

Effect Of TiO₂ Nanofluid Quenching On Mild Steel Mechanical Properties

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Abstract

Nanofluids are an innovative type of quenching medium that involves colloidal suspensions of nanoparticles in a base fluid, leading to enhanced heat transfer properties. The present study aims to examine the effectiveness of quenching mild steel using a quenching medium with dispersed nanoparticles. Various concentrations of nanofluids were prepared by adding 21 nm Titanium Dioxide (TiO₂) nanoparticles to Ethylene Glycol (EG). Five different volume concentrations (0.1%, 0.3%, 0.5%, 0.7% and 1.0%) of nanofluids were experimented with. Mild steel rods were heated to 900°C and rapidly quenched using the nanofluid. The extent of hardness is examined at multiple intervals to evaluate the variation in hardness of quenched specimens. In terms of stability, the 1.0% test solution demonstrates sustained superior dispersion with minimal sedimentation. Higher concentrations consistently demonstrated greater absorbance values, with the 1.0% solution displaying the highest absorption at all wavelengths. Furthermore, there is 1.0% stability at -42.33 mV, indicating exceptional stability and effective particle repulsion. Microscopic analysis reveals that mild steel quenched in 21nm nanofluids contains martensite and pearlite phases, indicating how the accelerated cooling process modified the material's crystal structure. In the hardness test, a 1.0% treatment resulted in favourable outcomes of 210 Hv to 217 Hv, whereas the untreated samples exhibited hardness levels of 180 Hv to 204 Hv. The findings indicate that a volume concentration of 1.0% was found to be the most effective, showcasing superior performance in facilitating efficient quenching processes and achieving maximum hardness in mild steel samples.

Key Words: *Titanium Dioxide, Nanofluids, Stability, Mild Steel, Quenching.*

1.0 Introduction

Nanofluids are a novel substance comprised of nanoparticles mixed with a base fluid like water, Ethylene Glycol, or oil and occasionally with a surfactant. Nanoparticles maintain their stability within the base fluid, providing improved heat transfer capabilities and overall thermal and conductivity properties efficiency, making them ideal for various applications across industries (Wang et al., 2023). Different materials serve as quench medium, each offering distinct cooling properties. This diversity in cooling characteristics highlights the importance of selecting the appropriate quench medium to achieve desired outcomes in industrial processes.

Selecting an appropriate quench medium is crucial to achieve components with minimal distortion, no cracks, and optimal mechanical properties. Low cooling rates are preferred for critical components with varying section thickness to mitigate residual stresses. High-rapid cooling should be avoided, as it increases the risk of cracking, particularly in critical sections (Baskaran et al., 2023). Properly matching the quench medium to the component is essential for successful heat treatment outcomes.

2.0 Materials and Methods

2.1 Preparation of TiO₂ Nanofluids

In this study, EG and 21 nm TiO₂ were utilized to enhance the stability of nanofluids. TiO₂ nanoparticles were selected for their excellent ability to reduce nanofluid agglomeration. The preparation process involved ultrasonication to disperse the structured nanoparticles in the base fluids effectively. Nanofluid production necessitates the suspension and dispersion of nanoparticles within the base fluid. The TiO₂ samples were prepared at volume fractions of 0.1%, 0.3%, 0.5%, 0.7% and 1.0%. Subsequently, the base fluid of EG and TiO₂ nanoparticles was mixed using a magnetic stirrer for 3 hours, followed by a 1-hour sonication bath. The samples were then monitored for 9 days.

