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Effect of Heat Treatment on Hardness and Abrasive Wear Resistance of Galvanized Steel and Medium Carbon Steel

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Abstract

This study examines the effects of four heat treatment regimens: quenching, tempering at 250 °C and 450 °C, and full annealing on the hardness and abrasion resistance of Galvanized steel and medium carbon steel. Identically prepared samples were evaluated by Vickers microhardness testing and ASTM G65 sand-spray abrasion trials. In Galvanized steel, quenching increased hardness by 36.6 %, while tempering at 250 °C and 450 °C reduced it by 20.5 % and 24.0 % relative to the quenched state; full annealing produced a further 40.6 % softening. Corresponding mass-loss values rose modestly (up to +14.4 %) after softer treatments, revealing the zinc coating's moderating effect. Medium carbon steel showed a greater hardness rise (+63.6 %) on quenching, followed by reductions of 15.8 %, 42.5 %, and 60.3 % after tempering and annealing; wear losses, however, escalated dramatically (up to +7,600 %), indicating embrittlement and microcracking. These results highlight the need to balance hardness, toughness, and surface protection. The findings provide a basis for optimising heat-treatment and coating strategies in industrial steel components.

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Keywords: heat treatment, hardness, abrasion resistance, Galvanized steel, Medium Carbon Steel, ASTM G65.

تأثير المعالجة الحرارية على الصلادة ومقاومة التآكل بالاحتكاك للفولاذ المجلفن والفولاذ متوسط الكربون

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الملخص

تستعرض هذه الدراسة تأثير أربعة أنظمة من المعالجات الحرارية ــ التبريد السريع، والتخمير عند درجتي حرارة 250 °C و450°C ، والتخمير الكامل ـــ على الصلادة ومقاومة التآكل بالاحتكاك لكل من الفولاذ المجلفن والفولاذ متوسط الكربون. جرى تقييم العينات المحضَّرة بنفس الطريقة باستخدام اختبار الصلادة الدقيقة (فيكرز) وتجارب التآكل الرملي وفق معيار ASTM G65. أظهر الفولاذ المجلفن زيادة في الصلادة بنسبة 36.6% بعد التبريد السريع، بينما أدى التخمير عند 250 °C و450 °C إلى انخفاض الصلادة بنسبة 20.5% و24.0% مقارنة بحالة التبريد، في حين سبّب التخمير الكامل انخفاضاً إضافياً بنسبة 40.6%. أما قيم الفقد في الكتلة فقد ارتفعت بشكل طفيف (حتى +14.4%) بعد المعالجات التي تقلل الصلادة، مما يكشف عن الدور المعتدل لطبقة الزنك الواقية. في المقابل، سجّل الفولاذ متوسط الكربون زيادة أكبر في الصلادة بلغت +63.6% بعد التبريد السريع، تلتها انخفاضات متتالية بنسبة 15.8% و42.5% و60.3% بعد التخمير عند 250 °C و450 °C والتخمير الكامل، على التوالي. ومع ذلك، ارتفعت خسائر التآكل بشكل كبير (حتى +7,600%)، مما يشير إلى حدوث هشاشة وتشققات مجهرية. تبرز هذه النتائج الحاجة إلى موازنة

الصلادة والمتانة والحماية السطحية، كما توفر أساساً لتحسين استراتيجيات المعالجة الحرارية وطلاء المكوّنات الفولاذية في التطبيقات الصناعية.

الكلمات المفتاحية: المعالجة الحرارية، الصلادة، مقاومة التآكل بالاحتكاك، الفولاذ المجلفن، الفولاذ متوسط الكربون، ASTM G65.

I. INTRODUCTION

Heat treatment processes play a pivotal role in enhancing the mechanical properties and corrosion resistance of metallic materials, particularly steel alloys, through precise control of thermal cycles. Medium-carbon steel, containing between 0.3 % and 0.6 % carbon, is widely employed in engineering applications due to its optimal balance of strength, ductility, and toughness. These characteristics are especially suitable for automotive components, structural members, and mechanical equipment [1].

Previous investigations have consistently demonstrated that different heat treatment techniques significantly influence the evolution of steel's microstructure and its resultant mechanical Behavior. Processes such as annealing, quenching, tempering, and normalising allow for control over phase transformations, microstructural morphology, grain size, and residual stresses, directly affecting hardness, ductility, wear resistance, and corrosion resistance [1.2].

