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Mechanical Properties Restoration of API 5L X60 Carbon Steel through Hot Induction Bending Followed by Quenching and Tempering Treatment

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ABSTRACT

Pipe bending is a critical process in the oil and gas industry to accommodate complex terrain while maintaining pipeline integrity. This study investigates the mechanical and micro structural responses of API 5L X60 seamless carbon steel pipes subjected to hot induction bending followed by quenching and tempering. Tensile testing, hardness measurements, and optical microscopy were employed to characterize the changes induced by these treatments. Post-treatment results demonstrated an increase in ultimate tensile strength from 580 N/mm² to 606 N/mm² (4.4%) and yield strength from 455 N/mm² to 495 N/mm² (8.7%), accompanied by a reduction in elongation from 27% to 23% and a slight decrease in hardness from 206 HV to 199 HV. Micro structural observations revealed finer grains (ASTM grain size 9.5) and the presence of tempered martensite, contributing to improved strength and toughness. The enhancements are attributed to strain hardening, phase transformation, and stress relief during tempering. These findings suggest that integrating hot bending with appropriate heat treatment effectively optimizes pipe performance for demanding service conditions.

KEYWORDS: *API 5L X60, Hot induction bending, Quenching, Tempering, Mechanical properties*.

1.0 INTRODUCTION

In engineering industries such as oil and gas, chemical plants, and pressure vessel manufacturing, the pipe specifications required for operations vary depending on the specific application, including pressure, temperature, type of fluid transported, operating environment (onshore or offshore), and industrial safety standards [1]. Oil and gas have become indispensable daily commodities, and their demand continues to rise with population growth. Most oil and gas reservoirs exhibit high levels of corrosion, posing a significant challenge for producers due to the associated lower cost.

The infrastructure for fuel oil and natural gas in Indonesia continues to grow each year. As of November 2024, the total length of natural gas pipelines has reached 22,520 kilometers. This includes 5,370 kilometers of transmission pipelines, 6,272 kilometers of distribution pipelines, and 10,877 kilometers of household gas network pipe lines [2]. In the development of the oil and gas industry, a commonly used material for transporting fluids or gases is pipe. The categories of pipe most widely using in the oil and gas industry is steel pipe. Steel material is chosen among other material due to various factors: Excellent mechanical properties, high durability and weld-ability with lower total cost of ownership [3]. In addition to the need for straight pipes, bent pipes are also required to accommodate the distribution of oil and gas, adjusted to the existing land surface topography conditions. Bend is an important fitting widely used in natural gas pipeline. Its primary role is to alter the pipeline direction in accordance with the design requirements [4].

The type of mother pipe for the manufacturing of induction bend is one of important factors that affect the bend quality. API 5L is a standard issued by the American Petroleum Institute for pipes used in transporting gas, water, and oil within the oil and gas industry [3]. API 5L pipes are classified into various grades and are further specified by several key parameters, including the manufacturing method (seamless pipes, which are produced without welds, and welded pipes, which include a longitudinal or spiral weld), testing requirements, dimensional tolerances, and available pipe sizes. Therefore, the selection of the appropriate pipe grade depends on operating conditions, pressure, and the type of media to be transported. The API 5L standard for steel pipes includes different specification levels that refer to varying quality and technical requirements, known as Product Specification Levels (PSL), namely PSL 1 and PSL 2. The differences between PSL 1 and PSL 2 relate to quality control, material properties, and testing requirements. PSL 1 is often used in applications that do not require high resistance to extreme conditions or high risk. In contrast to PSL 2 are often used in applications that require high resistance to extreme conditions or high risk.

One method for producing material is by using hot induction bending. Hot Induction Bending is a pipe bending process that utilizes localized heating through electromagnetic. This process is highly effective for forming pipes with small bending radius and is widely used in various industrial applications due to its precisely controlled and efficient technique [5]. Induction bending is often referred to as hot bending, incremental bending, or high-frequency bending [6]. Given the wide range of pipe diameters—from the smallest to the largest—the hot induction bending method not only reduces production costs but also enhances bending quality and contributes to lowering the overall production cost of the finished pipes [7]. Due to its process, hot induction bending will modify the microstructures within the affected area, resulting of changes on material properties, especially mechanical. During bending, the pipe experiences localized deformations, which can lead to the formation of residual stresses that may affect its ability to withstand internal pressures and external forces [8].

