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Effect of Hot Induction Bending Followed by Controlled Heat Treatment on the Mechanical and Microstructural Behavior of API 5L X65 Carbon Steel Pipes

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ABSTRACT

This study examines the mechanical and microstructural behavior of API 5L X65QS/QO PSL2 seamless carbon steel pipes subjected to a hot induction bending process followed by quenching and tempering. The research aimed to evaluate the combined effect of mechanical deformation and heat treatment on the material's strength, hardness, and toughness. Experimental procedures were performed on a 12-inch seamless pipe bent at 900 ± 15 °C, quenched in agitated water at 15 °C, and tempered at 660 ± 15 °C. Mechanical testing revealed that the Ultimate Tensile Strength (UTS) and Yield Strength (YS) increased by approximately 8.5%, while hardness decreased slightly from 215 HV to 210 HV. Elongation improved from 29% to 32%, indicating enhanced ductility. Microstructural analysis showed a fine ferrite–pearlite structure with an ASTM grain size number greater than 8, confirming effective grain refinement achieved through controlled heat treatment. Overall, the combined hot induction bending, quenching, and tempering processes successfully produced a fine-grained material with improved strength, ductility, and toughness, demonstrating its suitability for high-performance and high-pressure pipeline applications.

KEYWORDS: *API 5L X65, Hot induction bending, Quenching, Tempering, Mechanical properties.*

1. INTRODUCTION

Pipe line specifications in engineering sectors, such as the oil and gas industry, chemical plants, and pressure vessel manufacturing, must be meticulously adapted base on specific operational parameters. The crucial variables that determine the selection of piping materials and design include the system's pressure and temperature, the characteristics of the conveyed fluid, environmental conditions (e.g., onshore or offshore installations), and compliance with the applicable industrial safety standards [1]. Within anoxic (oxygen-depleted) piping systems conveying hydrocarbons (oil or gas) and offshore installations, a nutrient-rich substrate is provided which is necessary for the growth of anaerobic microorganisms. Hence, the biofilm attachment plays a key role in the initiation of interfacial changes at the metal surface. This micro-environmental change has the direct effect on the corrosion rate, which could be increasing or decreasing due to material degradation [2].

Presently, hydrocarbons (oil and gas) are the main primary energy products whose consumption continuously increases with world demographic growth. Operators thus face a daunting task, since most reservoirs have a natural corrosive environment. Corrosiveness of this magnitude can lead to the system efficiency and hence cost for producer, being dramatically reduced [3]. In the evolution of the oil and gas industry, piping often referred to as pipes is the usual medium used to transport fluids or gases. The most common type of pipe used in the oil and gas sectors is steel pipe. Steel is preferred over other materials for several reasons, including its superior mechanical properties, high durability, ease of fabrication and handling, and relatively low cost [4]. In addition to the requirement for straight piping, bent pipes are essential components that must be integrated to accommodate the alignment of oil and gas distribution routes with the actual ground surface topography. Elbows or bends serve as crucial fittings widely utilized within natural gas piping networks. The primary function of these components is to modify the direction of pipe flow in accordance with the network's required geometric design. The choice of mother pipe has a major impact on the induction bending product's quality. The American Petroleum Institute's international standard API 5L governs the pipes used in the oil and gas sector to carry hydrocarbons (oil, gas, and water). The API 5L specification uses a variety of important technical characteristics to further detail pipes and classify them into different grades.

The manufacturing process (e.g., seamless pipes without welded seams and welded pipes with longitudinal or spiral welded seams), testing specifications, dimensional tolerances, and pipe sizes are all included in these criteria. Accurate selection is crucial to maintaining the integrity of the hydrocarbon transportation system since each pipe grade has unique strength properties and corrosion resistance.By adhering to this standard, the oil and gas industry can minimize the risk of leakage and enhance operational efficiency [5].

Operational factors like pressure and the kind of fluid to be transported must be taken into consideration when choosing the grade of steel pipe. Different Product Specification Levels (PSL)—PSL 1 and PSL 2—are established by the API Specification 5L standard to classify the technical and quality criteria of the pipe the degree of quality control, material characteristics, and testing requirements are the main areas where PSL 1 and PSL 2 diverge, with PSL 2 requiring much more strict standards. Standard applications where operating conditions are not too harsh or dangerous are appropriate for PSL 1 pipes. On the other hand, PSL 2 pipes require superior toughness and structural integrity, as they are designed for high-risk applications and service in harsh environments[6]. Hot induction bending is a crucial material forming technique. This method of pipe bending makes use of electromagnetic induction-generated localized heating. Because of its inherent accuracy and efficiency, this technology is frequently used in a variety of industrial applications and is particularly useful for creating pipes with a short bending radius [7]. Other names for induction bending include high-frequency bending, incremental bending, and hot bending [8].