For instance, quenching, which is rapid cooling from elevated temperatures, produces a martensitic microstructure characterised by high hardness but reduces ductility and increases brittleness. Subsequent tempering mitigates brittleness while retaining adequate hardness, thereby improving mechanical performance and extending service life [1]. Furthermore, Jędrzejczyk and Szatkowska [3] have shown that precise heat treatment protocols can effectively increase microhardness and fine-tune corrosion resistance in zinc-coated steel substrates, underscoring the importance of thermal control in protective coatings.

Moreover, corrosion resistance is a critical attribute affecting the reliability of steel in severe industrial environments and is intrinsically linked to the microstructure shaped by heat treatment.

Katiyar et al. [4] reported pronounced differences in corrosion Behavior among pearlitic, bainitic, and martensitic structures, with pearlite and bainite exhibiting superior resistance compared to martensite and tempered martensite. Similarly, Nwigwe et al. [2] observed significant variations in the hardness and corrosion resistance of medium carbon steel depending on the quenching medium and immersion duration, highlighting the necessity of optimising processing parameters.

In this context, the materials selected for this study, Galvanized steel and medium carbon steel, are among the most commonly used steel types in the local market, particularly in structural and utility applications. Their widespread availability, cost-effectiveness, and versatility make them preferred choices for civil infrastructure and mechanical components. However, their frequent exposure to outdoor environments, including moisture, atmospheric pollutants, and temperature fluctuations, subjects them to combined degradation modes such as wear, oxidation, and corrosion. In addition, wind-driven sand impingement can accelerate surface abrasion and erode protective layers, further compounding material loss. This necessitates a better understanding of how heat treatment protocols can enhance their resistance to such environmental stresses.

On this basis, the present study aims to evaluate the effects of three common heat treatment processes, including quenching, annealing, and tempering, applied at two distinct temperature levels on the hardness and corrosion resistance of Galvanized steel and medium carbon steel specimens. Laboratory tests include Vickers microhardness measurements and sand-spray corrosion assessments, following a methodology comprised of sample sectioning, controlled thermal cycling, and surface finishing. This work seeks to provide quantitative and practical insights into the interplay between treatment type and substrate material, thereby supporting the deployment of these materials in demanding service conditions that require elevated hardness and corrosion resistance.

II. EXPERIMENTAL PROGRAM

The experimental procedure of the present study comprised laboratory tests designed to prepare and condition metallic samples following the application of various heat treatment regimes, and the subsequent evaluation of their effects on hardness and Sand-spray corrosion resistance. All sample preparation, heat treatments, and testing were carried out at the Materials Testing Laboratory, College of Engineering Technology Houn (Libya). The methodology unfolded as follows:

A. Materials

Two metallic materials (Fig. 1) were selected based on their industrial availability and relevance: (1) Galvanized steel, commonly employed in the fabrication of high voltage transmission tower structures for its combination of mechanical strength and zinc-coated corrosion protection. (2) Medium carbon steel (commercial steel) is used extensively in structural applications owing to its optimal trade-off between ductility and hardness. Both materials were classified according to standard industrial designations and subjected to the appropriate heat treatment protocols.