Improper bending, however, occurs when bending parameters such as radius, temperature, or feed rate are inadequately controlled, leading to excessive deformation or structural compromise. Such conditions can result in actual defects, including surface or internal cracks, laminar separations, laminations, buckling, and wrinkling, which it can critically affect the integrity and performance of the pipe in service [9], [10]. Therefore, a heat treatment process is required after hot induction bending to restore material properties after bending process which can induce residual stress and strain hardening. Heat treatment can be defined as a process that transforms the properties of a metal by changing its microstructure through controlled heating and cooling rates, with or without changing the material chemical composition [11]. The purpose of this process is to achieve the desired mechanical properties of the metal. Changes in the characteristics of the metal resulting from heat treatment may affect either the entire section or only a portion of the material. This study will concentrate on the quenching (hardening) and tempering heat-treatment processes.

The manufacturing process of bent API 5L seamless pipe involves a series of carefully controlled steps to ensure mechanical integrity and dimensional accuracy. It starts with material receipt, followed by incoming inspection to verify conformance to specifications. The pipe undergoes surface cleaning through blasting on the outside and inside diameters, then proceeds with visual inspection and ultrasonic thickness testing to detect surface or internal anomalies. After passing these checks, a bending process is performed, followed by an internal dimensional check. To recover and improve the mechanical properties affected by bending, post-bending heat treatments such as quenching and tempering are applied. The outer surface is then re-blasted to remove any oxidation or scale formed during the heat treatment. Non-destructive testing (NDT) is performed to ensure there are no hidden defects, after which both ends of the pipe are machined for uniformity. A final dimensional and visual inspection is performed before the pipe is officially released for use, ensuring the pipe meets all required quality and safety standards.

Theoretically, quenching has the potential to significantly alter the microstructure. For Carbon Steel, quenching process can. Transform stable phase (pearlite) into meta-stable phase (martensite) by lattice distortion, not diffusion. Quenching can be performed using various liquid or air media and other materials that can rapidly absorb heat. Commonly used media include freshwater, saltwater, forced air convection, oil, and special polymers. While water is adequate for achieving maximum hardness, there is a small risk of distortion and minor cracking [12].

When a steel specimen has been fully hardened, it exhibits very high hardness but also becomes brittle and contains significant residual stress. In this state, the steel is unstable and tends to experience shrinkage or distortion over time, particularly when exposed to external forces. These forces can further increase internal stresses and worsen the instability. To relieve this internal stress, a moderate heat treatment process called stress relieving is applied. If the process is also intended to lower hardness and improve toughness, it is referred to as tempering or sometimes drawing [13],[14]. After quenching the steel from its austenitizing temperature, the rapid cooling transforms the austenite into martensite, resulting in increased hardness., the material is reheated to a temperature below the critical range. It is then held at this temperature for a specific duration before being allowed to cool slowly in still air. The tempering temperature is chosen based on the steel's chemical composition and the desired compromise between hardness and toughness [15],[16].

Hot induction bending process followed by quenching and tempering is intended to maintain the same or higher material properties, especially mechanical, compared to its straight pipe condition. The thermal treatment procedure, which encompasses the stages of quenching and tempering, is conducted to ascertain its efficacy in accomplishing the desired objective, specifically, to evaluate whether it leads to an enhancement or reduction in the mechanical strength of the material [17].

