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Flame Straightening of ASTM A36 Steel: A Study on Mechanical and Microstructural Properties Evolution

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ABSTRACT

Flame straightening is widely employed in shipbuilding and metal fabrication to correct structural distortions caused by welding and other thermal processes. However, its effects on commonly used structural carbon steels, such as ASTM A36, may influence material performance. This study examines the impact of controlled flame straightening on the mechanical and microstructural properties of ASTM A36 steel. Experimental heat treatments were conducted using an oxy-acetylene torch, followed by hardness and tensile testing, as well as microstructural characterization through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The results indicate that flame straightening modifies the mechanical behavior of ASTM A36: short-duration heating enhances hardness and yield strength, whereas prolonged exposure causes microstructural softening due to grain coarsening and oxidation, ultimately reducing mechanical strength.

Keywords:
Flame strengthening, Mechanical properties, Microstructural, Low carbon steel, Heat Treatment, Hardness, Scanning Electron Microscopy

1. Introduction

Flame straightening is a widely utilized technique in the metal fabrication and shipbuilding industries to correct distortions in steel structures caused by welding or other thermal processes as indicated by Seong and Na [1]. This method involves the localized application of high-temperature heat to induce controlled plastic deformation, thereby restoring the desired shape of a steel component. While flame straightening is known for its efficiency and cost-effectiveness, its effects on the mechanical properties of carbon steel, particularly in terms of strength, ductility, hardness, and micro-structural integrity, remain a subject of investigation. Given the increasing demand for structurally sound and mechanically reliable steel components in various engineering applications,

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understanding the implications of flame straightening on mechanical properties is crucial for ensuring long-term performance and safety. Therefore, this paper focus on the mechanical properties of heat-treated carbon steel and its correlation to the micro-structural alterations.

Several studies have examined the influence of thermal treatments on steel, particularly in the context of flame straightening. Lacalle *et al.* [2] revealed that flame straightening significantly influences the microstructure, hardness, and fracture properties of structural steels, with the extent of changes strongly dependent on the material type. It was found that, heating beyond critical temperatures can lead to embrittlement and degradation of mechanical strength. Similarly, Gyura *et al.* [3] found that prolonged exposure to elevated temperatures during flame straightening can cause undesirable grain growth and hardness variations, significantly affecting material toughness. Other researchers, such as Kowalski *et al.* [4] reported that variations in heat input parameters influence the material's corrosion resistance and residual stress distribution of flame straightening of ship hull structures. Additionally, Lim and Lee [5] reported that line heating alters the microstructure of marine-grade steel plates by forming refined ferrite–pearlite zones in the heat-affected region and causes variations in yield strength, tensile strength, fracture strain, hardening exponent, and strength coefficient depending on plate thickness and heat input. These findings highlight the necessity of controlled heating parameters to mitigate adverse effects while optimizing mechanical properties.

Recent investigations have provided further insights into the temperature thresholds and duration limits for flame straightening. Hanus and Hubo [6] concluded that tensile and Charpy impact tests showed no significant changes for thermo-mechanically rolled structural steel within the temperature range of 650–950°C. Lange [7] confirmed that post-welding f lame straightening of X2CrNiN22-2-grade duplex steel at 950°C should not exceed one minute to prevent undesirable transformations. Additionally, Kowalski *et al.* [4] noted that micro and macroscopic examinations did not reveal distinct structural changes from heating with a burner. Fadly *et al.* [8] found that the surface hardness of fillet T-joint S355J2+N steel decreased, accompanied by alterations in microstructure. Molnár *et al.* [9] noted that flame straightening of S960 steel affects microstructure and hardness without embrittlement, but excessive heating may trigger carbide precipitation. Cai *et al.* [10] demonstrated that synchronous water-cooling reduces grain growth tendency and precipitation phase size. Gyura *et al.* [3] suggested that overheating in flame straightening can induce carbide and hard phase precipitation in Steel S960QL, while Molnar *et al.* [9] confirmed that welding conditions lead to heat-affected zone (HAZ) softening and grain growth. Moreover, Gyura *et al.* [3] identified high sensitivity to softening in XAR400 steel during straightening, whereas S960QL exhibited hardening at higher peak temperatures under water cooling. Despite these findings, the specific effects of flame straightening on commonly used structural carbon steels, such as ASTM A36, remain inadequately studied. Furthermore, existing research has yet to establish a systematic correlation between process parameters, mechanical property changes, and microstructural transformations.

