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ABSTRACT

The mechanical properties of high-density polyethylene pipe welded (and above all its resistance to brittle fracture) are a decisive factor in estimating the service life of two welded pipes use for the distribution of drinking water. The purpose of this research is to exploring the variation of the mechanical properties of welded and unwelded pipes made from HDPE under static loading. For that, our experiments tests are necessary to study the damage of the weld bead part and the resistance of the different zones of the bead welding through the point hardness short D measurement method. The experimental tests of welded and unwelded specimens were studies the mechanical properties and determine the deformations $\Delta\varepsilon t$ (r, θ). Tensile strength and break load of Ring specimen's tests were measured according to ASTM D2290. There have been performed under tensile and static loadings on welded and unwelded specimens. The structure and the mechanical properties of a butt weld in a high-density polyethylene pipe were examined and contrasted to unwelded HDPE pipe. In this work, Nol Ring tests will be carried out on HDPE welded and unwelded specimens with different crosshead speeds (10-50 mm/min).

Keywords: Density Polyethylene (HDPE) pipes; characteristics; damage; fragility; crack propagation.

1 INTRODUCTION

The mechanical properties of high-density polyethylene (HDPE) pipes materials with good effectiveness are often obtained using a Nol Ring test (Fig.4), cracking test (Fig.5) and hardness Shore D Test (Fig.8). Several works have been done on polymeric materials and especially the high-density polyethylene (HDPE). T. M. A. A. EL-Bagory and al. [1] studied the effect of strain rate and specimen configuration on the mechanical behavior of welded and unwelded pipes made from HDPE, the unwelded specimens indicate higher mechanical properties than welded specimen at all crosshead speeds.

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T. M. A. A. El-Bagory and al. [2] studied the effect of specimen geometry on the predicted mechanical behavior of polyethylene pipe material under different loading conditions. In the literature, various authors like Devilliers. C and al [3] used the Nol-Ring tests to characterization of aged HDPE pipes from drinking water distribution. An original method is proposed here to characterize the ageing effect of the pipe mechanical behavior. Inspired from the ASTM D 2290-04 standard [4], Nol Ring tests have been performed under tensile and creep loadings on smooth rings [5]. In this study, the Nol Ring Test, serving as an example of a hydrostatic pressure test capable of reproducing circumferential stresses such as those encountered under service conditions. The split disks were used to determine the hoop tensile strength. These tests have lower cost than hydrostatical tests and are very efficient in determine the performance of tubular structures which are usually used under internal pressure developing high hoop [6]. Proposed Ring shape of samples may be applied in axial tension test, internal pressure test, etc., as well as their combinations.

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Hoop tensile strength of Nol Ring specimens can be determined with help of split disk test [7]. Some recent studies [8], [9] have used split disk fixture to evaluate tubular structures, it was concluded that the ring tensile test is an adequate method to rapidly and inexpensively evaluate the mechanical properties and efficient to determine the performance of these structures which are usually utilized under internal pressure developing high hoop stresses. Joselin. R and al [10] say that using Nol Ring test the tensile strength can be obtained. In this case, a section cut from a thin cylinder by a plane that contains the axis is known as longitudinal section, were, the tensile stresses act in a direction tangential to the circumference. Sanchez et al. [11] and Yu and al. [12] did show that Nol Ring test subject the test specimen to a hoop stress, which, between the restricted areas, is quite similar to the stress induced by internal pressure.

2 EXPERIMENTAL WORK

The main aim of this study is studied the damage and material HDPE with two cases unwelded and welded specimens of HDPE by means of butt fusion procedure to know the physical quantities and the understanding of the effect of the deformation velocity on the mechanical behavior of the weld joint (bead) of a high-density polyethylene (HDPE) pipe welded by conditions proposed by us such as the melting temperature and the pressure force as defined in Table 1. We performed two trials for each case and for the same stretching rates (Ve). The temperature of all the tests equals the ambient temperature (Ta = 23°); the ratio of the nominal dimensions SDR of the tubes (diameter and thickness) is constant. This constant is determined in the following form:

$$SDR = \frac{D_e}{e} \tag{1}$$

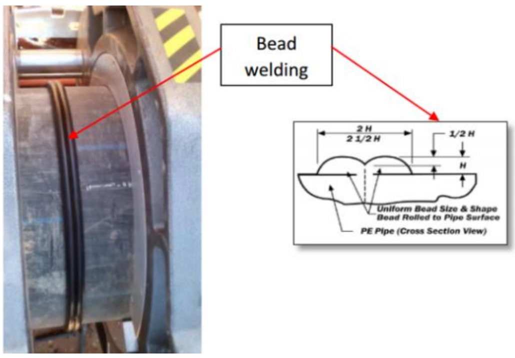

Figure 1 Formation of bead welding according to ASTM standard F2620-01[13].