A wide range of pipe sizes, from small to large, can be bent using the hot induction process [Figurer 1). This technique effectively reduces production costs while improving bend quality and lowering the overall cost of finished pipe fabrication [9]. The microstructure in the heat-affected zone is naturally altered by the hot induction bending process, which results in changes to the material's characteristics, especially its mechanical qualities. Additionally, the pipe experiences localized deformation during the bending operation, which may lead to the development of residual stress. The material's ability to tolerate internal pressure and external pressures is subsequently compromised by this residual stress [10]. If bending factors like feed speed, temperature, or radius are not carefully regulated, improper bends may result. A loss in structural strength or excessive deformation are frequently the results of such a lack of control. The integrity and functionality of the pipe during service may be seriously impacted by these degraded conditions, which may lead to visible flaws such internal or external cracks, delamination, folds, or wrinkles [8].

Therefore, in order to restore the material properties impacted by the bending process, which may result in residual stresses and strain hardening, a subsequent heat treatment procedure is necessary following hot induction bending. With or without affecting the material's chemical makeup, heat treatment is the process of modifying a metal's microstructure by carefully adjusting the rates at which it is heated and cooled [11].

Achieving the desired mechanical properties in metals is the aim of this process. The entire cross-section or just a portion of the material may be impacted by the subsequent changes in the metal's properties brought about by heat treatment. The quenching and tempering heat treatment procedures will be the specific subjects of this investigation. A number of strictly regulated steps are involved in the production of bent API 5L seamless pipes in order to guarantee both dimensional accuracy and mechanical integrity. After the material is received, an initial inspection is conducted to confirm that it complies with the specifications. After that, blasting is used to clean the pipe's inner and outer diameters. After cleaning, any surface or internal irregularities are found by visual inspection and ultrasonic thickness testing.

A number of strictly regulated steps are involved in the production of bent API 5L seamless pipes in order to guarantee both dimensional accuracy and mechanical integrity. After the material is received, an initial inspection is conducted to confirm that it complies with the specifications. After that, blasting is used to clean the pipe's inner and outer diameters. After cleaning, any surface or internal irregularities are found by visual inspection and ultrasonic thickness testing. After these phases are successfully finished, an internal dimensional inspection is conducted after the bending process. A post-bending heat treatment, such as quenching and tempering, is carried out to improve and restore the mechanical qualities impacted by the bending. After that, the exterior is blasted once more to get rid of any scale or oxidation that developed during the heat treatment procedure. Both pipe ends are then machined to achieve uniformity after non-destructive testing (NDT) is completed to make sure there are no hidden flaws. Before the pipe is formally declared ready for service, a final visual and dimensional inspection is carried out to ensure that it satisfies all necessary quality and safety standards.