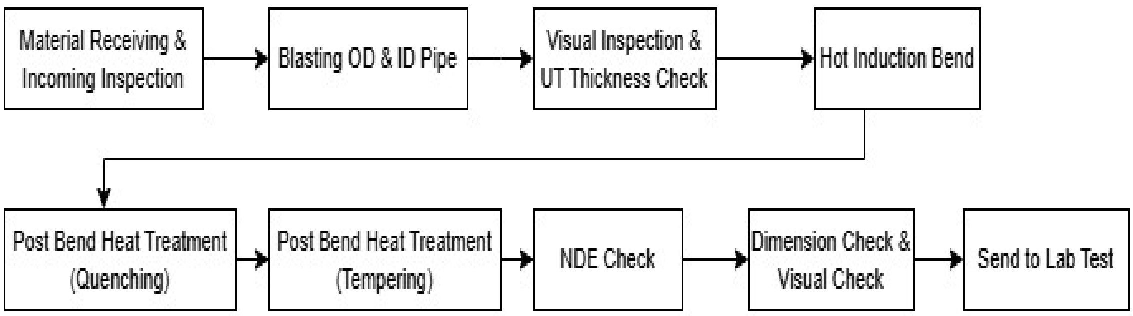

Figure 1: The process of Hot Induction Bending Manufacturing

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This study presents a novel approach by applying hot induction bending followed by quenching and tempering specifically to API 5L X60 carbon steel pipes, aiming to evaluate comprehensive changes in mechanical properties. Unlike previous studies, this research directly examines the effectiveness of the heat treatment in maintaining or enhancing the material strength after bending, while also analyzing the hardness distribution across critical points along the bend area.

2.0 METHOD

2.1 Hot Induction Bending Process

The material used is a seamless carbon steel pipe conforming to API 5L Grade X60QS PSL2, with OD16 inches (406.40 mm) and a wall thickness of 9.53 mm. The chemical composition and mechanical properties of the base metal are presented in Table 1 and Table 2, respectively.

Figure 2 shows the hot induction bending process applied. The pipe end is pushed while a rotating arm guides the pipe during the bending according to the desired bend radius, the other end remaining fixed. During the bending, the pipe passes through a high frequency coil that creates a concentrated magnetic field and induces an electric potential in the pipe creating a current flow. The pipe's resistance to the flow causes fast and localized heating that is followed by a water quenching, applied at the external pipe surface.

Table 1: Chemical composition of base metal API 5L grade X60QS PSL2

Chemical Composition	(%)	Chemical Composition	(%)
Carbon (C)	0.09	Titanium (Ti)	0.01
Silicon (Si)	0.3	Cooper (Cu)	0.02
Mangan (Mn)	1.23	Nickel (Ni)	0.01
Phosphorus (P)	0.009	Chromium (Cr)	0.12
Sulfur (S)	0.01	Molybdenum (Mo)	0.03
Vanadium (V)	0.05	Boron (B)	0.0005
Niobium (Nb)	0.01	Carbon Equivalent $_{(PCM)}$	0.18

Table 2: Mechanical properties of base metal API 5L Gr.60QS PSL2

Mechanical Properties	
Tensile Strength [MPa]	580
Yield Strength [MPa]	455
Elongation [%]	27
Average Hardness (HV10)	218
Average Impact Test/ Absorb Energy (J)	267

Table 3: Hot induction bending process parameter

Item	Setting	Tolerance	Unit
Bending speed	20	± 2.5	mm/min
Bending outside surface temperature (extrados and intrados)	900	± 25	°C
Start bending at temperature	850	None	°C
Coolant medium	Water	None	-
Coolant temperature	15	± 15	°C
Coolant flow pressure/ flow rate	50	± 10%	LPM
Induction Frequency	950	± 20%	Hz

The induction bending temperature was maintained at 900 (±25) ºC and 2032 mm bend radius with 90º bend angle was produced. Figure 3 shows the material API 5L Gr. X60QS PSL2 bending process. Note that, just after the passage of the heating coils, the pipe is water cooled externally. The parameters listed in Table 3 are those used in the hot induction bending process.

2.2 Post Bend Heat Treatment

After the hot induction bending process, the material undergoes post–bend heat treatment using batch furnace. The quenching (or hardening) process involves heating the material to a temperature of 955 °C with a holding time of 30 minutes and a heating rate of 95 °C/h. The pipe is then transferred within a maximum of 60 seconds into quench tank with agitated water at 15 °C to increase the hardness and strength of the material. The quenching process follows the parameters listed in Table 4.