In this research, we used the butt-welding technic; the butt-welding process is a technique for assembling thermo-plastics by melting the ends of two tubular elements by means of a heating plate called a mirror. This process consists of melting the material at the surface to be welded (Figure 1).

Table I - Butt-welding parameters.

Article		PN		Thickness (mm)		Tempera ture (c°)
De= 125 mm		PN 16		11.4 * 12.5		212
step 1		step 2		step 3		SDR
Bar	‖	Bar	Sec	Bar	Min	
66	10	1.5	120	10	900	10

2.1 MATERIAL

The material used in this study is high-density polyethylene (HDPE). It is a semi-crystalline thermo-plastic widely used to produce pipes used for water and gas transmission and pipelines [14].
In the literature, the microscopic structure high-density polyethylene (HDPE) has examined by various studies. The study material was manufactured in one time as granules; Imported by the company STPM CHIALI located in Sidi Bel Abbes (ALGERIA) [15]. It was then extruded to make tubes of different diameters. The extrusion conditions are determined to ensure the most homogeneous cooling.
The mechanisms of deformation of this last material can be very different according to the breaking strength, the temperature and the conditions of stress. The technical, physical and chemical specifications of the material studied are summarized in Table 2.

Table II - Characteristics of HDPE studied.

Density	930 Kg/m3
Molecular weight Mw	310000 (g/mole)
Crystallinity rate Xc	74 %
Fusion Temperature T_f	203 °C
Fluidity index	0,2 – 1; 4g/10 (min)
Black Carbon	2- 2,5 %

2.2 NOL RING TESTS

The Nol Ring test is a test that identifies damaged tubes and classifies the degradation of HDPE. The works of R. Joselin and al [10] confirmed the effectiveness and adequacy of this technique, and have demonstrated that the use of the Nol Ring test can reproduce constraints close to reality in the field. This type of test requires two half-disks and two fixing pins. In literature. M. Tarek and al [2] are among the first to use this type of test to study the effect of specimen geometry on the mechanical properties of HDPE pipes.
M. A. Bouchelarm and al [17] have realized a device Nol ring test according to standard ASTM D2290 [4] and have made experimental tests to study failures HDPE.
Burkin. V.E.[18] notes a small structural spherulitic formation in the weld plane. As a result, the microstructures of the different areas of the weld bead are widely different. (Figure 2).
Our study will therefore be based on the same works mentioned above but on HDPE tubes welded by the technique of fusion welding to study the rupture of the weld bead part.

ISSN 1590-8844
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For this, we use different half-discs (D0 = 100 mm and 92mm), since our work is done on welded tubes which requires half-discs of diameter (D0 = 92 mm).
To characterize the mechanical behavior of material studied tests performed on specimens in the form of rings. The specimens in the form of rings were cut directly from the fusion welded HDPE tubes. Thickness t = 12.5 mm, internal diameter D0 = 100 mm, width W = 12 mm. Particular attention has been paid to ensure that the specimens are prepared identically. The specimen rings are used according to standard ASTM 2290 [4]. The main dimensions are given in (Figure 4). Nol Ring tests on specimens in the form of rings were carried out with an INSTRAN 8516 servo-hydraulic fatigue machine with a capacity of 100 KN (Figure 6). [16]. For the two cases studied, we carried out two tests for the same stretching rates Ve = 10 and 50 mm / min to ensure the reproducibility of the measurements. The temperature of all the tests is equal to ambient Ta = 23 ° C. To study the effect of stretching rates on the behavior of HDPE.

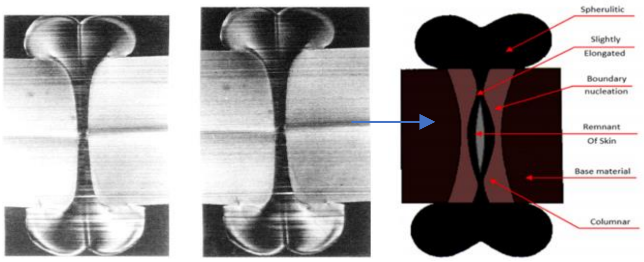

Figure 2 Illustration of the weld bead part.