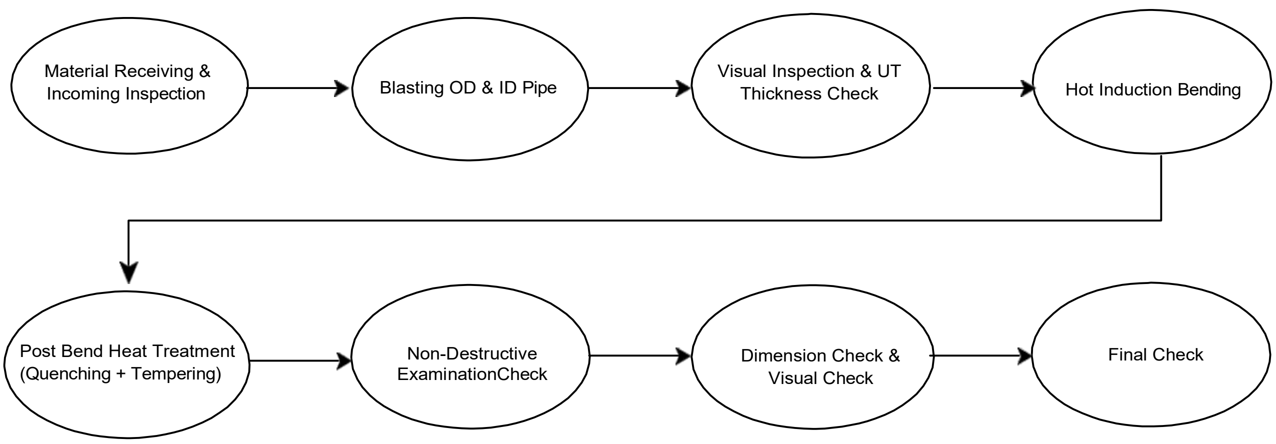

Figure 1: The process of hot induction bending manufacturing

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The microstructure could theoretically be totally changed by quenching. Instead of using diffusion, this process uses lattice distortion to change the stable pearlite phase in carbon steel into the metastable martensitic phase. Various liquid or air-based media, along with other materials that can extract heat quickly, can be used for quenching. Oil, saltwater, fresh water, forced air convection, and specialty polymers are examples of common media. Water can effectively achieve maximum hardness, but there is a small chance of distortion and minor cracking [12]. A fully hardened steel specimen achieves a very high level of hardness, but it also retains significant residual stresses and becomes brittle. The steel is unstable in this state and may progressively contract or distort, particularly when exposed to outside loads. Such forces have the potential to worsen the instability by increasing internal stresses. A gentle heat treatment called stress relieving is used to reduce these internal stresses. Tempering, or occasionally drawing, is the term used when the treatment is also meant to increase toughness and decrease hardness [13].

A fully hardened steel specimen achieves a very high level of hardness but also retains significant residual stresses, resulting in brittleness and dimensional instability. To relieve these stresses and restore ductility, the material is reheated to a subcritical temperature after quenching from the austenitizing range, followed by gradual cooling in still air. The tempering temperature is selected based on the steel's chemical composition and the required balance between strength and toughness. This thermal sequence ensures that the material maintains stable mechanical performance after forming. Despite the widespread use of API 5L X65 steel in the oil and gas industry, few studies have investigated the combined effects of hot induction bending and post-bend heat treatment under real industrial conditions. This research addresses that gap through direct experimental evaluation, providing practical insights for optimizing strength, toughness, and microstructural stability to enhance the reliability of pipeline system.

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2. METHOD

2.1 Hot Induction Bending Process

The material used is a seamless carbon steel pipe conforming to API 5L Grade X65QS/QO PSL2, with an outer diameter (OD) of 12 inches and a wall thickness of 23.4 mm. The chemical composition and mechanical properties of the base material are presented in Table 1 and Table 2 respectively [14].

Table 1: Chemical composition of base metal API 5L Grade X65QS/QO PSL

Chemical Composition	(%)	Chemical Composition	(%)
Carbon (C)	0,1	Titanium (Ti)	0.01
Silicon (Si)	0.25	Cooper (Cu)	0.06
Mangan (Mn)	1.29	Nickel (Ni)	0.1
Phosphorus (P)	0.15	Chromium (Cr)	0.11
Sulfur (S)	0.02	Molybdenum (Mo)	0.1
Vanadium (V)	0.05	Boron (B)	0.03
Niobium (Nb)	0.24	Carbon Equivalent$_{(PCM)}$	0.20

Table 2: Mechanical properties of base metal API Grade X65QS/QO PSL2

Mechanical Properties	
Tensile Strength [MPa]	580
Yield Strength [MPa]	485
Elongation [%]	29
Average Hardness (HV10)	215
Average Impact Test/ Absorb Energy (J)	336

The hot induction bending procedure is shown in Figure 2. This technique involves pushing one end of the pipe forward while keeping the other end stationary and using a rotating arm to guide it to follow the designated bend radius. The pipe passes through a high-frequency coil during the bending process, creating a concentrated magnetic field that induces an electric voltage and causes current to flow through the pipe. Rapid, localized heating is caused by the pipe's resistance to this current, and the outer surface is immediately quenched with water.

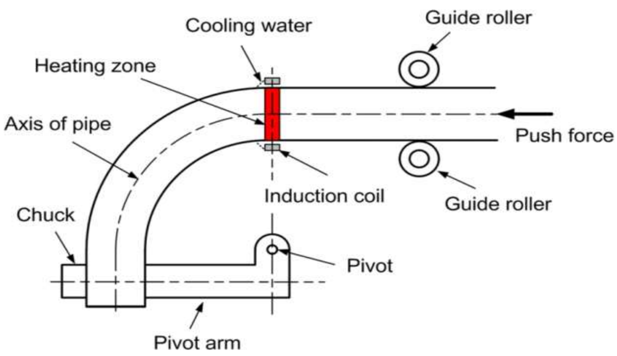

Figure 2: Schematic of hot induction bending process

A controlled temperature of 900 (±15) ºC was used for the induction bending process, which resulted in a bend radius of 1619.5 mm and a 45º bend angle. The bending process for the API 5L Gr. X65QS/QO PSL2 material is shown in Figure 3. It should be mentioned that the pipe is immediately externally cooled with water after going through the heating coil. The hot induction bending process makes use of the parameters indicated in Table 3.

