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Mechanical Properties Evaluation of X52 Pipeline Welds Using Advanced Techniques

Saleh A. Alawame
Mechanical Engineering Department, Faculty of Engineering
University of Benghazi
Benghazi, Libya
saleh.gadlla@uob.edu.ly

Abdelbaset R H Midawi
MME Engineering Department,
University of Waterloo & Faculty of Engineering University of Benghazi
Amidawi@uwaterloo.ca

Gamal Hashem
Mechanical Engineering Department, Faculty of Engineering
University of Benghazi
Benghazi, Libya gamal.hashem@uob.edu.ly

Farag I. Haider
Mechanical Engineering Department Faculty of Engineering
University of Benghazi
Benghazi, Libya farag.haider@uob.edu.ly

***Abstract*—In this study, the indentation approach was used to evaluate the mechanical properties of the gas metal arc weld (GMAW) joint of X52 line pipe steel. The GMAW process is the preferred welding process to join oil and gas pipelines due to its high productivity and ability to control the welding parameters. The indentation is considered a non-destructive technique and accurately estimates the mechanical properties. In this study, two different indenters geometries were applied; a flat face indenter was used to determine the yield strength of each zone across the weld, while a spherical tip indenter was used to obtain the true stress and plastic strain data using the multi-cyclic indentation approach. The stress-strain curves of each zone were constructed by fitting the data to the power law hardening model. The indentation data were then compared to the experimental stress-strain data obtained by conventional tensile testing. The digital image correlation (DIC) method was used to map the strain along the gauge length, and local stress strain data was extracted using the iso-stress assumption. The DIC tensile data results showed good agreement in terms of yield strength with a maximum error of 9%. The result suggests that instrumented indentation can be a suitable method to measure the local yield strengths of specific regions in a welded joint during the welding process development.**

Keywords*— *Pipeline weld, Hardness, HAZ, Cyclic indentation approach, nearly flat-tip indenter, Digital Image Correlation (DIC)

I. Introduction

Hardness tests have been a standard method to characterize engineering materials in industrial and research applications for a long time since they are easy, reliable, non-destructive, and affordable approaches [1]. Hardness testing has been used widely in recent years to determine the mechanical properties of engineering materials. A hard indenter typically composed of diamond or tungsten carbide is employed in the hardness test. The hardness number can be computed by measuring the indentation area left by the indenter form and knowing the applied load. Vickers, Brinell, and Rockwell hardness tests are three common ways to represent hardness value [1]. In 1950 Tabor suggested an approach to estimate the mechanical properties of engineering materials using a hardness test [1], [2]. However, his method depends on empirical equations and a fitting approach. Also, it cannot be generalized for all engineering materials since the Tabor method assumes that the material behavior is perfectly plastic, which is not the case for modern materials [3]. Instrumented indentation testing, also known as depth-sensing indentation instrument, is a test that uses calculations from an indenter load displacement curve to record the force during the indentation process as a function of penetration depth (displacement). Mechanical properties such as hardness, Young's modulus, and yield strength can be obtained. Accordingly, many experimental, theoretical, and numerical studies have been motivated to explore the instrumented indentation method to determine engineering materials' mechanical properties. The indentation process can be performed using different indenters shapes such as a pyramid, spherical, or flat indenters. Cyclic indentation approach, also known as Automated Ball Indentation (ABI), which Haggag suggested in 1983 [4]; this method is based on applying progressive loading with partial unloading. Data from each cycle is gathered and analyzed to calculate the true stress and plastic strain value for a specific material.