Therefore, this study aims to comprehensively analyse the effects of flame straightening on ASTM A36 steel by performing controlled heat treatments followed by mechanical and micro-structural evaluations. The methodology involves subjecting steel specimens to different heating conditions using an oxy-acetylene torch, followed by hardness testing, ten sile testing, and microstructural analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The correlation between process parameters, mechanical responses, and micro-structural alterations is systematically assessed to establish optimal heating conditions that minimize adverse effects.

2. Methodology
2.1 Materials

The steel plate utilized in this study conforms to the ASTM A36 standard, a specification that dictates the composition and mechanical properties of steel plates employed in shipyards for actual shipbuilding, as shown in Table 1 and Table 2. These plates exhibit a carbon content ranging from 0.25% to 0.29%, classifying them as low-carbon steel plates. Furthermore, the specimen plate was acquired with dimensions that conformed to the requirements of the study. The specimen's dimensions were 15 x 15 cm with a thickness of 8 mm. The plate dimensions are established based on information from relevant sources, stating that the spacing between heating points falls within a range of 10-15 cm. The total number of plates needed for this study is 18.

Table 1
Chemical Composition of ASTM A36 Steel

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)
0.25-0.29	0.60-1.20	≤ 0.04	≤ 0.05	0.15-0.40	≤ 0.20	≤ 0.40	≤ 0.20

Table 2
Mechanical Properties of ASTM A36 Steel

Property	Value
Tensile Strength	400 - 550 MPa
Yield Strength	≥ 250 MPa
Elongation (% in 200 mm)	≥ 20%
Hardness (Brinell)	119 - 159 HB
Impact Toughness (Charpy V-Notch)	≈ 27 J at-20°C

2.1 Experiment

Heat treatment was conducted using an oxy-acetylene torch, commonly used in oxy acetylene welding (OAW). The plate was heated via spot firing, replicating shipyard practices. The torch was held in the right hand, moving in a circular motion 5 to 10 cm above the plate, while a thermo-gun in the left hand measured the maximum temperature, ensuring it aligned with field references and equipment capabilities. Furthermore, nine heating variations were applied, each tested twice, yielding 18 samples. After heating, visual observations were documented through overhead photography and video recordings of the flame straightening process. Figure 1 shows a flame-straightened sample plate.

In this study, the microstructure of a heat-treated specimen plate was analysed using SEM-EDX. The surface microstructure was mapped using a carbon steel phase diagram, which indicates that at the maximum heat treatment conditions of 550°C for 3 minutes, no phase transformation occurs. This treatment closely resembles the annealing process, where microstructural changes occur without phase transitions. Given this consistency, as shown in Table 3 SEM-EDX analysis was conducted on a single representative specimen under controlled time and temperature variables.

Determining the material's hardness is essential, as it reflects its resistance to permanent indentation, deformation, and treatment-induced changes in ship plates. The hardness of specimen plates subjected to process annealing varies with heating time and temperature. However, existing literature indicates that hardness remains largely unaffected by temperature variations below the A1 temperature line, with changes primarily influenced by heating duration. Therefore, this study assesses the hardness of three specimen plates under the following time and temperature conditions, as indicated in Table 4.