Figure 3: Hot induction bending process base metal API Grade X65QS/QO PSL2

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Table 3: Hot induction bending process parameter

Item	Setting	Tolerance	Unit
Bending Speed	24	± 2.5	mm/min
Bending Outside Surface Temperature (Extrados and Intrados)	900	± 15	°C
Start Bending at Temperature	900	25	°C
Coolant Medium	Water	None	-
Coolant Temperature	20	± 15	°C
Coolant Flow Pressure/ Flow rate	30	± 10%	LPM
Induction Frequency	1000	± 20%	Hz

2.2 Post Bend Heat Treatment

The material was post-bend heated in a batch furnace following the hot induction bending process. During the quenching (hardening) stage, it was heated to 960 °C with a holding time of 72–87 minutes and a heating rate of 114 °C/h. The pipe was then transferred to a quench tank containing agitated water maintained at 15 °C within a maximum transfer time of 60 seconds to enhance the material's hardness and strength. The parameters listed in Table 4 were followed during the quenching process, while Figure 4 illustrates the quenching (hardening) procedure for the API 5L Grade X65QS/QO PSL2 material. The parameters listed in Table 4 are those used in Post Bend Heat – Quenching process.

The pipe material is sent back to the furnace for tempering after the quenching procedure. The quenched component is heated to 660 °C using this tempering heat treatment, with a holding time of 84 to 99 minutes and a heating rate of 101 °C/h. After that, the material is gradually cooled in ambient air to improve its ductility. The tempering process is shown in Figure 5. The tempering process follows the specified parameters as a reference for the testing. The tempering process is based on the parameters outlined in Table 5.

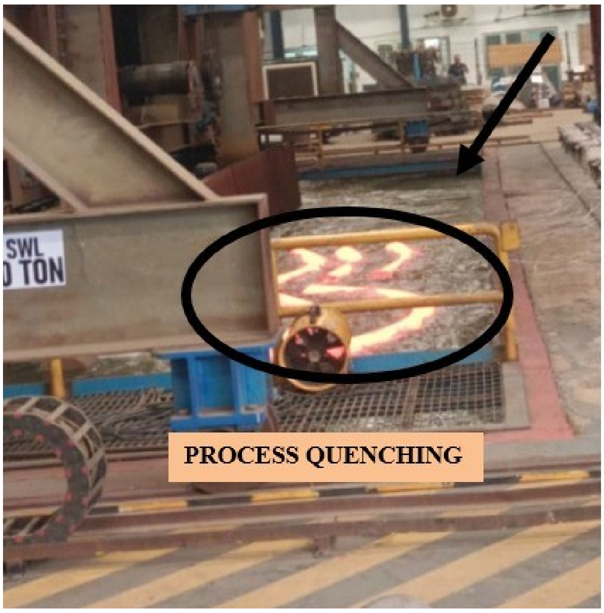

Figure 4: Post bend heat – quenching process

Table 4: Quenching parameter

Applicable Code / Specification	4497-YPSI-7-14-0002
Governing Thickness	26.0mmWT
Min. Thickness After Bending	23.4mmWT
Governing Material Grade	API 5L X65QS/QO PSL2
Location of TC Attachment	OD at Intrados
Holding Temperature and Time before quenching	960 ± 15 °C (Aim 960 °C) for 72 - 87 minutes (Aim 72 minutes)
Cooling Method	Quench Bath Agitated
Quench Media Temperature Before Quenching	15 °C max
Minimum Quenching Time	300 second

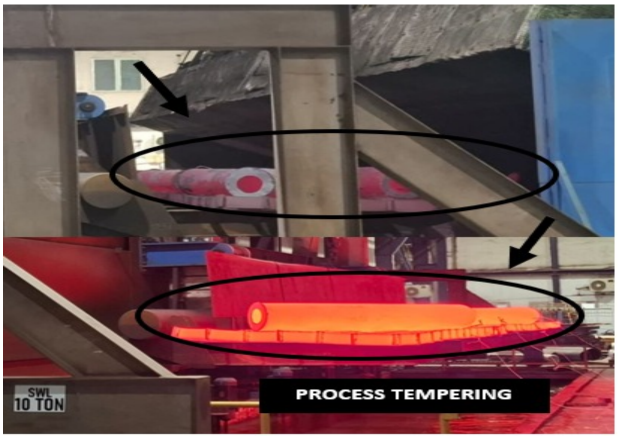

Figure 5: Post Bend Heat – Tempering process

Table 5: Tempering parameter

Applicable Code / Specification	4497-YPSI-7-14-0002
Governing Thickness	26.0mmWT
Min. Thickness After Bending	23.4mmWT
Governing Material Grade	API 5L X65QS/QO PSL2
Location of TC Attachment	OD at Intrados
Holding Temperature	660 ± 15 °C (Aim 660 °C)
Holding Time	84 - 99 minutes (Aim 84 minutes)
Heating Rate	101 °C/h
Cooling Method	Air Cooling

