43,5	43	43,5	43,5
3	41,5	42,5	43	43	43,5	43	43	43,5	43	43
4	41,5	43	42,5	42,5	42,5	43,5	43	43	43,5	43,5
5	41,5	42,5	43	43	42,5	43,5	43,5	43,5	43	43,5
Amount	207,5	213	214,5	215	214	215,5	216	215,5	216	217
Average	41,5	42,6	42,9	43	42,8	43,1	43,2	43,1	43,2	43,4

The graphical representation of the overall hardness values of ST37 equivalent steel specimens is shown in Figure 12.

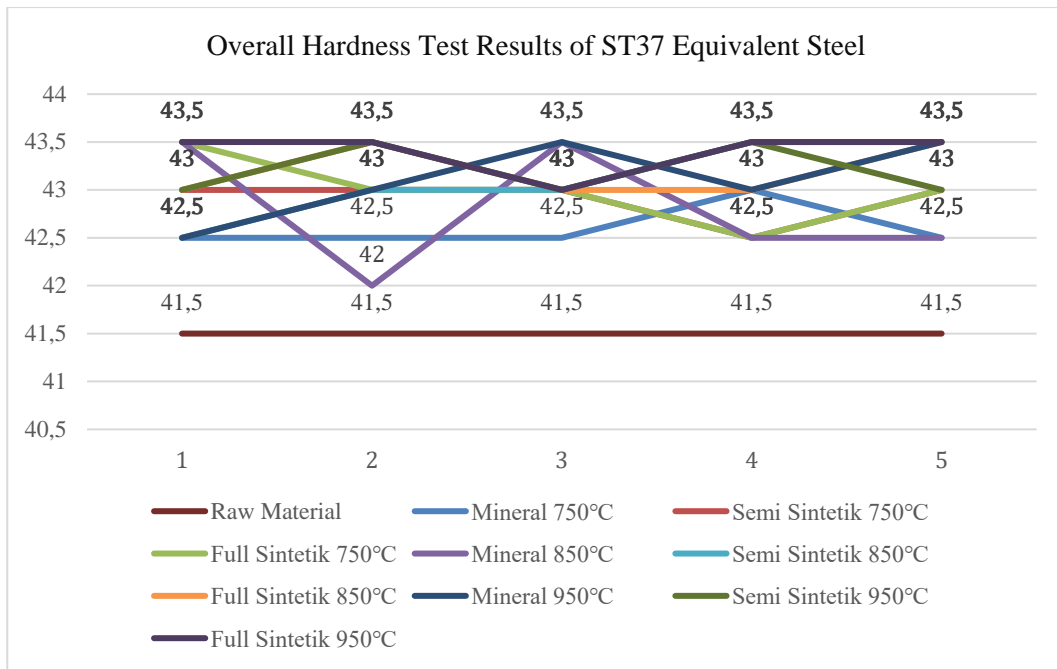


Fig. 12. Overall Hardness Test Results of ST37 Equivalent Steel

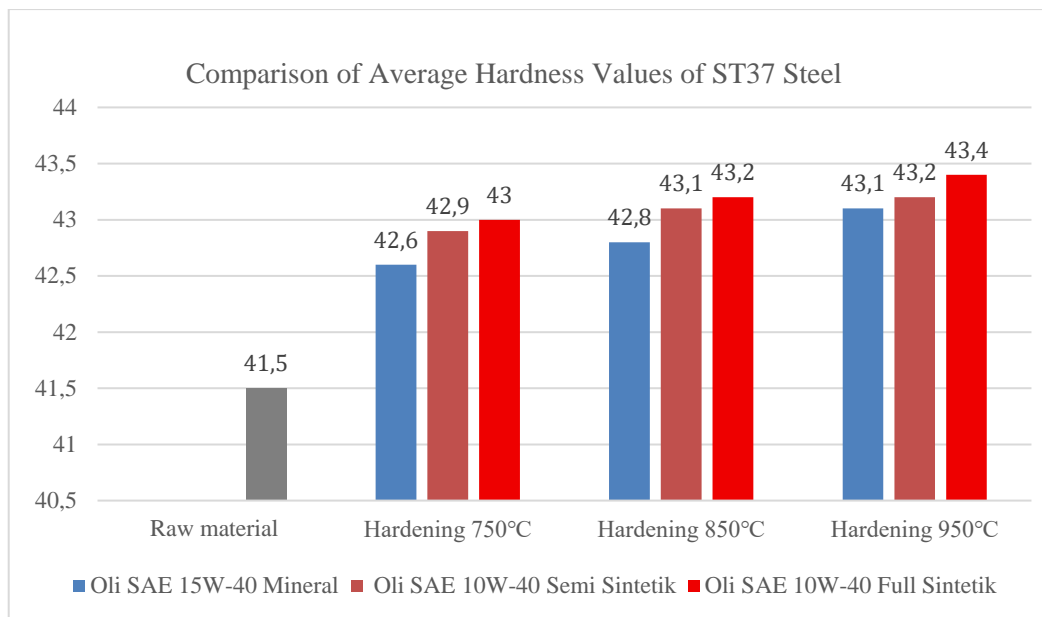


Fig. 13. Comparison of Average Hardness Values of ST37 Steel

For specimens annealed at 750°C with a holding time of 10 minutes, the highest average hardness value was obtained using SAE 10W-40 fully synthetic oil (43.0 HRB), followed by SAE 10W-40 semi-synthetic oil (42.9 HRB). The lowest average hardness was recorded for specimens quenched in SAE 15W-40 mineral oil, with an average value of 42.6 HRB.