The depth of the indentation increased with the load. Haggag *et al.* claim [5] that, in contrast to the latter uniaxial tensile test, the material volume beneath the indenter expands as the indentation depth increases and is forced to flow under multi-axial compression. The effect of material pile-up or sink-in on the actual contact area was also investigated in the literature. There is no one yield point since work hardening and yield strength develop simultaneously. The work hardening causes each cycle's yield strength to rise, and the spherical tipped indenters were carefully examined to provide stress-strain curves for different materials based on the cyclic indentation technique. Leroux [6] reported that a new method uses a flat indenter shape to determine yield strength. In this technique. Hu *et al.* [7] used a computational model to estimate the yield strength of different engineering alloys and support the experimental results using a flat tip indenter. Nevertheless, and to the authors' best knowledge, this method has not yet been used to describe the yield strength of the different zones of a welded joint; in this work, an experimental investigation to determine the mechanical properties of X52 pipeline welds using a dual indentation approach. Targeted zones included the base metal (BM), heat-affected zone (HAZ), and weld metal zones (WM). This experimental work was performed to evaluate the yield strength and hardness, which is considered a non-destructive technique and could be used in the field to check the strength of welded structures after being in the service for a long period or as a quality control technique.

II. Material and Experimental Work

The API 5L X52 with (minimum yield strength 52 kpsi or 350 MPa) line pipe steel material was used in this study, X52 line pipe material was welded using the GMAW process to evaluate the weld joint mechanical properties. Table I shows the nominal chemical composition of the base material:

TABLE I. The nominal chemical composition of the base material.

Element Wt. %	C	Mn	Si	S	P	V+Nb+Ti
API 5L X52	0.28	1.4	0.45	0.015	0.025	0.15 max

A. Welding

The GMAW process was used to join the material, three passes were needed to fill the gap (V-shape groove) using Miller XMT 400 constant voltage power supply. The contact tip working distance was kept constant at 20 mm to maintain the same arc length, while the current and voltage was measured from the welding plate. The shielding gas used in this study was 99.99% Argon with a 1.2 mm commercial welding consumable according to EN440: G3Si1 SG2 [8]. The wire feed speed (WFS), travel speed (TS), voltage (V), and current (I) are presented in Table II below. The plates were cut out of the API-X52 line pipe section, which has a diameter of 320 mm, and were welded using the constant voltage (CV) mode with a narrow groove on the machine, and prepare the curve sections of API-X52 steel pipe with dimensions of (150 mm 70 mm x 10 mm). These samples were cut from the welded pipe to characterize the weld joint in different zones.

TABLE II. The values of welding process parameters.

Pass	Root	Fill	Cap
Voltage V	24.2	23.2	21.2
Current A	310	289	255
Travel Speed cm/min	36.5	32.09	25.8
Wire Feed Speed m/min	6	5	4
Nominal Heat Input KJ/cm	12.33	12.54	12.57
Shielding gas	100 % Argon		

For metallographic examinations, samples were prepared according to ASTM E3-11 standard guide [8]. The cross sectioned specimens were first ground using silica grit paper then polished on a cloth pad with alumina paste and water lubricated up to 1µm. The samples were then etched with 5% Nital solution, rinsed and cleaned with alcohol.

B. Indentation testing

Instrumented indentation techniques were used in this study to estimate the mechanical properties of the local zones across the weld joint. Figure I show the indentation machine used to indent the material and determine the mechanical properties such as yield strength, hardness, and modulus of elasticity using different indenter geometries. The indenters used in this study are shown in SEM micrograph Figure II These indenters were chosen based on the previous work reported in the literature.

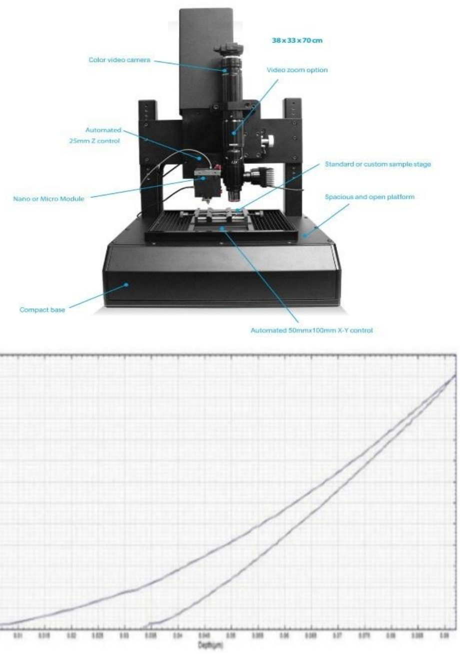

Figure I. Instrumented indentation machine layout and load _displacement.