Following the completion of the tempering process, the heat treatment and hot induction bending procedures are completed.

2.3 Equipment Testing

The detailed specifications of the various equipment relevant to the testing methods applied in the mechanical testing are presented in Table 6.

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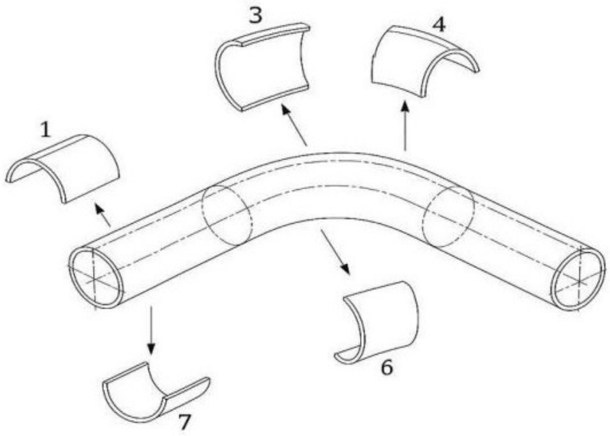
Table 6: Equipment testing list and specification

No	Method	Specification
1	Tensile Test	Instron Universal Testing Machine, S/N: 600DXR9024 Model: 600DX-C3A-G7F Reference Code : ISO 15590-1 Tested Method : ISO 4136 : 2012
2	Hardness Test	The Zwick Rockwell Hardness Testing Machine, Model Dura Scan 70 G5, S/N: DS251917 Has been verified using Euro Products Limited Standardized Blocks (Identity No: EP18202924, EP18203976 and EP12151209)| Reference Code : ISO 15590-1 Tested Method : ISO 6507 : 2021
3	Impact Test	ZWCIK Roel Charpy Testing Machine, S/N: 212670: 2013 The Charpy impact test was conducted at a temperature of -30°C, following the ISO 15590-1 procedure. The specimens used were sized 10 x 10 x 55 mm.
4	Metallography Test	Nkion Eclipsema20 optical microscope Test Method : ASTM E407-07(2015) e1 - Micro Examination and Photo - Determining Average Grain Size

3. RESULT

The material will be cut into test coupons for further mechanical testing after the hot induction bending, quenching, and tempering procedures are complete. The area shows in Figure 6 that was used to determine the testing locations.



1. Tangent
3. Bend Extrados
4. Finish Transition Zone (FTZ) Extrados
6. Bend Intrados
7. Start Transition Zone (STZ) Extrados

Figure 6: Location test coupon

3.1. Tensile Test Result

On the bent portion of the pipe, tensile test specimens were gathered from seven distinct spots. The straight (bare) pipe's initial mechanical characteristics were as follows: a yield strength (YS) of 485 N/mm2, an elongation of 29%, and an ultimate tensile strength (UTS) of 580 N/mm².

After the hot induction bending operation, as shown in Figure 3, the average values were 629 N/mm² for the Ultimate Tensile Strength (UTS), 526 N/mm² for the Yield Strength (YS), and 32% for the Elongation, as presented in Table 7.

Table 7: Ambient tensile test result

Location	UTS (N/mm²)	YS (N/mm²)	Elongation (%)
Bare Straight Pipe	580	485	29
Tangent	626	540	33
STZ Extrados	628	544	30
FTZ Extrados	643	541	30
Extrados	623	510	32
Intrados	627	496	34