For specimens annealed at 850°C with the same holding time, the highest average hardness value was again achieved using SAE 10W-40 fully synthetic oil (43.2 HRB), followed closely by SAE 10W-40 semi-synthetic oil (43.1 HRB). The lowest average hardness at this temperature was obtained using SAE 15W-40 mineral oil, with an average value of 42.8 HRB.

For specimens annealed at 950°C with a holding time of 10 minutes, the highest average hardness value was obtained using SAE 10W-40 fully synthetic oil (43.4 HRB), followed by SAE 10W-40 semi-synthetic oil (43.2 HRB). The lowest average hardness at this temperature was

recorded for specimens quenched in SAE 15W-40 mineral oil, with an average value of 43.1 HRB. A comparison was then conducted between the average hardness value of the raw material and all heat-treated specimens. This comparison was based on the percentage difference in hardness values obtained after heat treatment. The percentage comparison of hardness values is presented in Table 12.

Table 12 - Percentage Increase in Hardness Relative to Raw Material at 750°C

Cooling Medium	Average Hardness (HRB)	Raw Material (HRB)	Increase (%)
SAE 15W-40 Mineral Oil	42.6	41.5	2.65%
SAE 10W-40 Semi-Synthetic Oil	42.9	41.5	3.37%
SAE 10W-40 Fully Synthetic Oil	43.0	41.5	3.61%

Based on the results obtained from heat treatment at an annealing temperature of 750°C, specimens quenched in SAE 15W-40 mineral oil exhibited an average hardness of 42.6 HRB, corresponding to a 2.65% increase compared to the raw material. Specimens cooled using SAE 10W-40 semi-synthetic oil achieved an average hardness of 42.9 HRB, representing a 3.37% increase relative to the raw material. Meanwhile, the highest improvement was observed in specimens quenched in SAE 10W-40 fully synthetic oil, which attained an average hardness of 43.0 HRB, indicating a 3.61% increase compared to the untreated material.

Table 13 - Percentage Increase in Hardness Relative to Raw Material at 850°C

Cooling Medium	Average Hardness (HRB)	Raw Material (HRB)	Increase (%)
SAE 15W-40 Mineral Oil	42.8	41.5	3.13%
SAE 10W-40 Semi-Synthetic Oil	43.1	41.5	3.86%
SAE 10W-40 Fully Synthetic Oil	43.2	41.5	4.10%

For specimens subjected to annealing at 850°C, those quenched in SAE 15W-40 mineral oil exhibited an average hardness of 42.8 HRB, corresponding to a 3.13% increase compared to the raw material. Specimens cooled using SAE 10W-40 semi-synthetic oil achieved an average hardness of 43.1 HRB, representing a 3.86% improvement relative to the untreated material. The highest increase was obtained using SAE 10W-40 fully synthetic oil, which produced an average hardness of 43.2 HRB, indicating a 4.10% enhancement compared to the raw material.

Table 14 - Percentage Increase in Hardness Relative to Raw Material at 950°C

Cooling Medium	Average Hardness (HRB)	Raw Material (HRB)	Increase (%)
SAE 15W-40 Mineral Oil	43.1	41.5	3.86%
SAE 10W-40 Semi-Synthetic Oil	43.2	41.5	4.10%
SAE 10W-40 Fully Synthetic Oil	43.4	41.5	4.58%

Based on the results obtained at an annealing temperature of 950°C, specimens quenched in SAE 15W-40 mineral oil exhibited an average hardness of 43.1 HRB, corresponding to a 3.86% increase compared to the raw material. Specimens cooled using SAE 10W-40 semi-synthetic oil achieved an average hardness of 43.2 HRB, representing a 4.10% improvement relative to the untreated material. The highest enhancement was observed in specimens quenched in SAE 10W-40 fully synthetic oil, which attained an average hardness of 43.4 HRB, indicating a 4.58% increase compared to the raw material.

5. Conclusion

This study investigated the effect of annealing temperature and cooling medium on the hardness characteristics of the tested specimens. Based on the experimental results, it can be concluded that both annealing temperature and oil type significantly influence the resulting hardness values. At an annealing temperature of 750°C, the average hardness values were 42.6 HRB for SAE 15W-40 mineral oil, 42.9 HRB for SAE 10W-40 semi-synthetic oil, and 43.0 HRB for SAE 10W-40 fully synthetic oil. At 850°C, the hardness values increased to 42.8 HRB, 43.1 HRB, and 43.2 HRB, respectively. At 950°C, further increases were observed, with average

hardness values of 43.1 HRB (mineral oil), 43.2 HRB (semi-synthetic oil), and 43.4 HRB (fully synthetic oil).

Across all temperature variations, SAE 10W-40 fully synthetic oil consistently produced the highest average hardness values, whereas SAE 15W-40 mineral oil resulted in the lowest hardness. Furthermore, increasing the annealing temperature from 750°C to 950°C led to a progressive increase in hardness for all cooling media. The highest hardness values for each oil type were obtained at 950°C. Specifically, SAE 10W-40 fully synthetic oil achieved hardness values of 43.0 HRB at 750°C (3.61% increase relative to the raw material), 43.2 HRB at 850°C (4.10% increase), and 43.4 HRB at 950°C (4.58% increase). Overall, the cooling media can be ranked in terms of hardness performance as follows: SAE 10W-40 fully synthetic oil, SAE 10W-40 semi-synthetic oil, and SAE 15W-40 mineral oil.

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