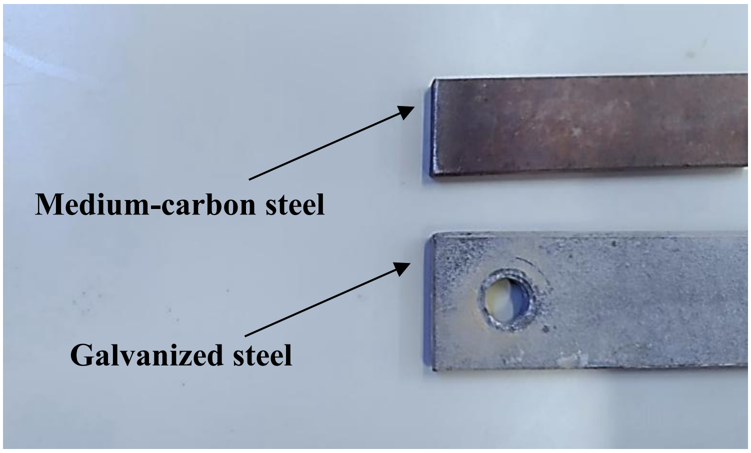

Fig. 1: Metal material tested in the study

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A. Sample Preparation

Rectangular specimens (15 mm × 15 mm) illustrated in Figure 2 were obtained from bulk plates using an electric-powered cutting saw. During cutting, water cooling was applied continuously to prevent thermal damage, microstructural alteration, or the introduction of residual stresses. Four replicates of each material type were prepared. The cut edges of all specimens were then filed to remove burrs and ensure uniform surface conditions before subsequent polishing and testing.

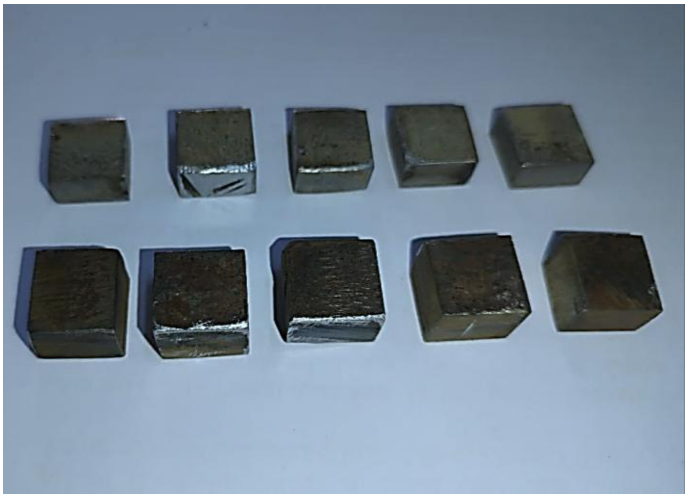

Fig. 2: Sectioned specimens before polishing

1) Heat Treatment of the Specimens

Several distinct heat treatment regimens were applied to the prepared samples as follows:

Quenching:

Quenching is a critical process aimed at increasing the steel's hardness by promoting the formation of martensite. In this study, the austenitizing temperature was chosen to ensure complete dissolution of carbon into the γ-iron matrix. The furnace was preheated and stabilised at 900 °C, as confirmed by a calibrated thermocouple. Once thermal equilibrium was reached, specimens

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were loaded into the furnace using high-temperature tongs, and the door was closed immediately to minimise heat loss.

The soaking time was calculated at 20 min per 25 mm of specimen thickness, in accordance with industry practice. Upon completion of the soak period, samples were rapidly extracted and quenched in water. To reduce the delay between furnace removal and immersion, quench tanks were positioned adjacent to the furnace. During quenching, specimens were agitated with gentle rotational motions to promote uniform martensitic transformation. After quenching, light surface grinding was performed with an abrasive wheel to remove the oxide scale formed during heating.

Annealing:

Annealing serves to soften the metal, increase ductility, and relieve internal stresses via slow heating and controlled cooling. For full austenitization, the furnace was ramped to 900 °C and held until temperature stability was verified. Specimens were then placed inside the furnace, and the furnace door was sealed to prevent heat loss. A dwell time of 30 minutes was maintained to ensure uniform microstructural transformation. Following the soak period, the furnace was turned off, and samples were allowed to cool gradually to ambient temperature inside the closed furnace chamber.

Tempering:

Tempering was conducted after quenching to improve toughness and reduce the brittleness induced by rapid quenching. Two tempering regimes were employed, at 250 °C and 450 °C, for both Galvanized steel and medium carbon steel specimens. In each case, the furnace was set to the target temperature and monitored until thermal equilibrium was achieved. Specimens were then introduced using tongs, and the door was promptly closed. After the prescribed hold time, samples were removed and quenched in water to complete the tempering cycle.