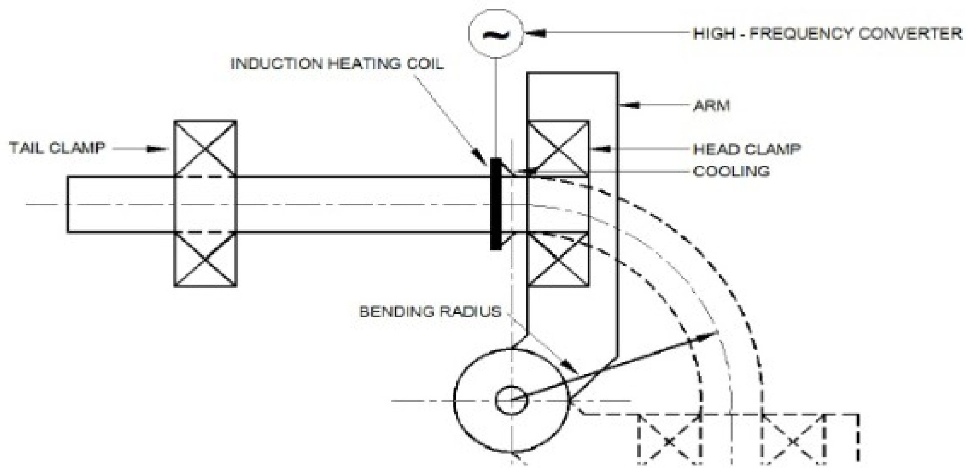


Figure 2: Schematic of hot induction bending process

Figure 3: Hot induction bending process

Table 4: Quenching parameter

Applicable code / specification	ISO 15590-1
Governing thickness	9.53mmWT
Min. thickness after bending	8.58mmWT
Governing material grade	API 5L X60 PSL2
Location of TC attachment	OD at Intrados
Holding temperature	955 ± 15 °C (Aim 955 °C)
Holding time	30 - 45 minutes (Aim 30 minutes)
Heating rate	95 °C/h
Cooling method	Quench Bath Agitated
Quench media temp. before quenching	15 °C
Max. transfer time	60 second

Table 5: Tempering parameter

Applicable code / specification	ISO 15590-1
Governing thickness	9.53mmWT
Min. thickness after bending	8.58mmWT
Governing material grade	API 5L X60 PSL2
Location of TC attachment	OD at Intrados
Holding temperature	655 ± 15 °C (Aim 655 °C)
Holding time	50 - 65 minutes (Aim 50 minutes)
Heating rate	153 °C/h
Cooling method	Air Cooling

After the quenching process, the material is reintroduced into the furnace for tempering. The tempering process involves reheating the pipe that has been quenched to a temperature of 655 °C with a holding time of 50 minutes and a heating rate of 153 °C/h. The material is then slowly cooled in ambient air to improve its ductility. 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. Once the tempering process is completed, the hot induction bending and heat treatment processes are finished.

2.3 Equipment Testing

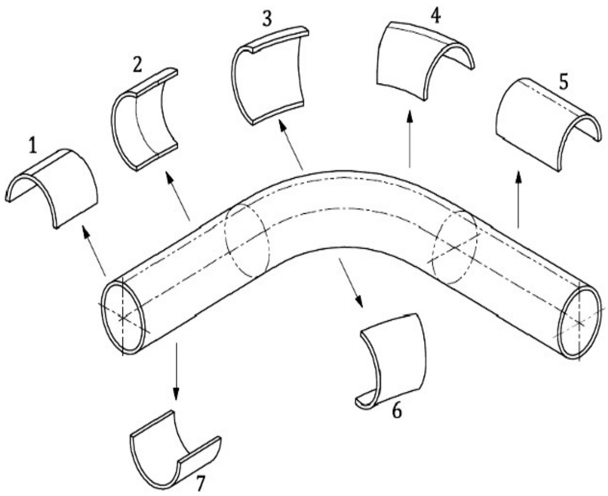
Several equipment specifications according to the testing methods used in the mechanical testing are listed in Table 6.