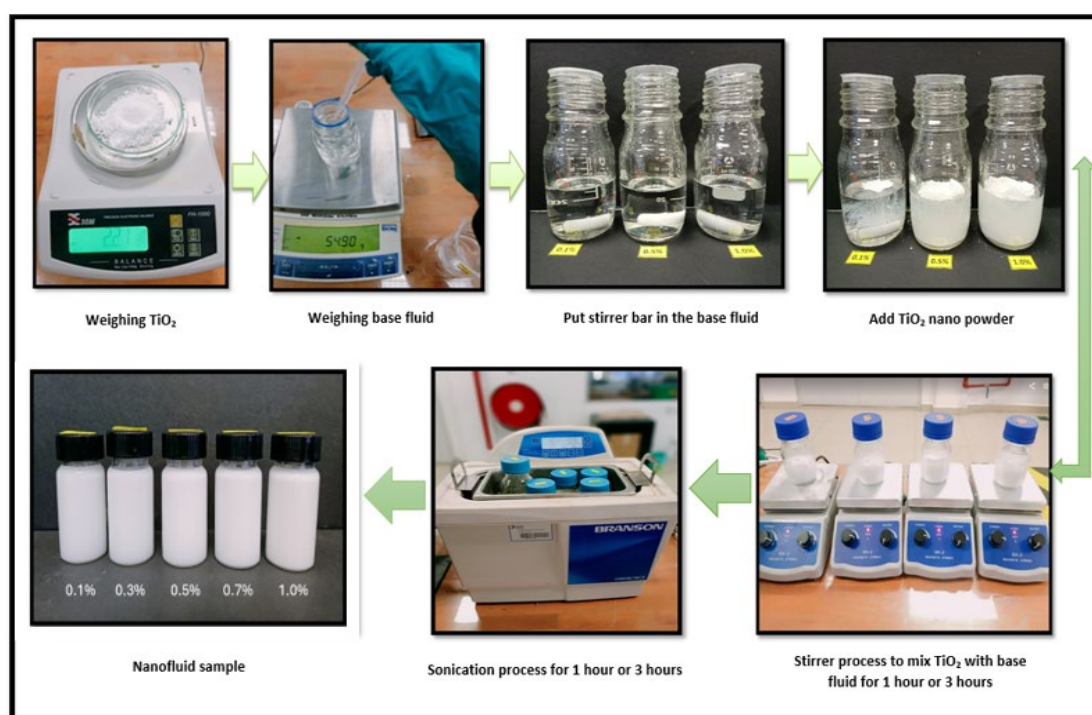


Figure 1: Preparation of TiO₂ nanofluids

Table 1: Thermophysical properties of TiO₂ were used in the study

Name	Abbreviation	Molecular Weight	Form	Purity	Manufacture Factory
Titanium Dioxide	TiO ₂	79.87 g/mol	White nanopowder	99.5%	Germany
Ethylene Glycol	EG	62.07 g/mol	Fluid	99%	Malaysia

2.2 Stability Test

Ultraviolet-Visible (UV-Vis) spectroscopy is used to analyze the absorbance or transmittance of discrete wavelengths, aiding in the detection of compounds in small amounts. This method involves creating coloured solutions through reactions and requires meticulous sonication. Results are typically achieved after 9 days, crucial in characterizing nanofluids accurately.