2) Sample Surface Preparation

Grinding:

Grinding was performed to remove the coarse scratches introduced during the initial cutting stage, using silicon carbide abrasive papers of progressively finer grit size. The sequence began with P120 grit,

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denoting approximately 120 abrasive particles per cm², and advanced stepwise through increasingly finer papers up to P1200. Abrasive papers were mounted on the grinding platen of the machine illustrated in Figure 3. Each specimen's surface was traversed over the platen under uniform manual pressure until the original deep scratches were eliminated and replaced by a finer scratch pattern aligned with the direction of grinding. Upon completion of each grit stage, the specimen was rotated 90° and the grinding process was repeated with the next finer paper, thereby ensuring the removal of any residual scratches from the preceding step. As the grit size increased, manual pressure was progressively reduced to prevent sample overheating or deformation. Throughout all grinding stages, a continuous water flow was maintained over the specimen surface to both cool the metal and wash away debris.

Fig 3: Grinding apparatus used for surface preparation.

B. Mechanical Evaluation Tests

1) Vickers Hardness Test

The Vickers method was used to measure the hardness of the base and heat-treated specimens. The test was performed by sectioning a small piece from each of the eight heat-treated samples (four

specimens per metal type) using a manual saw to avoid undesirable thermal effects. Before measurement, specimens underwent fine surface preparation to ensure reliable hardness results.
Once mounted on the tester's base (Fig. 4), the test was initiated via the integrated electronic system, which automatically measures the indentation and calculates the hardness number.

Fig. 4: Metallographic surface preparation (grinding) of the steel specimens.

2) Abrasion Resistance Test – ASTM G65

The abrasion resistance test was conducted to evaluate the resistance of the metal surface to wear induced by friction, using the ASTM G65 apparatus [5], which is designed to simulate the severe abrasion conditions experienced by mechanical components such as drilling and scraping tools. Figure 5 shows the general configuration of the apparatus and its components.

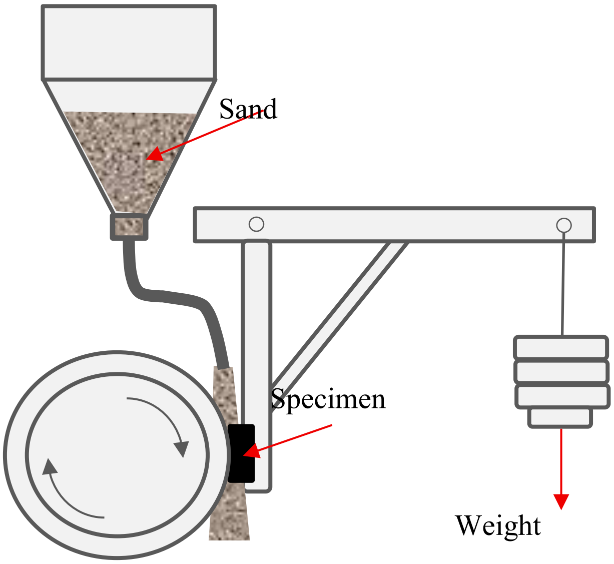

Fig. 5: ASTM G65 abrasion tester

The apparatus comprises a main metal frame on which the motor, speed control panel, specimen holding arm, and sand feeder hopper are mounted. The hopper connects to a conical cylinder ending in a lower tube that deposits purified sand directly onto the contact area between the specimen and the rotating platen. A hook and support bracket on either side of the specimen arm applies the vertical load and positions the specimen so that it contacts the rubber wheel mounted on the motor shaft. This wheel is driven at various speeds and is controlled by an electronic panel.

The test procedure was as follows: after powering the machine, the sand feed valve was confirmed closed, and then sand was added to the hopper. Each specimen was placed and secured in its holder, the motor was run at maximum speed, and the valve was opened to begin sand flow. After positioning the weight and adjusting the support bracket to contact the rubber wheel, three body abrasions commenced and continued for 30 minutes. Figure 6 shows the wear observed on the specimen surface after the test.

Fig. 6: Wear pattern on specimen surface after abrasion test.

These procedures were repeated for all heat-treated specimens, and the weight loss for each was calculated by weighing before and after testing. The mass loss was recorded as an indicator of surface wear resistance. Results are presented in detail in the Results and Data Analysis section.

I. RESULTS AND DISCUSSION

A. Vickers Hardness Test

The results of the Vickers hardness test showed clear variations in the mechanical response of both Galvanized steel and medium carbon steel under different heat treatment processes. As presented in Table 1 and Figure 7, the average hardness of Galvanized steel increased from 186 (as received condition) to 254 after quenching. This increase is attributed to the formation of martensitic and fine pearlitic structures resulting from rapid quenching after heating above the critical transformation temperature.