Table 6: Equipment testing list and specification

No	Method	Specification
1	Chemical Analysis	Model: Metal Analyzer OES 3460 SN. 4481 One test piece shall be taken from one of tangent pipe and specified in API 5L Table J.1.
2	Tensile Test	Universal Testing Machine 1000KN SN. 010967, Machine Type: WAW-1000E RUBICON Tensile samples in accordance with ASTM A370.
3	Hardness Test	Vickers Hardness Tester (Mitutoyo-HV) SN. 880405 The hardness test was conducted in accordance with the ASTM E92 standard.
4	Impact Test	Avery Denison Charpy Impact Machine Model: 6705 CA, SN. 00019. Striker Radius: 8 mm The Charpy impact test was conducted at a temperature of 0 °C, following the ASTM E23:2018 procedure. The specimens used were sized 7.5 x 10 x 55 mm.
5	Metallography Test	Microscope Manufacture: Olympus, Model: BX51, SN. 8L21102 polish and etched with No.74a (1 -5ml HNO_3) add (100ml Methanol).

3.0 RESULT

Once the hot induction bending, quenching, and tempering processes are finished, the material will be cut into test coupons for subsequent mechanical testing. The testing locations are determined based on the areas indicated in Figure 4.



Remarks:

1. Tangent
2. STZ Intrados
3. Bend Extrados
4. FTZ Extrados
5. FTZ Intrados
6. Bend Intrados
7. STZ Extrados

Figure 4: Location of the test coupon

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3.1 Chemical Composition Post Bend Heat Treatment

The chemical composition comparison between bare straight pipes with manufactured bend pipe are shown in Table 7.This shows that there is a change in the Carbon (C) content from 0.09% to 0.038%, suggesting the occurrence of decarburization and a slight reduction in surface strength. The Chromium (Cr) content decreased from 0.12% to 0.096%, Based on the corrosion test results, both straight and bend pipe corrosion performance are the same. However, the Nickel (Ni), Manganese (Mn), and Silicon (Si) contents remained stable, with no significant changes observed.

Table 7: Chemical composition of base metal API 5L Gr. X60 (X414) PSL2 after process

Chemical Composition	(%)	Chemical Composition	(%)
Carbon (C)	0.038	Titanium (Ti)	0.002
Silica (Si)	0.28	Cuprum (Cu)	0.020
Mangan (Mn)	1.21	Nickel (Ni)	0.012
Phosphorus (P)	0.011	Chromium (Cr)	0.096
Sulfur (S)	0.003	Molybdenum (Mo)	0.025
Vanadium (V)	0.052	Boron (B)	0.0003
Niobium (Nb)	0.0001	Carbon $Equivalent_{(PCM)}$	0.12

3.2. Tensile Test Result

Tensile test specimens were extracted on 7 locations within the bend pipe. Based on bare pipe straight pipe condition, the values for Ultimate Tensile Strength (UTS) were 580 N/mm², Yield Strength (YS) was 455 N/mm², and Elongation was 27%. After hot induction bend manufacturing processes, the average values for UTS are 606 N/mm², YS is 495 N/mm², and elongation is 23%. (STZ: Start Transition Zone; FTZ: Finish Transition Zone)

Table 8: Tensile test result

Location	UTS (N/mm²)	YS (N/mm²)	Elongation (%)
Bare straight pipe	580	455	27
Tangent	604	495	23
Start Transition Zone (STZ) Extrados	610	505	23
Start Transition Zone (STZ) Intrados	608	489	24
Finish Transition Zone (FTZ) Extrados	608	502	23
Finish Transition Zone (FTZ) Intrados	602	489	23
Extrados	607	503	21
Intrados	603	483	26

3.3. Hardness Test Result

The average hardness value obtained on bare pipe straight pipe processes was 206 HV. The hardness testing was conducted on 7 samples, as shown in Figure 4, with the locations identified in Figure 5 for each sample. Line 1 represents the outer surface of the specimen, Line 2 represents the middle surface, and Line 3 represents the innermost surface of the specimen.