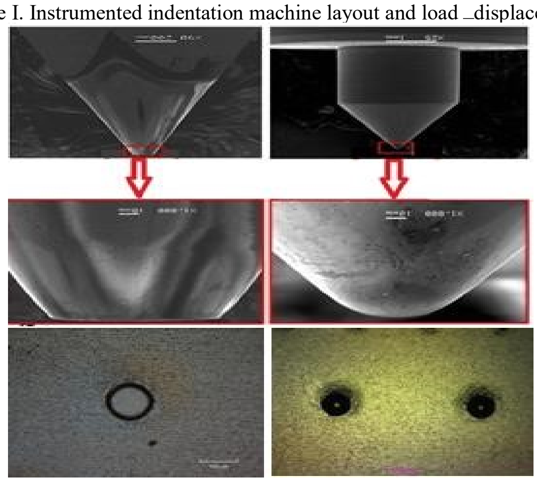

Figure II. Secondary electron SEM images show a) The flat-tip indenter and b) a spherical tip indenter.

The cyclic spherical indentation technique was used in this study to determine the flow properties of the X52 line pipe weldment across the joint, including WM, HAZ, and BM. The nearly flat-tip indenter with a 100 µm diameter was used to extract the yield strength. With this approach, the load-displacement curves can be used to calculate the yield strength directly.

C. Experimental tensile test and DIC setting

Cross weld sub-size tensile test coupons were cut from the weld joint following an ASTM E8/E8M [9] to get a stress-strain curve and compare the results of the indentation technique with the mechanical properties, such as yield strength, tensile strength, and strain hardening exponent. The locations of the tensile samples that were removed using a water jet cutter are shown in Figure III.

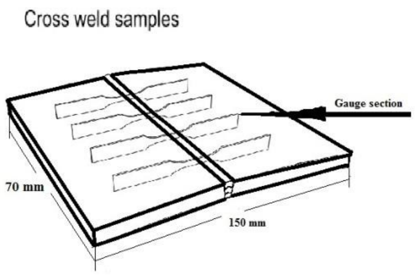

Figure III. A schematic diagram shows the tensile coupons cross weld samples in transverse directions and all weld samples in longitudinal directions.

Due to the differences in constituents of the microstructure of BM, WM, and HAZ the deformation was measured using the Digital Image Correlation (DIC) method [10], [11]. A correlation function compares the displacements of the deformed and un-deformed states. A correlation method is utilized to determine the digital image correlation DIC; It results in a visual representation of the displacement magnitudes compared to the original state in different directions. It may be used to calculate the whole strain map across the entire region after the points on the surface have been displaced. DIC was utilized to analyze the deformation on the specimen surface and extract the strain in each zone throughout the weld. The DIC setup is schematically represented in Figure IV. The default values of the subset size and step size were used in the DIC analysis which was 7 and 21 respectively.

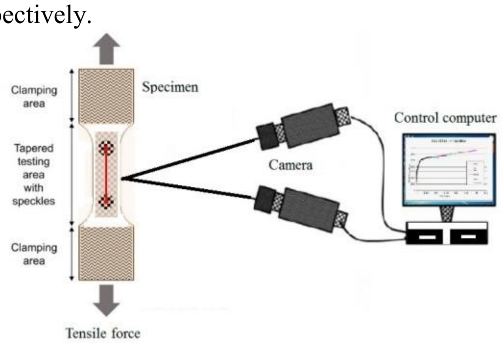

Figure IV. The schematic shows the digital image correlation (DIC) apparatus used to map the strain.