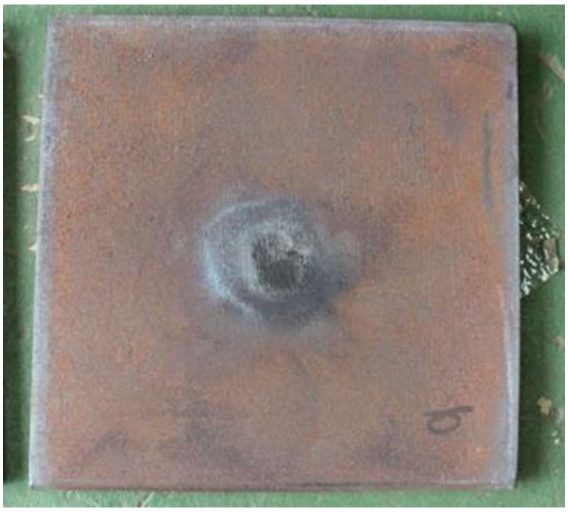


Fig. 1. Specimen after flame straightening

Table 3
SEM-EDAX Specimen Test Variables

Specimen	Temperature(°C)	Time(minute)
2.9	550	3

Table 4
Hardness Specimen Test Variable

Specimen	Temperature(°C)	Time(minute)
2.3	550	1
2.6	550	2
2.9	550	3

Tensile tests are performed to determine the material’s tensile strength, which is closely linked to its ductility and hardness. Variations in hardness, influenced by heating time, are expected to affect tensile strength. To investigate this relationship, three tensile specimens are tested under different heating durations and temperatures as presented in Table 5.

Table 5
Tensile Specimen Test Variable

Specimen	Temperature(°C)	Time(minute)
1.3	550	1
1.6	550	2
1.9	550	3

3. Results

3.1. Heat Treatment and Observations

Heat treatment with an oxy-acetylene burner caused visible surface colour changes on specimen plates. These changes, detailed in Table 6, were analysed under varying temperature and time conditions.

Table 6
Test Variable Terms

Specimen	Temperature(°C)	Time(minute)	Diameter (cm)
1.1 and 2.1	500	1	3.3
1.2 and 2.2	525	2	3.85
1.3 and 2.3	550	3	3.15
1.4 and 2.4	500	1	3.1
1.5 and 2.5	525	2	3.25
1.6 and 2.6	550	3	3.45
1.7 and 2.7	500	1	3.05
1.8 and 2.8	525	2	3.35
1.9 and 2.9	550	3	3

Figures 2 and Figure 3 depict plates after heat treatment. Before treatment, the plates were reddish-brown, transitioning to white and black after exposure. The discoloration was circular, with diameters ranging from 3.00 to 3.85 cm and a median of 3.25 cm. Temperature and exposure duration influenced these variations.

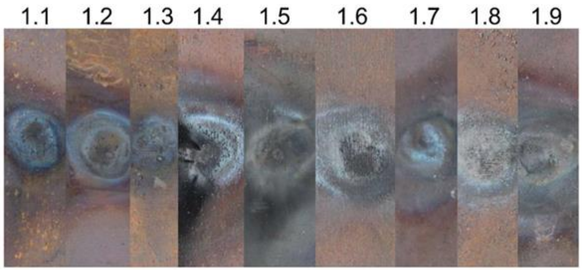


Fig. 2. Comparison of plate colour changes (Group 1)

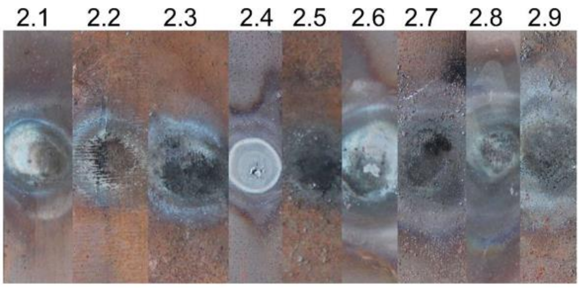


Fig. 3. Comparison of plate colour changes (Group 2)

As shown in Figure 4, plates treated at 500°C for 1–3 minutes had diameters between 3 and 3.4 cm. At 525°C, the range increased to 3.2–3.85 cm, while 550°C resulted in 3–3.45 cm diameters. Across all conditions, the diameter ranged from 3 to 3.4 cm, attributed to bending during flame straightening. The results suggest that temperature and time do not significantly affect colour patterns but influence diameter size. Variations in discoloration size and shape were due to the operator's hand movements and the flame shape of the oxy-acetylene torch.