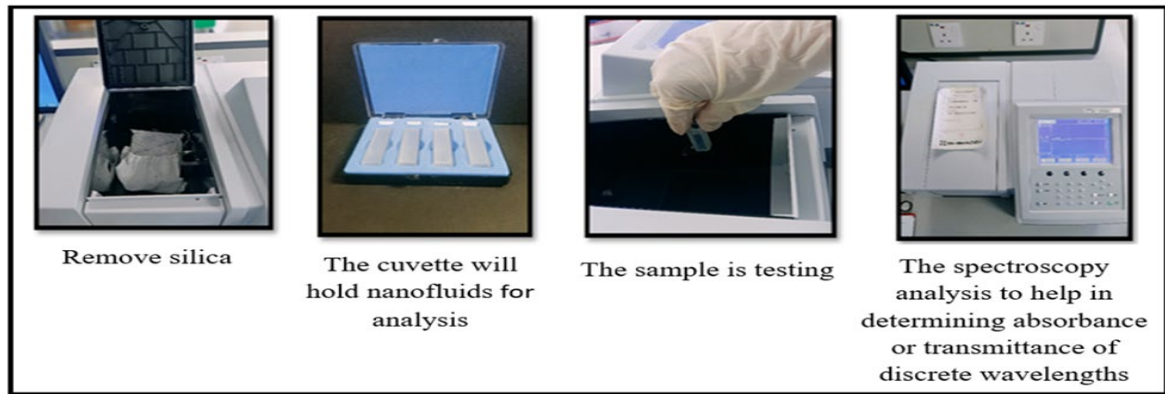


Figure 2: UV-Vis spectroscopy-based sedimentation test

2.3 Research Method of Quenching

In the quenching process of mild steel using nanofluid, the steel specimen is immersed in the nanofluid bath for rapid cooling. The nanofluid's enhanced thermal properties facilitate efficient heat transfer, resulting in improved hardness and dimensional stability of the steel component post-quenching. Quenching with TiO_2 nanofluid involves the rapid cooling of hot metal in a liquid infused with TiO_2 nanoparticles.

This method facilitates enhanced hardness and strength of the metal through swift cooling. Leveraging the superior heat transfer properties of TiO_2 nanofluid over conventional cooling fluids results in more effective quenching processes. By utilizing TiO_2 nanofluid, the likelihood of cracks and deformations in the metal is mitigated, while upholding the mechanical characteristics attained from prior heat treatments. This technology proves invaluable in industries requiring precise management of metal strength and hardness.

2.4 Grinding and Polishing

The experiments conclusively demonstrate the efficacy of both grinding and polishing tools in attaining impeccably smooth and polished surfaces. By integrating both tools in a single process, the surface can be expertly prepared, guaranteeing a streamlined and potent surface treatment method. Grinding reduces surface roughness, whereas polishing contributes smoothness and gloss, culminating in a top-tier finish that is ideal for various industrial applications due to its exceptional quality.

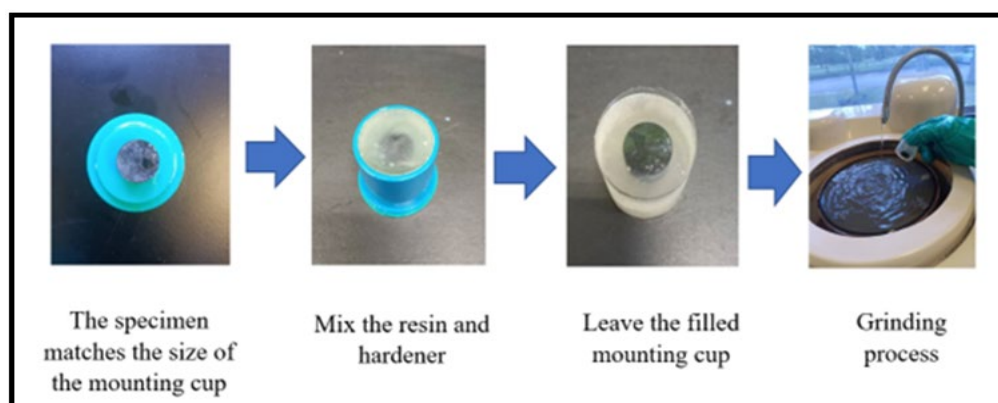


Figure 3: The efficiency and effectiveness of surface preparation

2.5 Microstructural Observation

Microstructural analyses were conducted using advanced 3D laser technology. Specimens underwent meticulous preparation, including grinding with silicon carbide (SiC) papers and polishing with diamond suspension to ensure surface uniformity. Subsequent etching in Nital solutions revealed material microstructures, aiding in precise observations and Vickers hardness testing. This systematic approach guaranteed accurate analysis of microstructural features and hardness characteristics.

2.6 Vickers Hardness Test

The Vickers Hardness Test is a pivotal method for evaluating the hardness of mild steel following quenching in TiO₂ nanofluids. It plays a crucial role in gauging the extent of material hardening post-quenching. This test involves applying a diamond-shaped indenter with precise force onto the quenched mild steel surface, followed by meticulous indentation measurement using a microscope. A smaller indentation signifies higher material hardness, with the Vickers Hardness Number (VHN) calculated by dividing the applied force by the indentation's surface area. This precise measurement technique enables the assessment of the enhanced hardness of mild steel after quenching in TiO₂ nanofluids.