III. RESULTS AND DISCUSSION

A. Flat-tip indentation

The parameters used in the flat-tip indentation test are shown in Table III below.

Table III. The parameters used to perform the nearly flat-tip indentation test.

Material	Indenter	Load N	Loading / unloading rate N/min		Contact load *µN*	Speed *µm/min*
X52-Steel	Nearly flattip	20	40	40	10	3

The experimental load-displacement curves for different zones for API-X52 are shown in Figure V, indicating the nearly flat-tip indentation (S-shape).

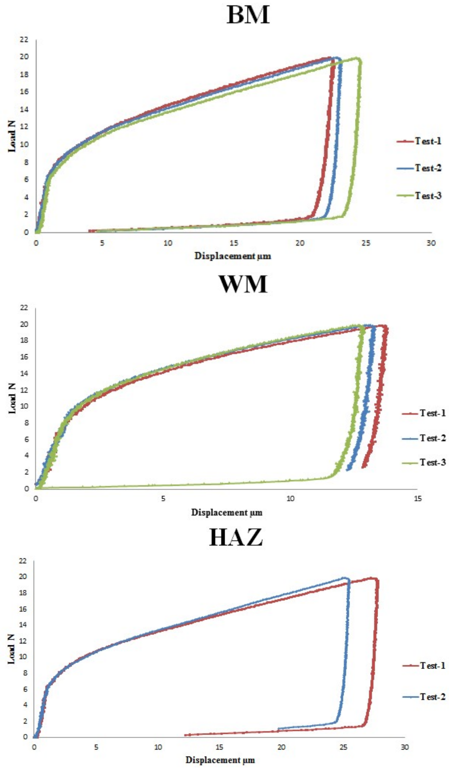

Figure V. Load-Displacement curves for the testes of a nearly flat tip for X52.

After several tests on each zone, BM, HAZ, and WM, the average curve is shown in Figure VI; using the load and displacement curve, the yield strength value was calculated using the slip line formula suggested by Midawi *et al.* [13] as in the following equation:

$$\sigma_y = \frac{1}{3.28}\frac{F_s}{\pi\, a^2} \qquad (1)$$

Which was suggested by Shield [11], [13], using the slip-line method from the average curves, and The maximum yield strength was measured in the weld metal at 313 MPa, while the BM and HAZ were 310 and 238 MPa, respectively.

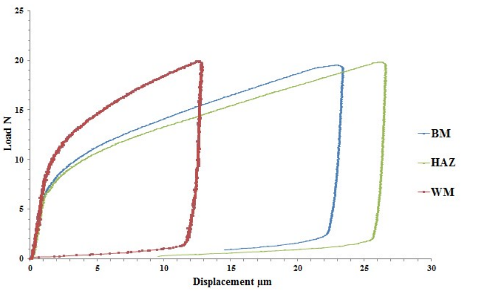

Figure VI. Average indentation load-displacement curves for the X52 weld for the base metal, the heat-affected zone, and the weld metal.

B. Spherical indentation

The instrumented indentation machine, which contains a microscope to determine the zone of indentation on a microscopic level, was used with a spherical indenter (diameter of 400 µm) to estimate the flow properties of each zone. The parameters utilized to perform the spherical indentation tests are listed in Table IV below.

TABLE IV. THE PARAMETERS USED TO PERFORM THE SPHERICAL INDENTATION TEST.

Parameters	Value
Load (N)	20
Loading/Unloading rate (N/min)	60
Contact Load (µN)	10
Approaching Speed (µm/min)	10
No of Cycles	9
Percent of load release %	50

The graphs of experimental tests of the load Displacement curve, as shown in Figure VII, show the cyclic spherical indentation to different zones for API-X52. So, because of the test's small scale, it may produce negative effects such as the local surface defect on the curves (sinking in or pileup effect). Therefore, the test was applied repeatedly on the same surface at different places to avoid that. Where can be observed that the material has different behavior as a load is progressively applied to reach a maximum load, then start unloading using the same loading rate.