We use two split discs respectively (D = 102 mm and D = 100mm) (Figure 3), since our work is done on welded tubes which requires split discs of diameter (D = 92 mm). The experimental input data are summarized in Table 3. The uniaxial tensile tests UT were carried out on ring welded and unwelded specimens (Figure 4).

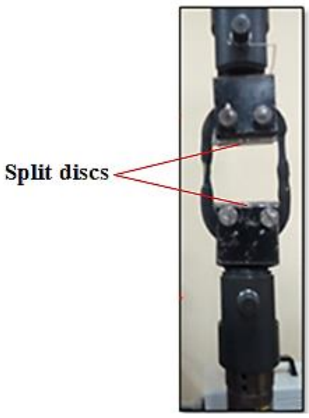

Figure 3 Nol ring test on full specimens (illustration of split discs).

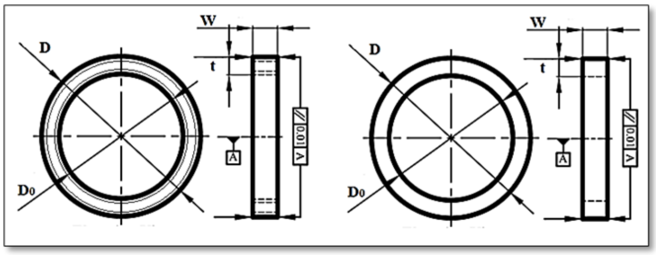

Figure 4 Specimens of Nol Ring test: unwelded and welded.

Table III - Experimental input data of the uniaxial tensile tests

Parameters	Unwelded specimens	Welded specimens
Exterior diameter D (mm)	100	102
Internal Diameter D_0 (mm)	92	90
Width W (mm)	12	12
Thickness t (mm)	8	12

2.3 CRACKING TEST

The cracking tests on the ring specimens mentioned above were carried out in the laboratory of materials and reactive systems (LMSR) of the University of Sidi Bel Abbes on an INSTRON 8516 machine.
Two different ring geometries, with the inner major radius a different from 90 to 92 mm and two rings for each geometry, in total 4 rings, were tested subject to restrained shrinkage under the drying environment of 23°C.
The wall thickness was 8 and 12 mm for the steel and concrete rings, respectively.
In experiments, four strain gauges were attached, each at one equidistant midheight, on the inner surface of the steel ring. The cracking tests on the ring specimens mentioned above were carried out at the laboratory of materials and reactive systems (LMSR) of the University of Sidi Bel Abbes on an INSTRON 8516 machine.
This machine makes it possible to impose uniaxial forces to measure the displacement jaws of the machine and the load applied to the internal surface of the welded and unwelded pipes at a maximum frequency of 50 Hz.
To perform the cracking test, we created a longitudinal crack on the internal surface of the bead of the weld to ensure crack propagation through the thickness of the tube.
We chose, in our case, a double crack whose ratio a / t = 0.04.

2.3.1 Procedure

The local strain at the head of a crack increases near a crack. At the end of the latter, two zones appear.

- A plastic zone (ZA);
- An unelastic zone (ZB) which surrounds the first one of larger dimensions.

In order to get as close as possible to the end of the crack in the plasticized area, to detect local plastic deformations, we used a technique which is based on the shore D hardness measurement at the end of the crack.
This measurement allows giving a relation of the type:

$$\Delta sh = f(r, \theta) \tag{2}$$

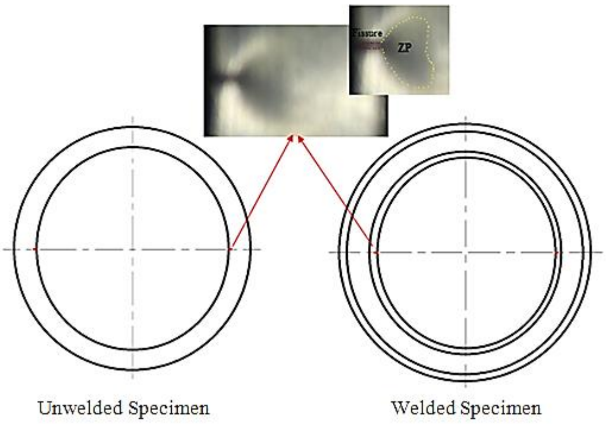

Figure 5 The case studied for the measurement of hardness at the head of a crack.