3.0 Results and Discussion

3.1 Sedimentation Test

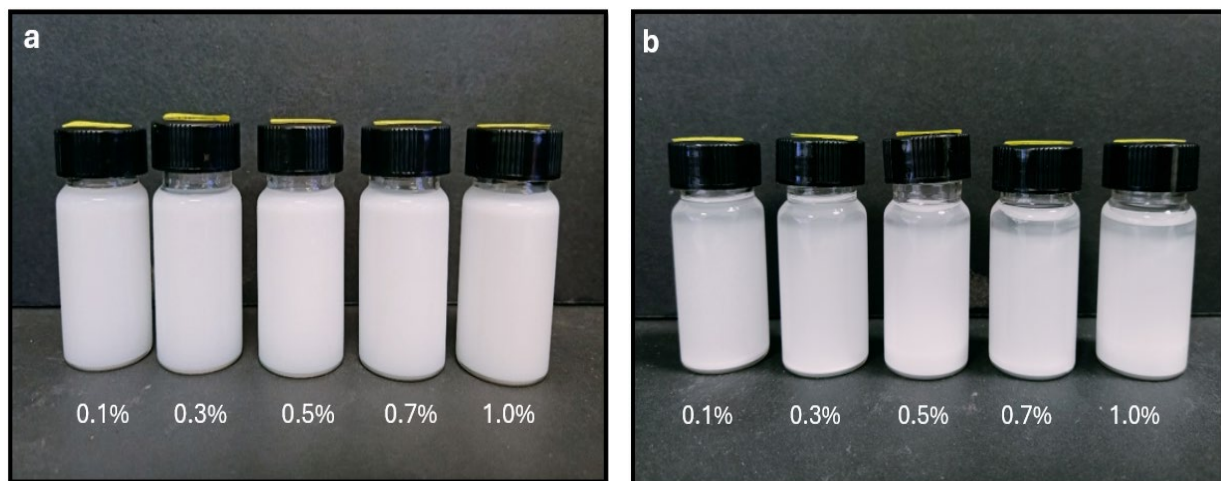


Figure 4: Sedimentation observation of TiO₂ nanofluids (a) day 1 (b) day 9

The research conducted to assess the stability of TiO₂ nanofluids unveiled important findings through images captured at different time points, as illustrated in Figure 5. The sedimentation test visually demonstrates that TiO₂ nanofluid stability is strongly concentration-dependent over time. While all samples (0.1% to 1.0%) showed good initial dispersion on day 1, significant differences emerged by day 9. Lower concentrations (0.1% and 0.3%) exhibited poor stability with clear particle settling and phase separation, while higher concentrations (0.5%, 0.7%, and 1.0%) maintained superior dispersion with minimal sedimentation. The 1.0% concentration showed optimal long-term stability, confirming its suitability for industrial applications. These visual results support the zeta potential findings, establishing that higher concentrations provide better electrostatic stabilization and long-term performance for nanofluid quenching systems (Chen et al., 2020; Shah & Rather, 2020).