The hardness measurements across various regions of the pipe provide critical insights into the material response following hot induction bending and subsequent quenching and tempering treatments. The average hardness values ranged from 187 HV to 213 HV, indicating significant variation influenced by the location and extent of thermal-mechanical exposure. The tangent zone, which is largely unaffected by bending, exhibited the lowest average hardness values 187–204 HV, representing the base material or minimally affected structure. In contrast, the start transformation zone and finish transformation zone demonstrated moderately higher hardness values, particularly in the FTZ where values reached up to 205 HV. Notably, the extrados of Line 3 recorded the highest average hardness 213 HV and the greatest standard deviation (SD) 9.29 HV, suggesting intense deformation and micro structural in-homogeneity likely due to non-uniform cooling or localized strain. Conversely, the lowest SD 1.89 HV was observed in extrados line 2, indicating a more uniform transformation. The results from the hardness test can be seen in Table 9.

3.4. Charpy Impact Test Result

The charpy impact test results offer valuable insights into the material's toughness behavior following hot induction bending and subsequent quenching and tempering. The bare straight pipe, serving as a reference, demonstrated a high and consistent average impact energy of 2667 J, confirming the inherent ductility and toughness of the base API 5L X60 material. Similarly, the tangent zone, which experienced minimal deformation, retained a comparable toughness level 264 J with only slight variability (SD = 8.06 J), indicating that the mechanical integrity of the material remained largely unaffected in the unbent region. In contrast, zones located on the extrados side, particularly STZ Extrados and FTZ Extrados, exhibited a notable reduction in average impact energy 232 J and 247 J, respectively accompanied by elevated standard deviations 17.15 J and 15.69 J, respectively. These values suggest a significant degradation in toughness and greater micro structural heterogeneity, most likely due to excessive strain, high thermal gradients, or localized phase transformation during quenching.

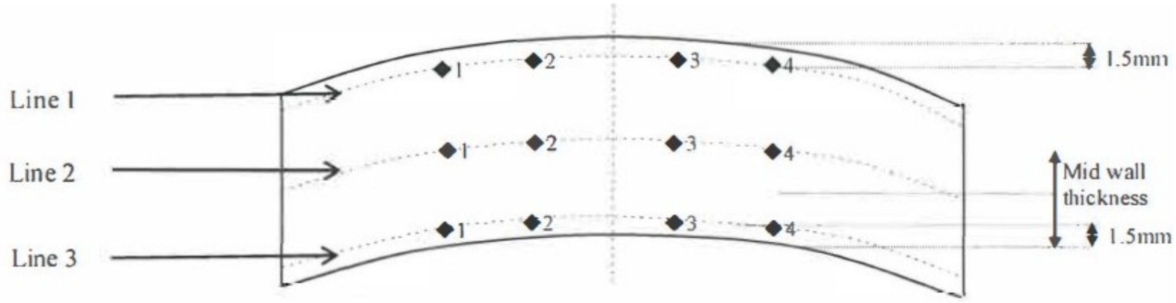

Figure5: Hardness Vickers test location

Table 9: Vickers hardness result

Location	Position						
	Line No.	1 (HV10)	2 (HV10)	3 (HV10)	4 (HV10)	Average (HV10)	St. Dev.
Tangent	Line 1	204	203	201	206	204	2.06
	Line 2	175	190	193	191	187	7.17
	Line 3	192	192	195	186	191	3.77
STZ Extrados	Line 1	203	196	203	199	200	3.40
	Line 2	195	202	200	200	199	2.99
	Line 3	200	210	213	201	206	6.48
STZ Intrados	Line 1	201	192	190	202	196	5.24
	Line 2	187	190	201	190	192	5.38
	Line 3	196	196	205	208	201	5.07
FTZ Extrados	Line 1	189	192	193	202	194	5.60
	Line 2	203	198	194	200	199	3.77
	Line 3	196	205	210	208	205	6.18
FTZ Intrados	Line 1	194	189	202	194	195	5.38
	Line 2	195	205	199	198	199	4.19
	Line 3	209	210	204	203	207	3.51
Extrados	Line 1	195	190	197	200	196	4.20
	Line 2	202	202	206	203	203	1.89
	Line 3	208	204	225	216	213	9.29
Intrados	Line 1	199	195	193	198	196	2.75
	Line 2	200	194	206	195	199	5.50
	Line 3	200	204	201	198	201	2.50