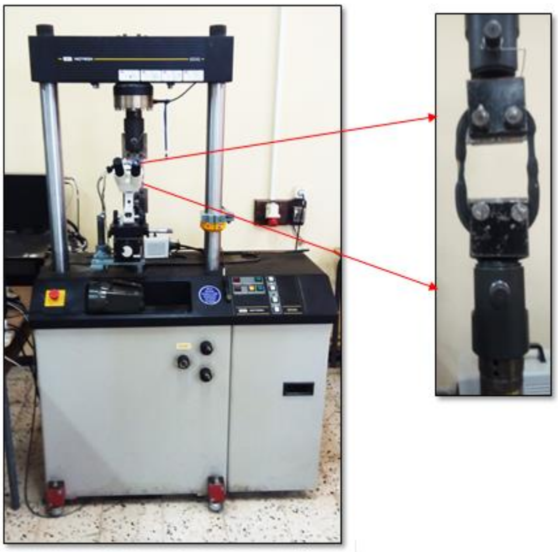

Figure 6 Overview of the test system [7].

2.4 HARDNESS SHORE D TESTS

The hardness shore D measurement gives us a first evaluation of the mechanical properties after butt-welding. By this technique, we have tested the hardness shore D at the head of a crack with a / t = 0.8 mm in plasticity zone (ZP) (Figure 5). The hardness shore D tests were carried out according to ASTM standard D2240-00 [19] by a shore D durometer set on a milling machine. The indenter is moved into the test material under a preliminary distance from 2.5 mm; this distance is set according to the ASTM standard D2240-00 (Fig. 7). We first consider the different directions defined by the values of (θ) indicated in Table 4.

Generally, the technique of measuring hardness shore D at the head of a crack is used to determine the deformations Δεt (r, θ). It is used to take the existence of the anelastic zone (ZB) which surrounds the plastic zone (ZA) at the end of crack, local deformation at the head of a crack increases near a crack. For each of these directions, we measured the hardness Shore D for radius values (r) decreasing from 2 to 0.5 mm from the tip of the crack, with variable steps (Figure 9). In order to get as close as possible to the end of the crack in the plasticized zone, to detect local plastic deformations, we used a technique that is based on measuring the hardness shore D at the end of the crack. The hardness shore D tests specimens are prepared by cutting several slabs from the pipe in the longitudinal direction (Figure 8).

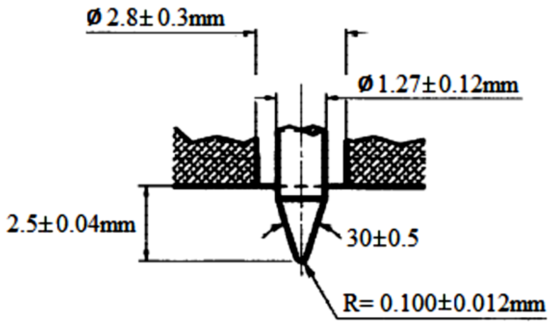

Figure 7 Hardness measurement according to ASTM D2240.

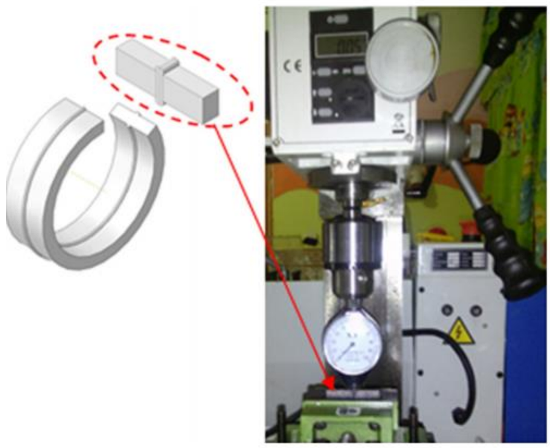

Figure 8 Hardness shore D specimen and fixing the hardness measuring hardness tester.

2.4.1 Procedure

For the shore D hardness measurement at the head of a crack, we use the punctual method. This method is based on the technique for measuring the hardness which makes it possible to determine the deformations Δεt (r, θ). She is employed to take the existence of the anelastic zone (ZB) which surrounds the plastic zone (ZA) at the end of crack, by using the law of the type Ludwick presented by:

$$\Delta W = K\left(\frac{\Delta\varepsilon_1}{2}\right)^n \tag{3}$$

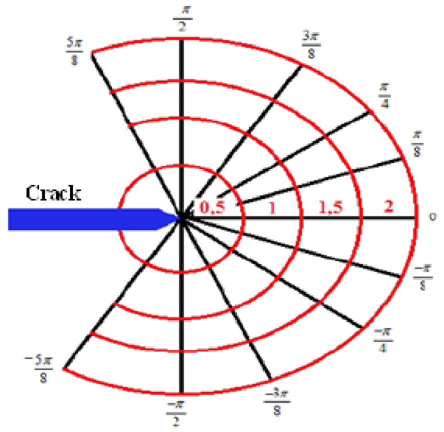

Figure 9 Presentation of the directions and measurement steps of the shore D hardness at the end of crack.