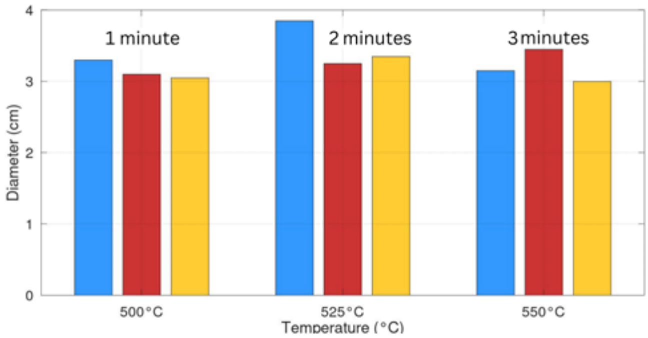


Fig. 4. Diameter-Temperatures (Group 2)

3.2 Hardness test

The hardness test was conducted by applying a load of 100 kilograms to prepared specimen plates. Preparation involved cutting the plates into 40 x 40 mm fragments, sanding the surfaces to ensure an even texture, and testing hardness at five points per specimen. The hardness values at these points were averaged to determine the specimen's hardness. Figure 5 shows the visual outcomes of the hardness tests.

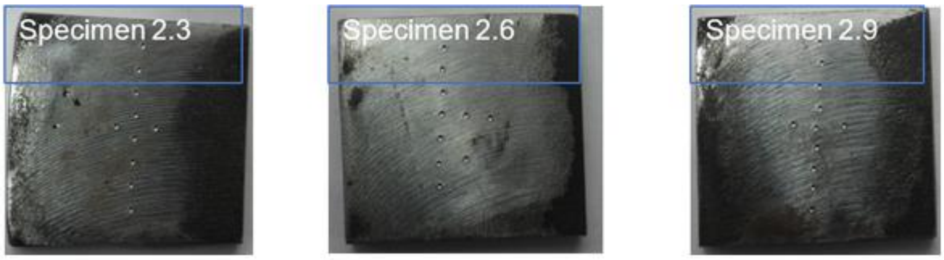


Fig. 5. Hardness test results

Quantitative results of the hardness tests for three specimens are provided in Table 7. Plate 2.3 exhibited hardness values ranging from 82.5 to 83.6, with an average hardness of 83 HRB. Plate 2.6 had a range of 77.0 to 77.7, averaging 77 HRB. Plate 2.9 showed hardness values from 79.1 to 80.3, averaging 80 HRB.

Table 7
Hardness Test Results

Specimen Code	Indentation	Hardness Value	Average
	I	82.5	
	II	82.5	
2.3	III	82.8	83 HRB
	IV	83.1	
	V	83.6	
	I	77.0	
	II	77.3	
2.6	III	77.5	77 HRB
	IV	77.7	
	V	77.7	
	I	79.1	
	II	79.4	
2.9	III	79.8	80 HRB
	IV	79.7	
	V	80.3	

When evaluated through a graphical interface, the mean hardness values for the three specimens are represented in Figure 6. The graph shows hardness values ranging between 77 and 83 HRB after heat treatment at 550°C, with the hardest specimens being heated for 1 minute.

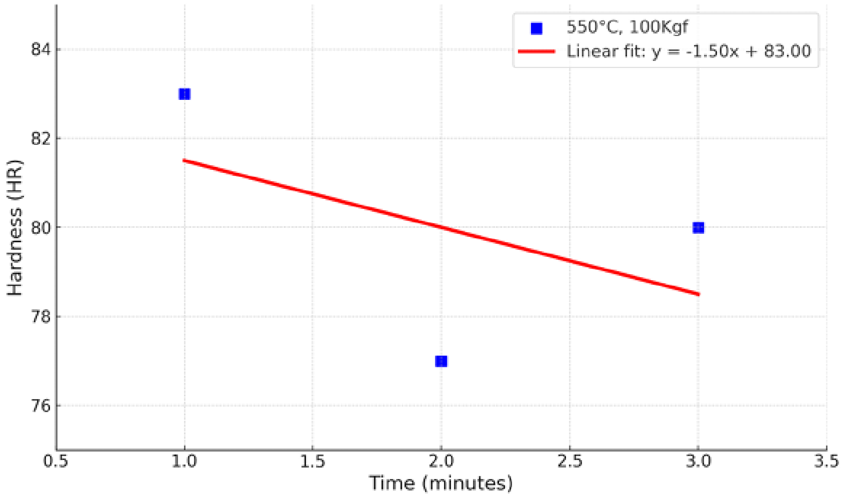


Fig. 6. Hardness vs. Time

The graph also highlights that hardness increases after heat treatment, with Pearlite Ferrite phases initially exhibiting a hardness of 71 HRB. Heat treatment added 6–12 HRB, with the highest hardness observed at 550°C for 1 minute. However, the addition of hardness for heating durations of 2 and 3 minutes followed a random pattern, attributed to inherent variability in flame straightening activities. Variations in outcomes may also result from the torch's configuration, gas composition, and operator-induced error.