Subsequent tempering at 250 °C resulted in a moderate reduction in hardness to 202, while tempering at 450 °C and annealing yielded further reductions to 193 and 151, respectively. These decreases are consistent with recovery and softening mechanisms, which reduce internal stresses and hardness but improve ductility and toughness as well.

On the other hand, medium carbon steel exhibited significantly higher hardness values, with an increase from 371 in the as-received state to a maximum of 607 after quenching. This represents the highest hardness recorded among all samples. Tempering at 250 °C and 450 °C resulted in hardness values of 511 and 349, respectively, while annealing reduced the hardness to 241. These results confirm the sensitivity of medium carbon steel to thermal treatment and its potential for property Optimization through controlled heat treatment.

Table 1. Average Vickers hardness values for different heat treatment conditions.

Material	Heat Treatment	Avg. Hardness (HV)
Galvanized Steel	As received	186
	Quenching	254
	Tempering at 250 °C	202
	Tempering at 450 °C	193
	Annealing	151
Medium Carbon Steel	As received	371
	Quenching	607
	Tempering at 250 °C	511
	Tempering at 450 °C	349
	Annealing	241

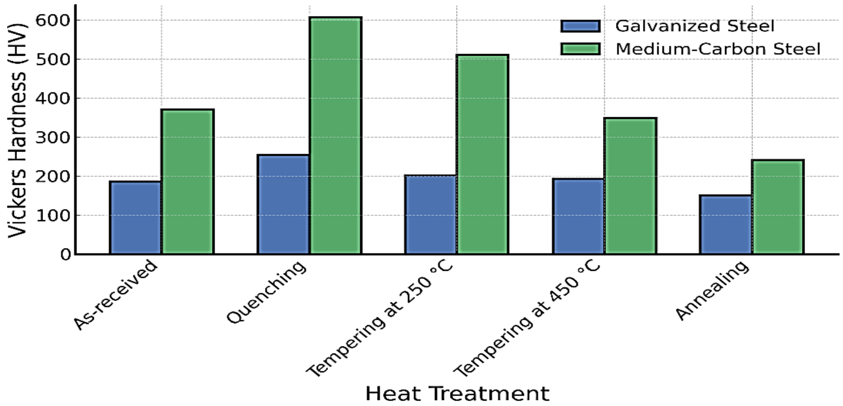

Fig 7: Effect of heat treatment on the average Vickers hardness of Galvanized steel and medium carbon steel.

B. Abrasion Resistance Test (ASTM G65)

The abrasion resistance test results (Table 2 and Fig. 8) corroborate the hardness measurements. Galvanized steel exhibited the lowest

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weight loss in the hardened condition (4.66 g), indicating superior surface wear resistance. After tempering at 250 °C, weight loss rose slightly to 4.88 g and 5.09 g at 450 °C, before peaking at 5.33 g following annealing. This progression reflects the expected gradual reduction in hardness and abrasion resistance due to thermal softening.

By contrast, medium carbon steel showed outstanding abrasion resistance when hardened, with a negligible weight loss of just 0.02 g. Tempering at 250 °C increased the loss to 0.35 g, and to 0.82 g at 450 °C, while annealing produced the greatest loss (1.54 g). These findings suggest that annealing diminishes the material's hardness and wear resistance more than the tempering treatments applied.

Table 2. Weight loss in the abrasion test (ASTM G65) under different heat treatments.

Material	Heat Treatment	Weight Loss Δw (g)
Galvanized Steel	Quenching	4.66
	Tempering at 250 °C	4.88
	Tempering at 450 °C	5.09
	Annealing	5.33
Medium Carbon Steel	Quenching	0.02
	Tempering at 250 °C	0.35
	Tempering at 450 °C	0.82
	Annealing	1.54