After conducting several tests on each zone BM, HAZ, and WM through the welding joint using a spherical indenter. Figure VII shows the average load-displacement curves.

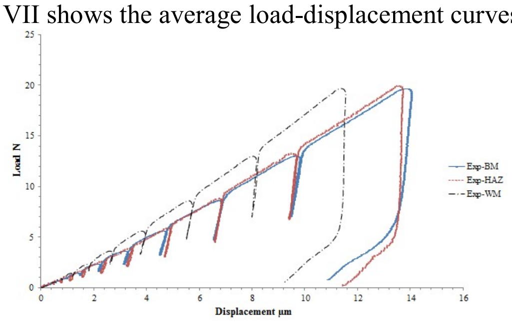

Figure VII. The average experimental load-displacement curves for BM, WM and HAZ across the weld joint.

To extract the plastic stress-strain data for each zone, WM, HAZ, and BM equations 2 and 3 were used to calculate the stress-strain curve for each zone. Table V below shows the list of calculated stress-strain values for each zone.

$$\sigma_t = \frac{4\,P}{\pi\, d_p^2\, \delta} \quad (2)$$

$$\varepsilon_p = 0.2\,\frac{d_p}{D} \quad (3)$$

TABLE V. THE CALCULATED PLASTIC STRESS-STRAIN VALUES FOR EACH ZONE.

BM-average data		HAZ-Average		WM-Average	
Plastic Strain	True Stress (MPa)	Plastic Strain	True Stress (MPa)	Plastic Strain	True Stress (MPa)
0.0227	303	0.0236	305.1	0.0252	378.1
0.0292	295.7	0.0282	327.8	0.0299	437.4
0.0345	331	0.0345	350	0.0369	446.1
0.0412	361.5	0.0407	368.5	0.0450	463.8
0.0498	381.7	0.0494	391.7	0.0546	483.8
0.0599	391.6	0.0598	404.1	0.0654	506.5
0.0717	422	0.0714	429.6		

The true stress plastic strain data for each zone WM, HAZ, and BM may be produced using the data in Table V, as shown in Figure VIII. The extracted data were then fitted to a hardening model (power law hardening model). The results showed that the weld metal has mechanical properties with higher stress values than BM and HAZ.

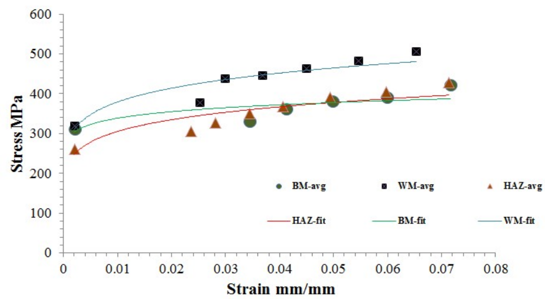

Figure VIII. The fitted stress-strain curves and the points of the indentation stress-strain.

The concept of coupled indentation test is introduced by combining nearly flat-tip (yield strength) and cyclic spherical indentation (plastic part of the curve) to get the elasto-plastic properties for engineering materials. The coupled indentation test will be used to estimate the stress strain properties of a welded structure, as shown in Figure IX.

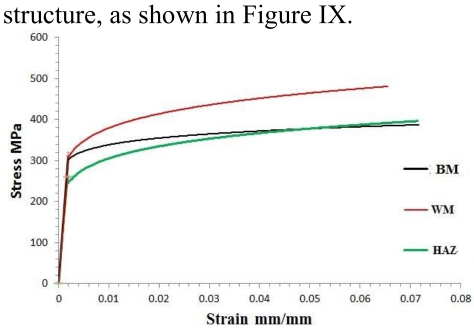

Figure IX. Stress-Strain curve for coupled indentation techniques.