Additionally, the heat treatment (flame straightening) at 550°C is close to the annealing process, which occurs within the temperature range of 260–760°C. Annealing is known to alter the physical properties of materials, reducing hardness and increasing malleability.

3.3 Tensile test

Tensile tests were conducted at MRC lt. 1 using ASTM E8 standard. The specimen plate is prepared before testing by cutting it into a standard form of testing. According to the standard, the following Figure 7 of specimens that are ready for testing.

Fig. 7. Tensile test specimen's pre-treatment

After the test, an additional post-treatment photograph was obtained in Figure 8. The test results are observed from multiple value points, including the yield strength point value, ultimate tensile strength, fracture point load, and maximum elongation. The obtained data results are in Table 8.

Fig. 8. Tensile test specimens' post-treatment

Table 8
Mechanical Properties of Specimens at 550°C

Specimen	T (°C)	t (min)	σ_y (MPa)	σ_{uts} (MPa)	$F_{fracture}$ (MPa)	ΔL_{max} (mm)
1.3	500	1	356.45	474.93	327.13	17.83
1.6	525	2	374.88	476.78	353.85	18.45
1.9	550	3	393.93	478.06	362.86	20.52

The Figure 9 presents the tensile test results for the three specimens after the heat treatment. The tensile test results show that increasing exposure time at 550°C improves the material's mechanical properties. Yield strength rises from 356.45 MPa (Specimen 1.3) to 393.93 MPa (Specimen 1.9), enhancing resistance to plastic deformation, while fracture load increases from 327.13 MPa to 362.86 MPa, indicating improved toughness. Ultimate tensile strength (UTS) remains stable, slightly rising from 474.93 MPa to 478.06 MPa, suggesting minimal effect from heat exposure. Maximum elongation increases from 17.83 mm to 20.52 mm, signifying greater ductility and reduced brittleness.

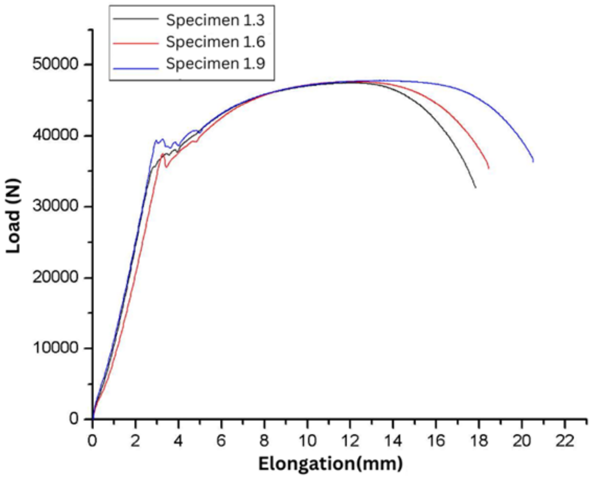


Fig. 9. Tensile test results

These trends imply microstructural strengthening through grain stabilization or precipitation effects and improved deformation capacity due to reduced internal defects. Specimen 1.9 exhibits the best strength-ductility balance, making it the most resilient, whereas Specimen 1.3 performs the weakest. In conclusion, prolonged exposure at 550°C enhances strength, toughness, and ductility without compromising UTS, demonstrating the potential of controlled heat treatment to optimize steel structures for high-temperature applications.