The extrados region recorded the lowest toughness 230 J and the highest standard deviation 34.62 J among all specimens, highlighting it as the most vulnerable zone in terms of resistance to impact and crack propagation. This pronounced scatter in data strongly implies the presence of residual stresses, non-uniform martensitic transformation, or possible initiation of micro-cracks during bending and cooling. On the other hand, the Intrados regions consistently maintained high impact energy values 272 J in the Intrados and 267 J in the STZ Intrados with minimal variability (SD = 1.73 J and 2.83 J, respectively), reflecting a more uniform and ductile microstructure. The charpy impact test results on bend pipe are shown in Table 10.

Table 10: Charpy impact test result

Location	Specimen				
	1 (J)	2 (J)	3 (J)	Average (J)	Standard Deviation
Bare Straight Pipe	262	261	277	267	7.32
Tangent	257	275	259	264	8.06
STZ Extrados	253	231	211	232	17.15
STZ Intrados	271	265	265	267	2.83
FTZ Extrados	264	250	226	247	15.69
FTZ Intrados	268	259	261	263	4.73
Extrados	212	272	205	230	34.62
Intrados	273	273	270	272	1.73

3.4. Micro Examination

The test specimens were taken from several areas, namely the STZ Extrados, as shown in Figures 6 and 7. After the bending and heat treatment processes at this location, the ASTM grain size number was found to be 9.5, which indicates that the material possesses a fine and uniformly distributed grain structure [4]. At the FTZ Extrados location, as shown in Figures 8 and 9, after the bending and heat treatment processes, the ASTM grain size number was found to be 9.5, which indicates that the material possesses a fine and uniformly distributed grain structure.

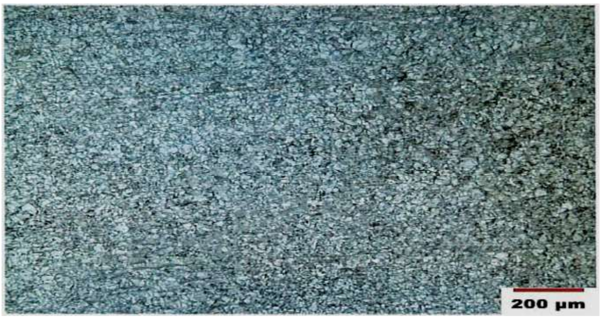

Figure 6: STZ Extrados Magnification of 100x

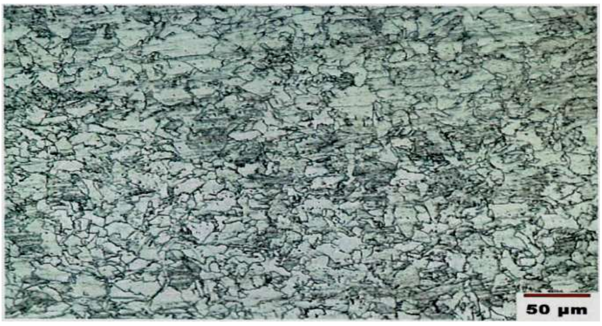

Figure 7: STZ Extrados Magnification of 400x

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Figure 8: FTZ Extrados Magnification of 100x