C. DIC Tensile test

The weld metal exhibited improved strength with an average of 319 MPa compared to 313 MPa from indentation; in contrast, it was found that the base metal yield strength produced by DIC was 311 MPa as compared to 310 MPa from indentation. According to the DIC data, the minimum yield strength was obtained in the HAZ, as suggested by the indentation method.

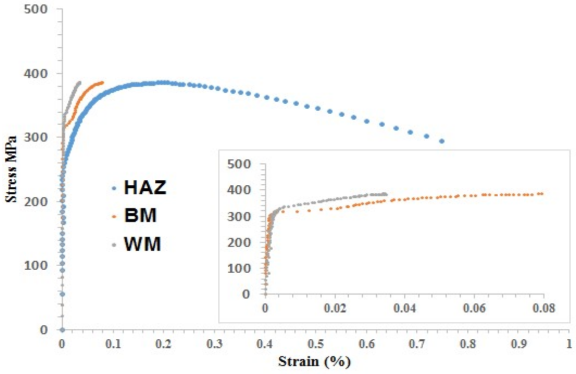

Figure X. Engineering stress-strain curve and DIC local strain mapping for API-X52.

As determined by DIC measurements, the yield strength for the HAZ was about 260 MPa for the specimen and 238 MPa from indentation, as shown in Figure X. The maximum error for this measurement compared to the indentation method is 0.896 %. It was noticed that the average strain of the WM was 3.5 % of Figure XI, the DIC local strain map. While the HAZ has a maximum strain of 36.7%, then BM at almost 9%, the lowest strain was accumulated in the WM at 3.5%. This also confirms that the yield strength, YS, of the HAZ should be lower than BM, and the maximum yield strength was measured in WM. In addition, the indentation depth leads to the same conclusion: HAZ has the maximum depth than the BM, and the lower indentation depth was measured in WM.

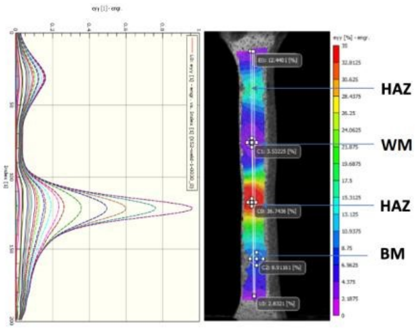

Figure XI. Strain distribution in different zones.

Table VI shows the yield stress values obtained from the DIC tensile test compared to the experimental indentation test using the slip-line theory method. Thus, the results showed that the difference is acceptable.

TABLE VI. A COMPARISON OF THE YIELD STRENGTHS FOR THE DIFFERENT ZONES AS DETERMINED BY THE TENSILE TEST AND THE INDENTATION TECHNIQUE (DIC).

Specimen X52	DIC Tensile Test (MPa)	Experimental Indentation Test (MPa)	Error (%)
BM	311	310	0.32
WM	319	313	1.92
HAZ	260	238	9.24

D. The welding macro and microstructure

The cross-section of the weld joint is shown in Figure XV. The microstructures of each zone across the weld zone were investigated using an optical microscope. Two phases appear in the microstructure of X52 base material, as shown in Figure XIII: intergranular ferrite (IGF) and grain boundary ferrite (GBF). This steel microstructure is comparable to that of ferrite and pearlite (Dark phase pearlite) surrounded by ferrite (light phase).

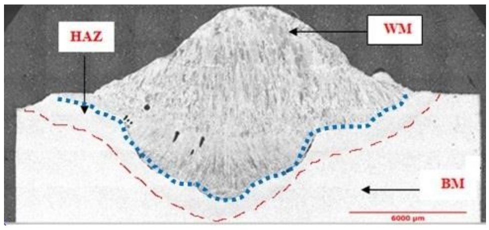

Figure XII. Macrograph for the bead on plate weld show different zones

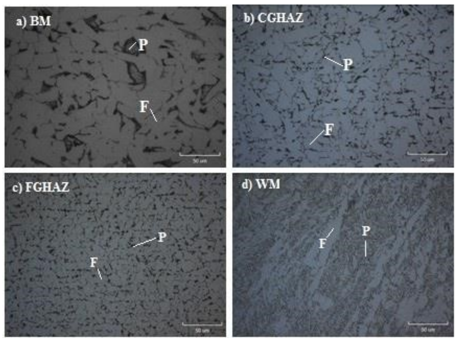

Figure XIII. The micrographs show the microstructure for a) base metal, BM. b) coarse grain heat-affected zone, CGHAZ. c) Fine-grain heat affected zone, FGHAZ and d) Weld metal, WM.