3.4. Correlation analysis between visual appearance, hardness value, and tensile test

This study provides a comprehensive correlation analysis between visual observations (diameter), hardness tests (HRB), and tensile tests (yield strength, UTS, fracture load, and elongation) in relation to heat treatment parameters. Results indicate that prolonged heat treatment at 550°C leads to increased yield strength and elongation, while hardness tends to decrease due to the annealing effect. This section presents regression plots illustrating the impact of heat treatment time on various mechanical properties of steel structures. The following Figure 10 and Figure 11 visualize the correlation between time and yield strength, ultimate tensile strength (UTS), fracture load, elongation, and hardness. Regression analysis reveals a strong positive correlation between time and yield strength, with an equation of Yield Strength = 356.45 + 18.74 × Time, whereas UTS remains relatively stable (UTS = 474.93 + 1.56 × Time). Fracture load increases moderately with extended heat exposure, and maximum elongation follows a similar trend, indicating improved ductility. However, hardness decreases slightly as exposure time increases (Hardness = 83 − 1.5 × Time). Visual observations confirm that larger heat-affected zones correspond with reduced hardness values. These findings suggest that controlling heat treatment duration optimizes the balance between strength and ductility, making flame straightening a crucial process for enhancing mechanical performance in steel structures.

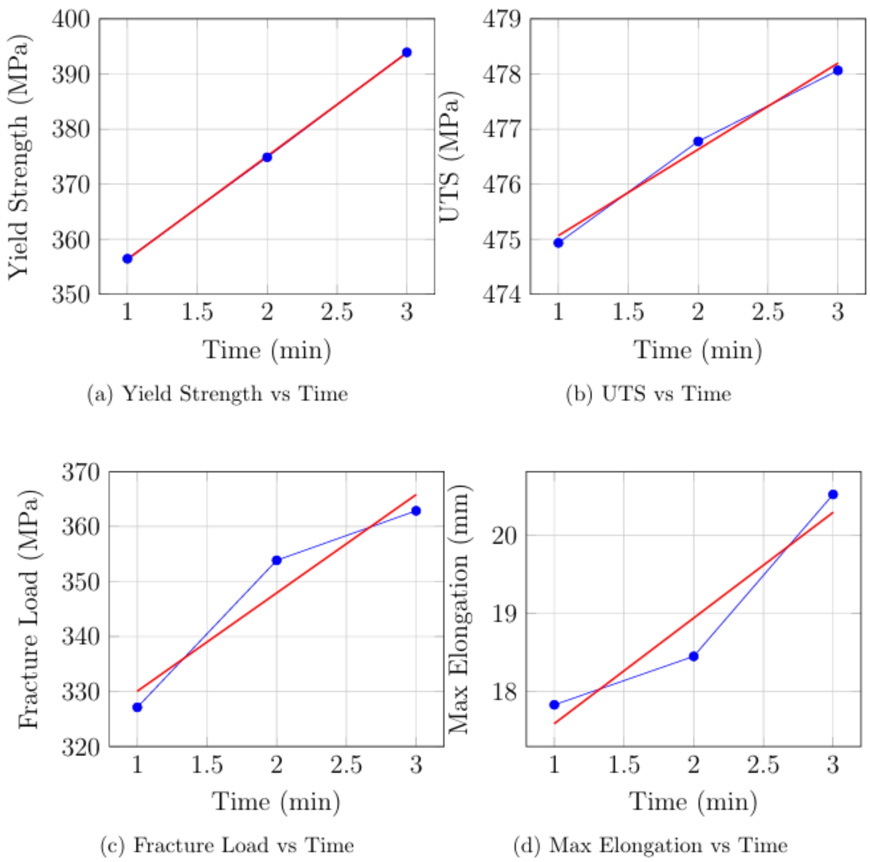


Fig. 10. Regression Analysis of Tensile strength vs Time