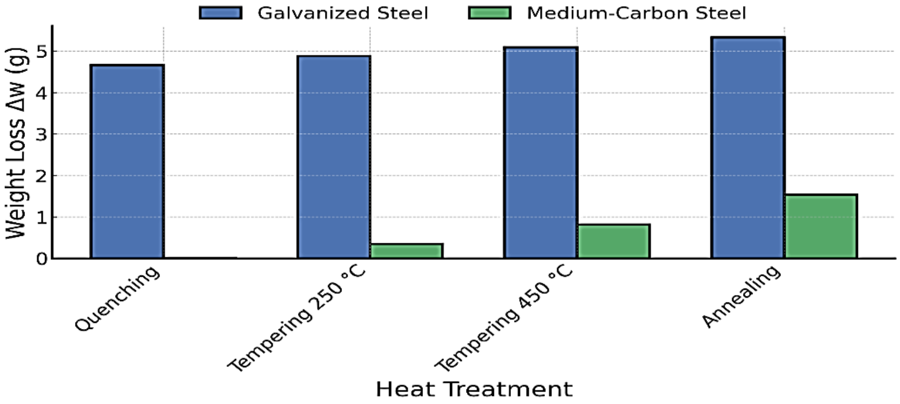

Fig 8: Average Weight Loss for Different Heat Treatments

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II. DISCUSSION

The combined hardness and abrasion data demonstrate that each heat-treatment step produces characteristic properties and changes that dictate wear performance. In Galvanized steel, quenching raises Vickers hardness from 186 HV (as received) to 254 HV, we can refer to this low value of hardness only to the low carbon content, as we know after quenching the martensite structure developed, where the hardness of this structure highly depends on the carbon content, Tempering at 250 °C relieves internal stresses and promotes carbon clustering, reducing hardness to 202 HV, while further tempering at 450 °C encourages carbide coarsening and ferrite recovery, lowering hardness to 193 HV. Full annealing yields the softest ferrite–pearlite structure (151 HV). Medium carbon steel exhibits a more pronounced response: quenching increases hardness from 371 HV to 607 HV, indicative of an almost complete martensitic transformation in its 0.3–0.4 % C matrix, while tempering at 250 °C and 450 °C reduces hardness to 511 HV and 349 HV, respectively, via carbide precipitation and dislocation annihilation. Annealing restores a ferrite–pearlite aggregate at 241 HV, which remains harder than annealed steel owing to a finer, inclusion-free microstructure.

Abrasion losses mirror these hardness trends but with markedly different sensitivities. In Galvanized steel, weight loss increases gradually from 4.66 g in the hardened state to 4.88 g and 5.09 g after tempering at 250 °C and 450 °C, rising to 5.33 g upon annealing. The modest slope of this hardness–wear relationship suggests that the ductile Zn-rich coating has low carbon content. By contrast, hardened medium carbon steel suffers a negligible loss of 0.02 g, yet tempering at 250 °C amplifies wear by over an order of magnitude (0.35 g), and further tempering at 450 °C and annealing produces more weight losses of 0.82 g and 1.54 g, respectively. This sharp escalation at 250 °C indicates that tempered-martensite and carbide-assisted microcracking become operative even though macro-hardness remains high, while higher-temperature tempering partially restores toughness and reduces residual stresses.

Figure 9 complements this analysis by plotting Vickers hardness against weight loss for each treatment, revealing a gentle decline in wear for Galvanized steel, contrasted with a steep inverse relationship in medium carbon steel. The differential slopes of these trend lines visually underscore the role of coating mechanics in decoupling wear from hardness in Galvanized steel and the pronounced embrittlement-driven wear escalation in tempered medium carbon steel.

These contrasting Behaviors have practical consequences. Medium carbon steel tempered at 250 °C combines very high hardness (511 HV) with minimal mass loss (0.35 g), but at the expense of increased brittleness; tempering at 450 °C (349 HV, 0.82 g loss) offers a more balanced compromise of hardness, toughness, and wear resistance suitable for impact abrasion environments such as scraper blades. Galvanized steel, despite its lower absolute hardness, retains adequate wear resistance after tempering at 250 °C (202 HV, 4.88 g loss) while preserving its corrosion-protective zinc layer, making it ideal for fasteners and tower hardware subject to intermittent abrasion and atmospheric attack.