A pyramidal indenter was used to determine each region's Vickers joint hardness of the welded microstructure to correlate the hardness data with the microstructure. The hardness measurements from the cap pass toward the base material near the root pass are shown in Figure XIV. The maximum hardness measured in the weld metal WM is 200 $HV_{0.5}$. The HAZ 160 was $HV_{0.5}$ due to the thermal cycle of welding, where there was no significant change in the HAZ, and noted a sudden decrease from the WM to HAZ, as the reason was the mismatch because the hardness was very high and then decreased.

The hardness profile through weld is shown in Figure XIV. The maximum hardness measured in weld metal WM is 200 $HV_{0.5}$. Looking at the micrograph of the weld metal in Figure XV, the microstructure is a mixture of two phases of granular ferrite (IGF) and grain ferrite (GBF). The thermal welding cycle led to the transformation of austenite into upper grains and grain boundary ferrite, as shown in Figure XV for WM. As the distance from the melting line increases, the hardness decreases until it reaches the value of BM hardness, which is 160 $HV_{0.5}$. The BM of the X52 steel pipeline is a mixture of ferrite and cementite (Fe_3C), as shown in Figure XV. This microstructure is dominated by a ferritic structure, which is the main reason for the base metal's lower hardness and strength values.

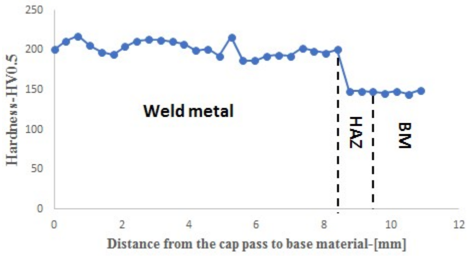

Figure XIV. Hardness profile from the cap pass to the base material near the root pass.

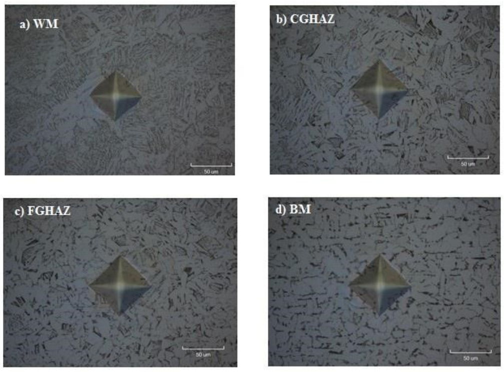

Figure XV. Weld metal WM, heat-affected zone HAZ, and base material BM micrographs.

E. CONCLUSION

In this study the mechanical properties of X52 line pipe weldment were investigated using instrumented indentation approach and DIC tensile testing, the following points can draw out from the study:

1- The instrumented indentation technique, using the spherical indenter cyclic indentation approach and nearly flat-tip indenter, was successful in determining the flow curves across the weld joint (WM, HAZ, and BM).
2- The weld metal microstructure was dominated by intergranular ferrite microstructure (IGF) and the HAZ shows a grain boundary ferrite and bainitic microstructure, which improved the mechanical performance compared to the base metal microstructure BM (ferrite and cementite Fe_3C).
3- The yield strength obtained from the indentation method was compared with the DIC tensile testing results and the maximum error was bounded by 9%.
4- A good correlation between strength measurements and hardness results. This agreement can be used to develop a statistical model that correlate hardness with yield strength for different pipeline materials.

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