3.2 Effect of Different Volume Concentrations on Stability

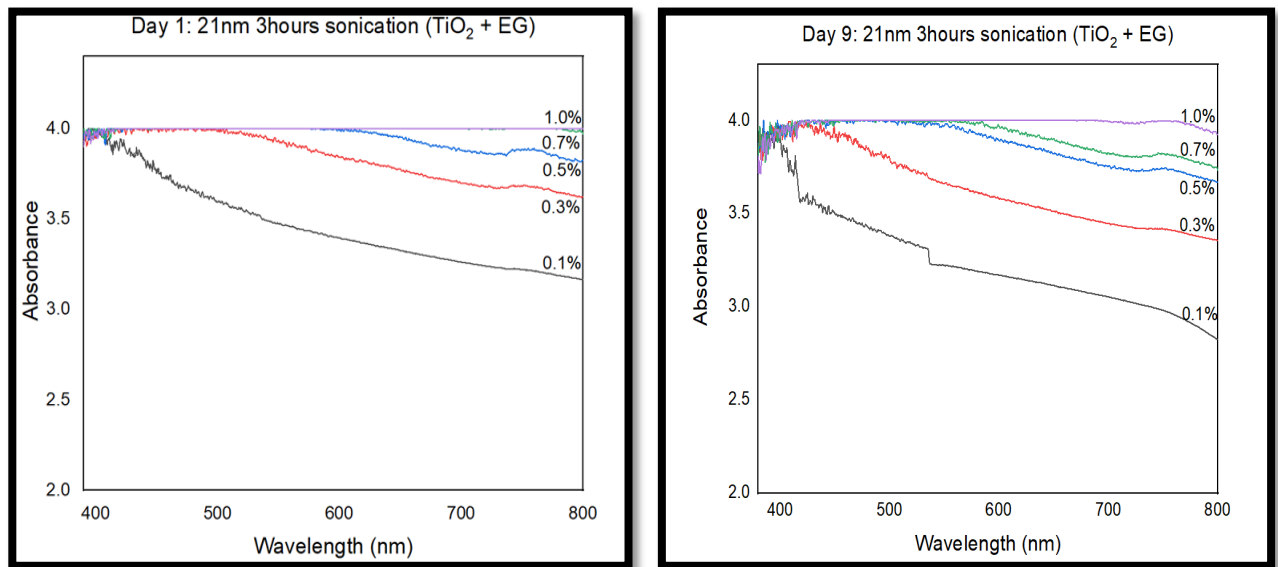


Figure 5: UV-Visible absorption spectra comparing the degradation of TiO₂ nanofluids

Graph 6 shows the degradation of TiO₂ nanofluid solutions over time under sonication treatment. The experiments tested various concentrations (0.1%, 0.3%, 0.5%, 0.7%, and 1.0%) across wavelengths from 400-800 nm. The spectra reveal that higher concentrations consistently show greater absorbance values, with the 1.0% solution displaying the highest absorption across all wavelengths. Over time, there appears to be a general decrease in absorbance for most concentrations when comparing day 1 to day 9 results, suggesting potential degradation or settling of the TiO₂ particles. The absorption patterns show a characteristic decline from shorter to longer wavelengths, which is typical for TiO₂ suspensions. The sonication treatment appears to maintain relatively stable dispersion characteristics, although some concentration-dependent changes are evident between the two time points, indicating the system's evolution over the 9 days (Asadi et al., 2019; Chakraborty, 2019; Zhang et al., 2022).

3.3 Zeta Potential Test of EG

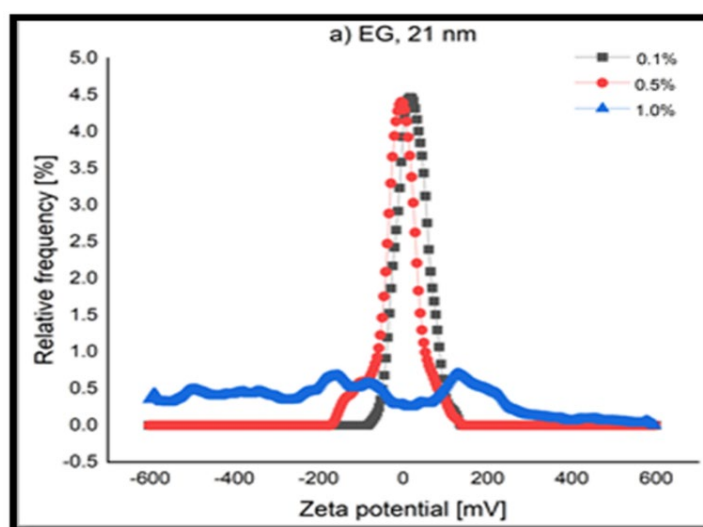


Figure 6: Graph of colloidal stability across different volume concentrations

Table 2: Zeta potential result measurement of different volume concentrations

Percentage	Mean zeta potential (mV)	Standard deviation (mV)
0.1%	-5.794416678	5.399452445
0.5%	-38.16773403	3.041559519
1.0%	-42.32621407	3.055454873