Overall, these findings underscore that maximising hardness alone does not guarantee optimal service performance. In Galvanized steel, surface chemistry and coating mechanics decouple wear from bulk hardness, whereas in medium carbon steel, microstructural embrittlement at moderate tempering temperatures can dramatically increase wear despite high hardness. Effective design, therefore, requires tailoring heat treatments to achieve the right balance of hardness, toughness, and microstructural stability for the intended abrasive and corrosive regime.

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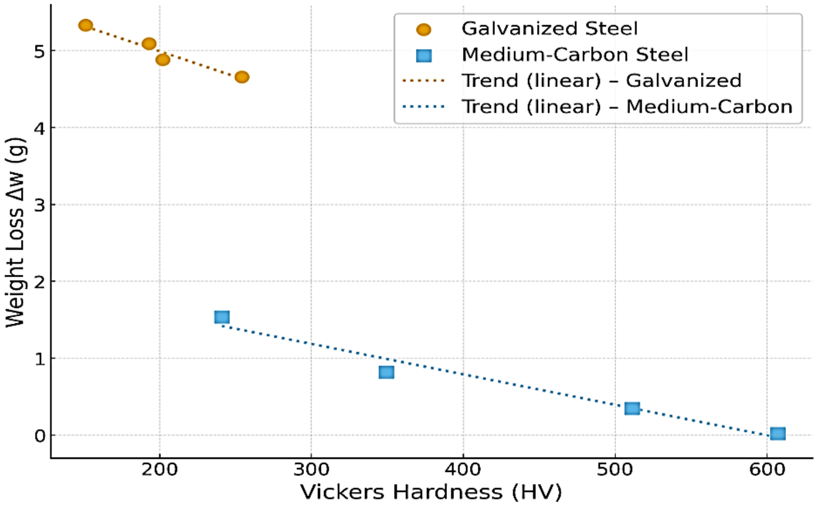

Fig. 9: Correlation between Vickers hardness and weight loss under different heat treatments

III. CONCLUSION

This study evaluates the effect of four heat treatment regimes, including quenching, tempering at 250 °C, tempering at 450 °C, and full annealing, on the hardness and abrasion resistance of Galvanized steel and medium carbon steel, using Vickers microhardness and ASTM G65 Sand-spray tests on identically prepared samples.

For the Galvanized steel, quenching increased the hardness by 36.6 % compared to the as-received condition. Tempering at 250 °C reduced the hardness by 20.5 % relative to the quenched state, and tempering at 450 °C further reduced the hardness by 24.0 % relative to the quenched state. Full annealing produced the greatest softening, with a hardness 40.6 % lower than the quenched condition. Correspondingly, mass loss in the abrasion test rose by 4.7 % after tempering at 250 °C (compared to quenching), by 9.2 % after tempering at 450 °C, and by 14.4 % after annealing, demonstrating the moderating role of the zinc coating in decoupling wear from bulk hardness changes.

In medium carbon steel, quenching elevated the hardness by 63.6 % compared to the as-received material. Tempering at 250 °C lowered hardness by 15.8 % relative to the quenched state, and tempering at 450 °C reduced it by 42.5 % relative to the quenched state; full annealing led to a 60.3 % reduction in the hardness compared to the quenched condition. Wear losses escalated sharply: tempering at 250 °C caused a 1650% increase in mass loss relative to the quenched sample, while tempering at 450 °C and annealing amplified wear by approximately 4,000 % and 7,600 % versus the quenched baseline.

From a practical standpoint, tempering medium carbon steel at 450 °C offers a balanced compromise with hardness reduced by 42.5 % relative to the quenched state, and a tolerable wear increase of 4,000 % making it suitable for components exposed to combined impact and abrasion. Galvanized steel, although inherently softer after tempering (–20.5 % hardness versus quenching), maintains only a modest wear increase (+4.7 %) while preserving its corrosion protective layer, which is ideal for outdoor hardware subject to intermittent abrasion.

Overall, these findings underscore that optimising service performance requires tailoring heat treatments to balance hardness, toughness, and surface chemistry. Maximising hardness alone does not guarantee the best wear or corrosion resistance. Future work could explore zinc coating thickness and alternative surface treatments to see how they affect the hardness-wear relationship. It might also test intermediate tempering temperatures to refine the hardness–abrasion balance. Complementary SEM, EBSD and XRD analyses could then link microstructural features to the observed performance trends.

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