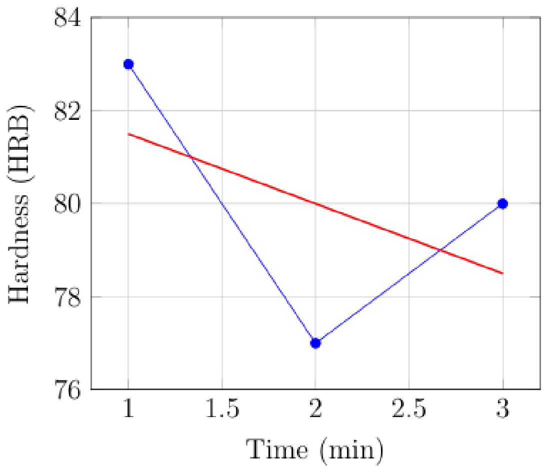
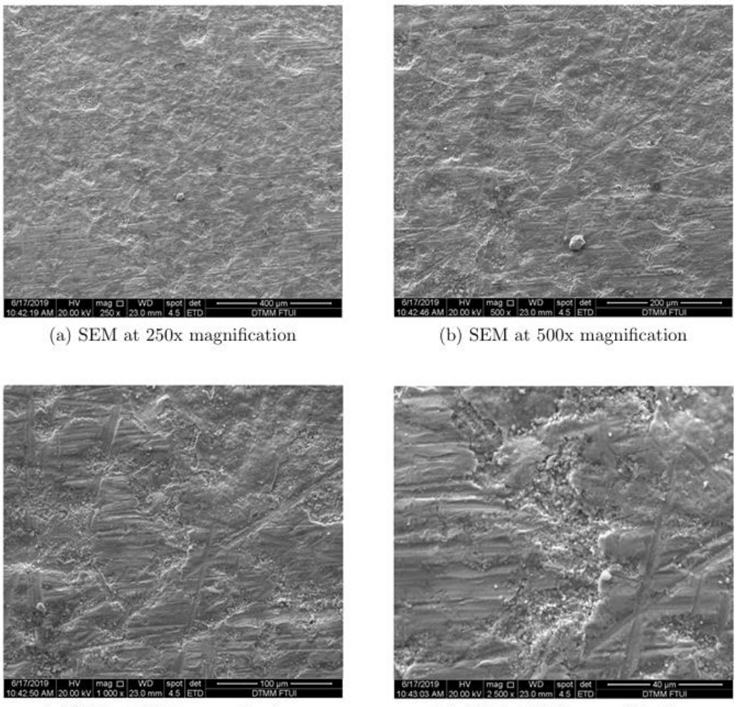


Fig. 11. Regression Analysis of Hardness vs Time

3.5 SEM-EDX Analysis

This section comprehensively analyses the microstructural and elemental changes in ASTM A36 steel after flame straightening using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). SEM was performed at 250x, 500x, 1000x, and 5000x magnifications to evaluate grain morphology, oxidation, and potential carbide precipitation, while EDX was used to analyse elemental composition variations in the heat-affected zones (HAZ).

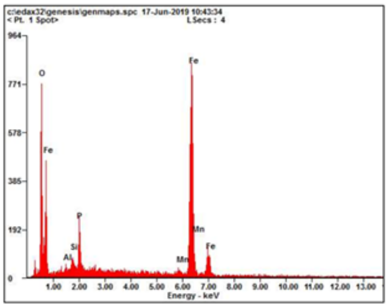
Figures 12a-d depict the SEM images at different magnifications. At lower magnifications (250x and 500x), surface oxidation and deformation bands are observed, indicating thermal stress and grain coarsening. At 1000x magnification, grain boundary modifications and phase transformations become more pronounced. The highest magnification (5000x) reveals a finer grain structure with potential carbide precipitates and submicron oxide inclusions, suggesting localized recrystallization and stress relief.



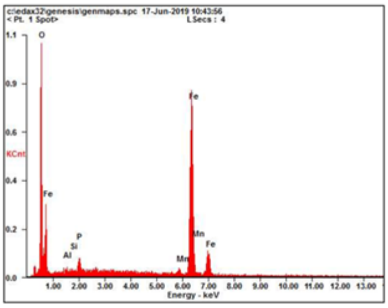
(a) SEM at 250x magnification
(b) SEM at 500x magnification
(c) SEM at 1000x magnification
(d) SEM at 5000x magnification

Fig. 12. SEM images of the flame-straightened steel surface at different magnifications

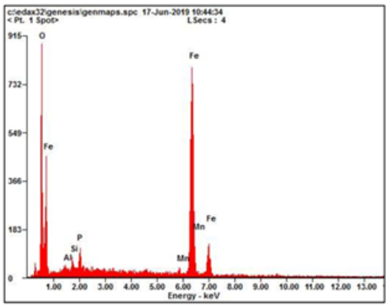
To complement the SEM findings, EDX analysis was performed at three different locations to determine elemental variations in the heat-treated steel. The results, shown in Figure 13, indicate oxidation levels and alloying element diffusion across different regions.