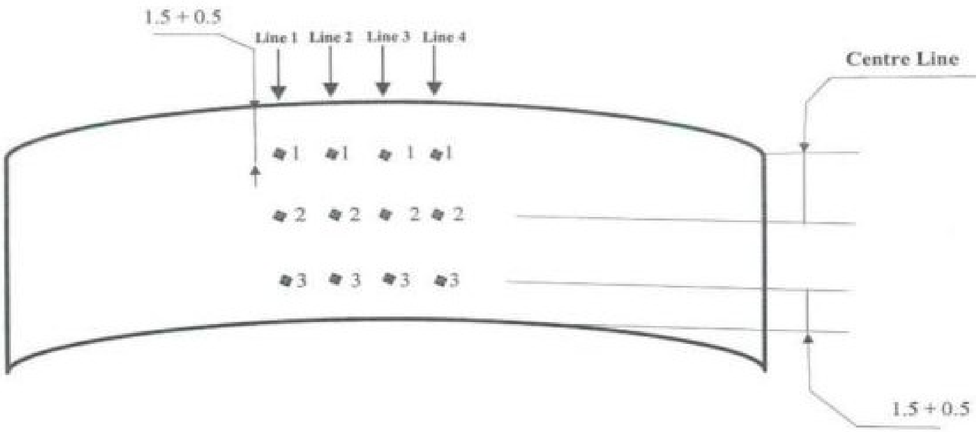


Figure 7: Hardness Vickers sketch test location

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3.2. Hardness Test Result

The average hardness of the as-received straight pipe was measured at 215 HV. After the hot induction bending process, the average value slightly decreased to 210 HV. Hardness testing was performed on several specimens, as shown in Figure 6, with the specific measurement points indicated in Figure 7. The detailed hardness results are summarized in Table 8.

Table 8.Vickers Hardness result

Location	Position					
	Line No.	1 (HV10)	2 (HV10)	3 (HV10)	4 (HV10)	AVG (HV10)
Tangent	Line 1	213	207	213	210	211
	Line 2	203	197	199	203	201
	Line 3	215	211	213	212	213
STZ Intrados	Line 1	203	207	213	210	208
	Line 2	203	197	199	203	201
	Line 3	215	211	213	212	213
FTZ Extrados	Line 1	210	216	215	209	213
	Line 2	213	208	209	213	211
	Line 3	206	218	216	211	213
Extrados	Line 1	206	214	204	215	210
	Line 2	211	214	205	201	208
	Line 3	211	216	214	207	212
Intrados	Line 1	210	216	214	216	214
	Line 2	207	201	199	209	204
	Line 3	211	212	214	216	213

3.3 . Charpy Impact Test Result

For the situation of bare straight pipes, the average Charpy impact energy was 274 J. Table 9 below displays the bent pipe's impact test results.

Table 9: Charpy Impact test result

Location	Specimen			AVG (J)
	1 (J)	2 (J)	3 (J)	
Bare Straight Pipe	332	362	328	341
Tangent	318	214	286	264
STZ Extrados	318	297	306	307
FTZ Extrados	185	297	179	220
Extrados	219	319	208	249
Intrados	219	223	318	254

3.4 Metallographic Test Result

3.4.1 Micro Examination and Photo

The microstructural examination of the extrados region, taken 2 mm from the external surface of the bent API 5L X65 steel pipe, revealed a ferrite–pearlite matrix, where ferrite appeared as the light phase and pearlite as the dark phase. Observations made using an optical microscope at magnifications of 100× and 400× showed a uniform and fine-grained structure with clearly defined grain boundaries. Test specimens were taken from two regions, namely the STZ extrados (Figures 8 and 9) and FTZ extrados (Figures 10 and 11). After the bending and heat treatment processes, both regions exhibited similar microstructural characteristics dominated by ferrite and pearlite phases. The average grain size obtained from the measurement was greater than 8, indicating a fine-grained structure.