Figure 7 shows, 0.1% produces the weakest performance with a sharp peak at -40 mV but lower intensity around 4.3%, indicating only moderate particle stability. Both higher concentrations perform much better, with 0.5% showing a well-defined peak at -40 mV with 4.4% intensity, demonstrating good particle dispersion. The 1.0% achieves the highest peak intensity at 4.5% and maintains the same -40 mV centre but also shows some additional activity in the positive zeta potential range around +100 to +200 mV. This secondary distribution at 1.0% suggests some particle interactions or population variations that don't occur at lower concentrations. Overall, both 0.5% and 1.0% offer good stability, highlighting the impact of TiO₂ concentrations on zeta potential distribution and stability in EG base fluids (Chen et al., 2020; Shah & Rather, 2020; Shaikh et al., 2016).

Table 1 shows a clear concentration-dependent behaviour that's quite informative for colloidal stability assessment. The system shows a dramatic transition from near neutral to highly negative zeta potential as concentration increases. Stability Assessment by Concentration indicates 0.1% at -5.79 mV, which is in the unstable region (typically ± 0 to ± 30 mV indicates rapid coagulation). Meanwhile, 0.5% at -38.17 mV, this enters the stable region with good electrostatic stabilization. In addition, 1.0% at -42.33 mV, which shows excellent stability with strong particle repulsion. The standard deviations (3-5 mV) indicate good measurement reproducibility across all concentrations, with the 0.1% sample showing slightly higher variability, which is typical for low-concentration measurements.

3.4 Microstructure of Quenching Medium

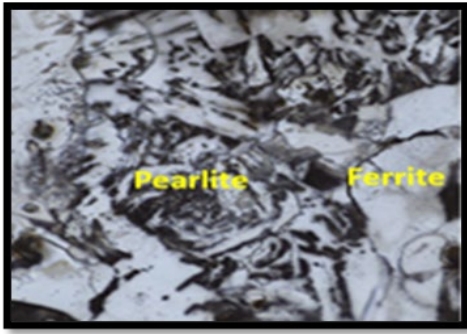
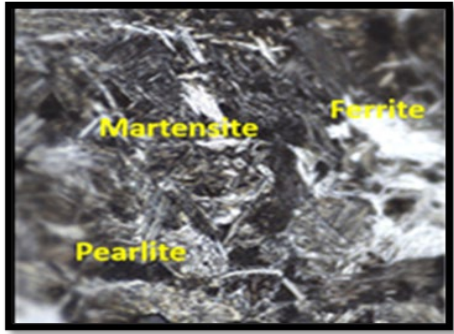
Specimen	Untreated quenched	1.0% quenched
100x magnificent		

Figure 7: Microstructure image of untreated and 1.0% quenched

This microstructural analysis in Figure 8 demonstrates that 1.0% nanofluid quenching produces superior results compared to untreated quenching. The key finding is that nanofluid-enhanced quenching creates a more complex microstructure with martensite formation alongside pearlite and ferrite phases, while untreated specimens show only uniform pearlite-ferrite distribution (Maleki et al., 2021). The 21nm nanofluids improve heat transfer efficiency during quenching, enabling faster cooling rates that promote beneficial phase transformations and result in harder, stronger material properties. This microstructural evidence directly supports the observed hardness improvements, confirming that nanofluid quenching technology offers significant advantages over conventional quenching methods (Chinchole et al., 2016).