(a) EDX results at point 1



(b) EDX results at point 2



(c) EDX results at point 3

Fig. 13. EDX results at different analysis points on the flame-straightened steel surface

The EDX results indicate variations in oxidation and elemental diffusion. Point 1 contains higher Fe (73.62%) and moderate oxidation, suggesting minimal heat-induced oxidation. Point 2 exhibits the highest oxygen content (23.26%), signifying significant oxidation effects due to prolonged thermal exposure. Point 3 presents intermediate oxidation (19.69%), indicative of a transitional heat-affected zone.

Mn, Si, and P in varying amounts suggest elemental migration due to thermal diffusion, influencing hardness and ductility. Higher oxidation levels, particularly at Point 2, indicate surface degradation, which could affect long-term performance. These observations align with previous studies on heat treatment and flame straightening, confirming that controlled thermal exposure is crucial to balancing microstructural stability and mechanical performance [2, 11-13].

The SEM-EDX analysis confirms that flame straightening alters microstructure through grain refinement, oxidation, and carbide precipitation, affecting the material's strength, ductility, and hardness [14,15]. The oxidation and diffusion trends observed in EDX analysis highlight the need for optimized heat control strategies to prevent excessive microstructural degradation.

4. Conclusions

This research investigates the influence of flame straightening, a process involving heat treatment applied to carbon steel conforming to ASTM A36, on its mechanical characteristics. The heat treatments involved the use of oxy-acetylene welding, a technique that results in dot marking on the surface of the carbon steel. Hardness characteristics of the heat-treated surface were assessed via the Brinell test, and tensile tests were used to evaluate the material's strength at various heat exposure times. The surface morphology, microstructure, and chemical composition were examined using a scanning electron microscope (SEM) equipped with energy-dispersive X-ray(EDX) analysis. The findings are presented below:

- Hardness initially increased due to microstructural modifications but declined with prolonged heat exposure, attributed to annealing-induced grain growth. A maximum hardness of 83 HRB was recorded at 550°C for 1 minute, decreasing to 77 HRB in 3 minutes. Furthermore, yield strength rose from 356.45 MPa to 393.93 MPa with increased exposure time, enhancing resistance to plastic deformation. UTS remained stable (474-478 MPa), indicating minimal impact on peak load-bearing capacity. Fracture load increased from 327.13 MPa to 362.86 MPa, confirming improved toughness, while elongation increased from 17.83 mm to 20.52 mm, signifying enhanced ductility. Moreover, a positive linear correlation was observed between heat exposure and yield strength, fracture load, and elongation. Hardness exhibited an inverse trend, confirming the softening effect of prolonged heating, while UTS remained stable, suggesting grain coarsening had little impact on peak strength under controlled conditions.
- SEM analysis at 250x and 500x magnifications revealed oxidation layers and deformation bands, indicating thermal stress and grain coarsening. At 1000x magnification, grain boundary modifications and pearlitic phase dissolution suggested partial recrystallization. The 5000x images confirmed fine carbide precipitates and submicron oxide inclusions, indicating localized stress relief and potential embrittlement. Furthermore, EDX analysis showed increased oxidation in heat-affected zones, with oxygen content rising from 17.57% at Point 1 to 23.26% at Point 2, suggesting progressive degradation. Mn segregation influenced hardenability, while P and Si diffusion suggested phase modifications affecting local mechanical properties.
- Controlled flame straightening optimizes mechanical properties by enhancing yield strength and elongation while maintaining structural integrity, making it viable for steel structure repair. Overheating risks must be managed, as excessive exposure leads to grain coarsening, oxidation, and reduced ductility, compromising performance. Optimized heating parameters (550°C, 1-3 minutes) provide the best balance of strength and ductility, reinforcing the importance of controlled thermal exposure for structural stability. These findings align with prior studies, confirming that precise thermal control mitigates embrittlement while preserving mechanical resilience.

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