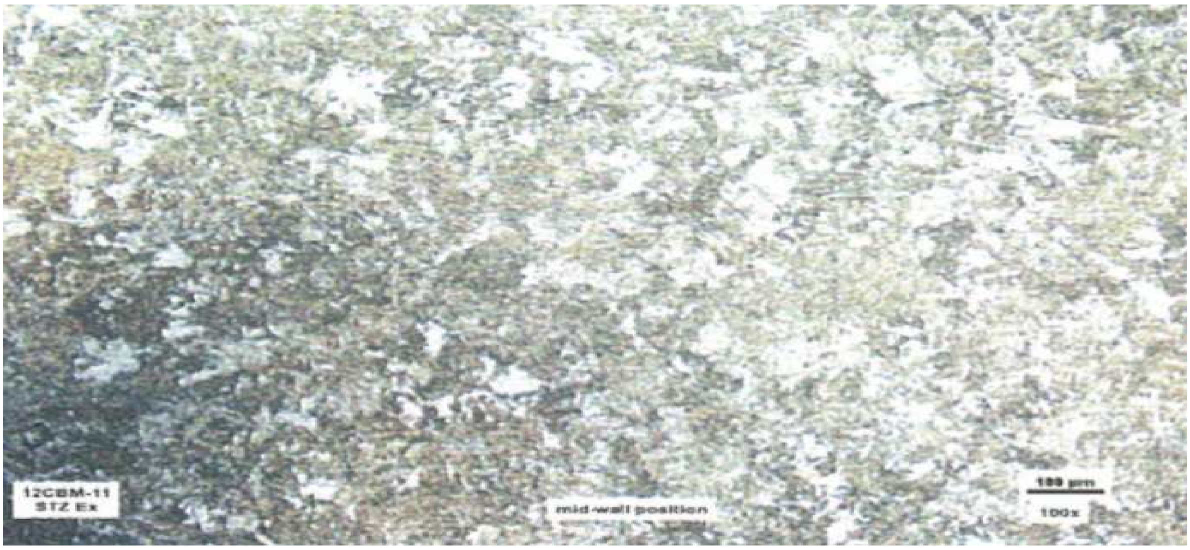

Figure 8: STZ extrados magnification 100 x

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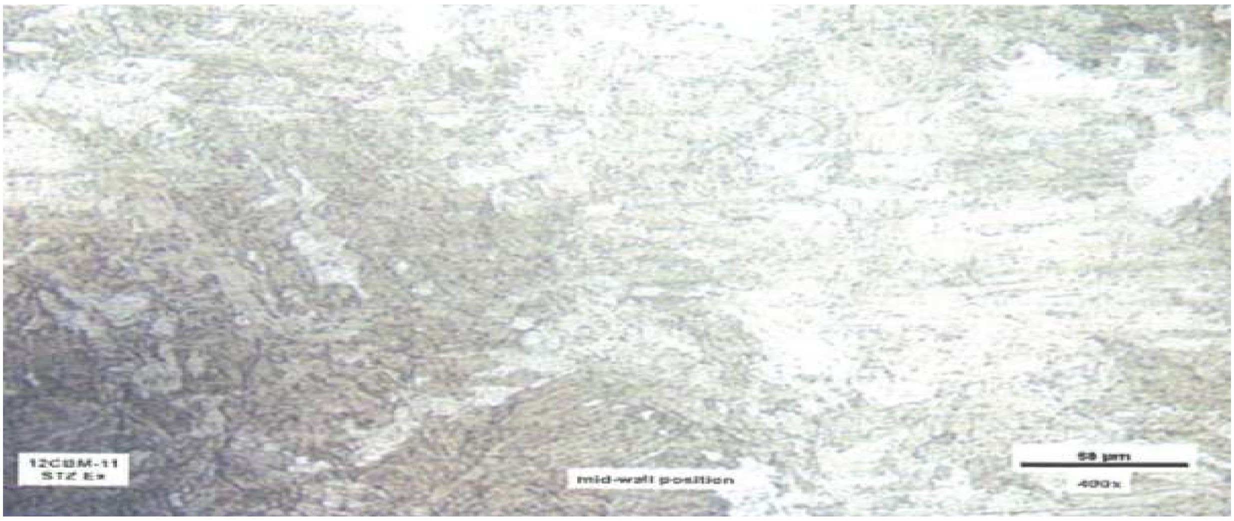