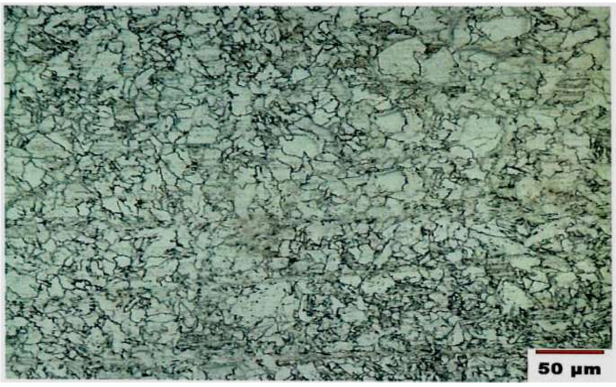

Figure 9: FTZ Extrados Magnification of 400x

4.0 DISCUSSION

4.1 Strengthening Mechanisms

Based on the test results, the values of UTS and YS increased after bending, quenching, and tempering processes, with UTS rising from 580N/mm^2 to 606N/mm^2, and YS increasing from 455 N/mm^2 to 495 N/mm^2. However, elongation and hardness decreased, with elongation dropping from 27% to 23%, and hardness decreasing from 206 J to 199 J. The hardness value of the bare straight pipe may be slightly higher due to the presence of residual stresses and a harder microstructure resulting from the initial manufacturing process. After undergoing bending and subsequent heat treatment (quenching and tempering), the microstructure becomes more stable and tougher; however, the hardness may slightly decrease due to tempering, which reduces martensitic hardness and relieves internal stresses. The Carbon content decreased from 0.09% to 0.038%, and Chromium content decreased from 0.12% to 0.096%.

The observed increase in mechanical strength, as indicated by the rise in UTS from 580 N/mm^2 to 606 N/mm^2 and YS from 455 N/mm^2 to 495 N/mm^2, can be attributed to a combination of metallurgical strengthening mechanisms activated during the bending, quenching, and tempering processes. One of the primary contributors to this improvement is grain refinement. According to the Hall–Petch relationship, finer grains increase the resistance to dislocation motion, thereby enhancing strength. The micro structural analysis revealed an ASTM grain size number of 9.5, which indicates that the material possesses a fine and uniformly distributed grain structure, enhancing both the strength and the consistency of mechanical performance.

In addition to grain refinement, the mechanical deformation from bending likely increased the dislocation density within the material. This form of strain hardening raises yield strength by making it more difficult for dislocations to move. The quenching process may have transformed the microstructure into a harder phase such as martensite or bainite, depending on the alloy composition and cooling rate [4]. Martensitic transformation in particular is known to contribute significantly to strength due to its supersaturated carbon structure and high internal stress. However, the tempering stage that follows quenching leads to a partial reduction in internal stresses and dislocation density, stabilizing the structure while slightly compromising hardness. In addition, there is a micro structural transformation during tempering where martensite can be transformed into tempered martensite, thereby increasing materials ductility and toughness properties.

Interestingly, the decrease in elongation from 27% to 23% and the hardness from 206 HV to 199 HV though not significantly reduced, suggests that while the material's strength may have increased, its ductility and resistance to indentation slightly declined. This can be partially explained by the chemical changes observed during processing. The reduction in carbon content from 0.09% to 0.038%, and chromium content from 0.12% to 0.096%, likely results from decarburization and chromium carbide precipitation at elevated temperatures. Both carbon and chromium play key roles in solid-solution and precipitation strengthening; their depletion leads to a softer matrix and potentially reduced corrosion resistance and ductility due to carbide formation at grain boundaries.

4.2 Microstructure

The microstructure analysis revealed an ASTM grain size number of 9.5, which indicates that the material possesses a fine and uniformly distributed grain structure. According to ASTM E112 standards, a higher grain size number corresponds to smaller grain diameters, which enhance mechanical properties through grain boundary strengthening. Finer grains increase the number of grain boundaries, which act as barriers to dislocation movement, thereby improving both the yield strength and ultimate tensile strength of the material.

5.0 CONCLUSION

This study demonstrated that hot induction bending followed by quenching and tempering effectively enhances the mechanical performance of API 5L X60 seamless carbon steel pipes. The treatment led to a 4.4% increase in ultimate tensile strength and an 8.7% increase in yield strength, with a controlled 8.7% reduction in hardness, remaining within the acceptable range (175–225 HV). Impact toughness was well preserved in intrados regions, exhibiting high energy absorption (up to 272 J, SD 1.73 J), while extrados regions showed lower toughness and greater variability, indicating localized micro structural heterogeneity. Overall, the process achieved a desirable balance of strength, toughness, and ductility, confirming its suitability for demanding pipeline applications.

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