3.5 Vickers Hardness Test

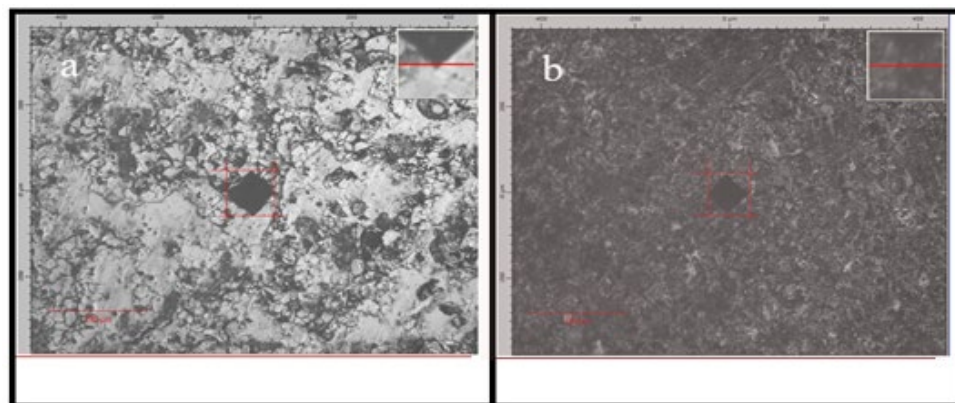


Figure 8: Indent specimens in (a) untreated (b) 1.0% quenched

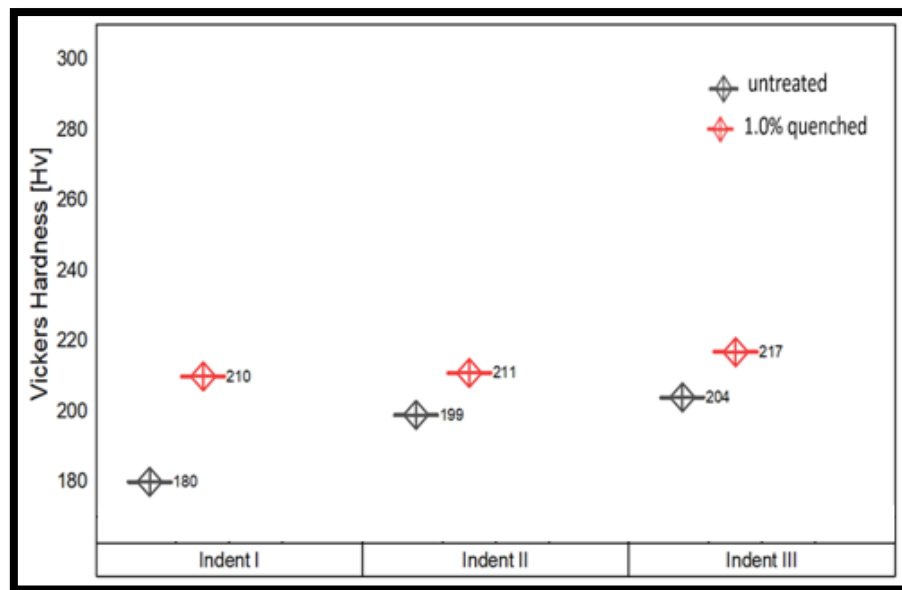


Figure 9: Evaluate the hardness of mild steel

According to Figure 10, quenching mild steel specimens in nanofluids generally results in greater hardness compared to untreated specimens not quenched in nanofluids. This is because nanofluids offer a more effective and efficient way to achieve greater hardness by facilitating faster heat dissipation during the quenching process (Shaikh et al., 2016). The presence of nanoparticles in the quenching medium enhances the cooling rate, resulting in a harder microstructure in the mild steel.

Furthermore, the microstructures of mild steel quenched in nanofluids typically exhibit finer grain sizes and more uniform distribution of phases compared to untreated specimens. These refined microstructures contribute to the increased hardness of the specimen. Overall, quenching mild steel in nanofluids is a promising technique for enhancing hardness and improving the mechanical properties of the material (Chinchole et al., 2016).

4.0 Conclusion

This study demonstrates that nanofluid-enhanced quenching significantly improves mild steel properties through optimized stability and thermal performance. Key findings include that nanofluid stability depends critically on sonication duration, volume fractions, and proper preparation techniques. Meanwhile, quenching with nanofluids increased hardness from 210 HV to 217 HV due to enhanced heat transfer and refined martensitic structure formation. Notably, 1.0% volume concentration proved optimal for achieving maximum hardness and quenching efficiency. The research establishes that base fluid selection, nanoparticle size, and concentration are crucial parameters for developing effective nanofluid quenching systems with superior cooling performance compared to conventional methods.

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