Figure 9: STZ extrados magnification 400 x

Figure 10: FTZ extrados magnification 100 x

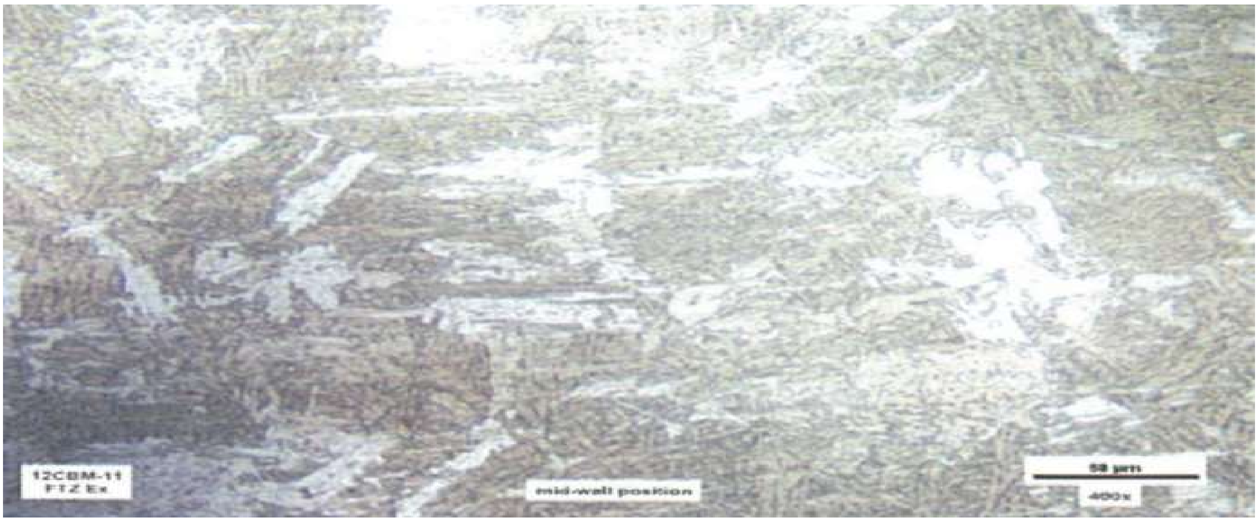

Figure 11: FTZ extrados magnification 400 x

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4. DISCUSSION

4.1 Strengthening Mechanisms

Based on the test results, the values of UTS and YS increased after the bending, quenching, and tempering processes, with the UTS rising from 580 N/mm² to 629 N/mm² and the YS increasing from 485 N/mm² to 526 N/mm². Furthermore, an improvement in elongation was observed, increasing from 29% to 32%, while the average hardness slightly decreased from 215 HV to 210 HV. The slightly higher hardness observed in the as-received straight pipe can be attributed to residual stresses and a relatively harder microstructure formed during the initial manufacturing process. Following the bending process and subsequent heat treatment, the microstructure transformed into a more stable and tougher state. Nevertheless, a minor reduction in hardness occurred due to the tempering stage, which reduced martensitic hardness and relieved internal stresses.

The observed increase in mechanical strength, as indicated by the rise in UTS and YS values, can be associated with several metallurgical strengthening mechanisms activated during the bending and heat treatment processes. One of the main contributors to this improvement is grain refinement, as finer grains increase resistance to dislocation motion, thereby enhancing strength according to the Hall–Petch relationship [15]. Microstructural analysis revealed the presence of ferrite (light phase) and pearlite (dark phase), which contribute to improved strength and consistency in the mechanical performance.

In addition to grain refinement, the mechanical deformation introduced during bending is expected to have increased the dislocation density within the material. This mechanism, known as strain hardening (or work hardening), enhances the yield strength by impeding the motion of dislocations [16]. The quenching process likely induced a microstructural transformation toward harder phases such as martensite or bainite, depending on the alloy composition and the applied cooling rate [17]. The martensitic transformation is a key contributor to strength development, primarily due to the severe lattice distortion resulting from a supersaturated carbon structure and the associated internal stresses [18]. The subsequent tempering stage partially relieves these stresses and reduces dislocation density, thereby stabilizing the microstructure at the expense of a slight decrease in hardness. Simultaneously, tempering promotes the transformation of as-quenched martensite into tempered martensite, a process essential for improving ductility and toughness [19].

Interestingly, the slight increase in elongation (from 29% to 32%) accompanied by a small reduction in hardness (from 215 HV to 210 HV) indicates that the overall strength was preserved while ductility improved and indentation resistance marginally decreased. Further microstructural examination supports this observation.

4.2 Microstructure

Microstructural analysis conducted through the Determination of Average Grain Size test showed an ASTM grain size number greater than 8, indicating a fine-grained structure. This finding confirms that the material has a very small grain size, consistent with the ASTM E112 standard, where an increase in grain size number corresponds to a reduction in actual grain diameter[20]. Such refinement enhances mechanical performance through grain boundary strengthening, as the enlarged total boundary area impedes dislocation motion. Consequently, the fine-grained ferrite–pearlite microstructure contributes to the observed improvement in both Yield Strength (YS) and Ultimate Tensile Strength (UTS) of the material[21].

5. CONCLUSION

This study investigated API 5L X65QS/QO PSL2 seamless carbon steel pipes subjected to a hot induction bending process followed by quenching and tempering. The mechanical test results demonstrated a significant enhancement in performance, with both the Ultimate Tensile Strength (UTS) and Yield Strength (YS) increasing by approximately 8.5%. In contrast, the material's hardness showed only a slight reduction of about 2.3%. Microstructural analysis revealed a fine-grained ferrite–pearlite structure with an ASTM grain size number greater than 8, indicating effective grain refinement resulting from the controlled heat treatment process. Overall, the combined process effectively achieved a notable improvement in strength with only a minor decrease in hardness, resulting in a fine-grained material with enhanced toughness and structural stability, consistent with the intended objective of this investigation.

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