Table IV - Values (θ) considered.

θ (rad)	5π/8	π/2	3π/4	π/4	π/8	0	-π/8	-π/4	-3π/8	-π/2	-5π/8

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1. NOL RING TESTS

The Load - Displacement curves obtained by the Nol Ring method make it possible to characterize the degradation of a high density polyethylene pipe welded by butt fusion. Effectively, all the samples of the welded pipes tested conform to the standard requirement whereas no difference in modulus of elasticity was found in a non-degraded pipe. The results of Nol Ring test for unwelded pipes for different strain rates are illustrated in (Figures 10 and 11). We observe that there is a significant decrease in the elongation at break as a function of the level of degradation of the pipe tested for a strain rate Ve = 50 mm / min.

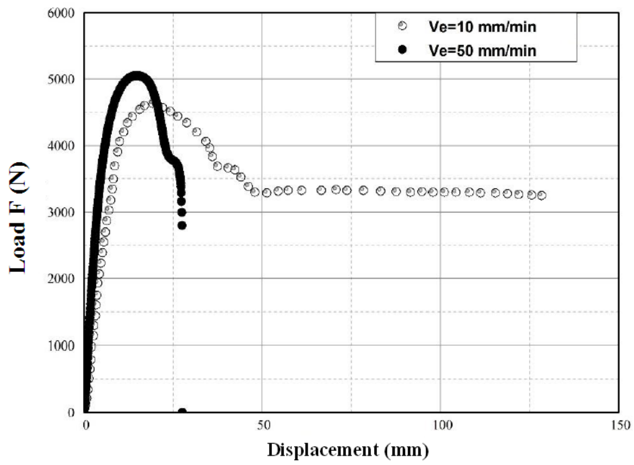

Figure 10 Load-displacement response of the Nol Ring tests of base material (BM).

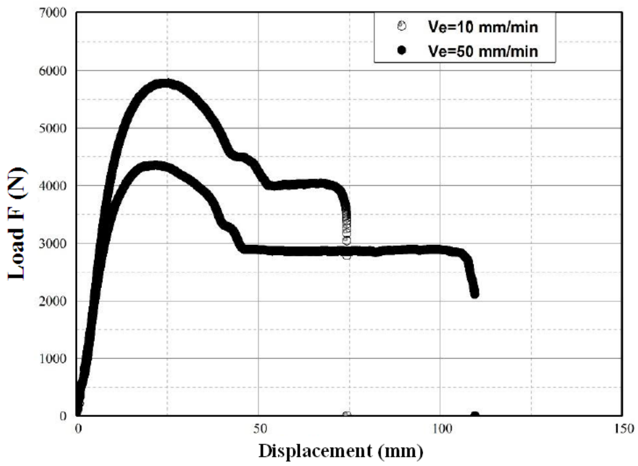

Figure 11 Load-displacement response of the Nol Ring tests of welded specimens.

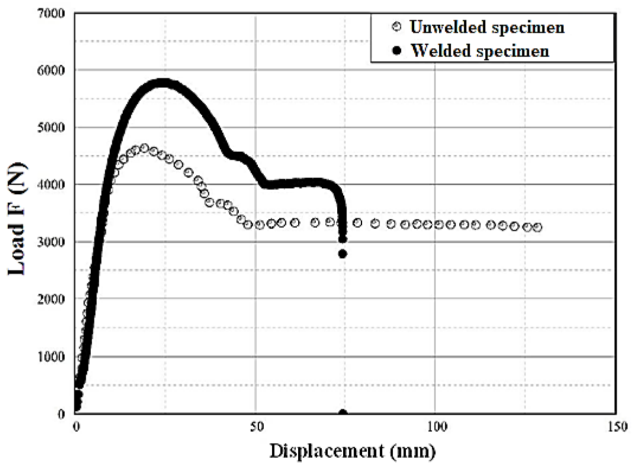

Figure 12 Load-displacement response of the Nol Ring tests, Ve = 10 mm / min.

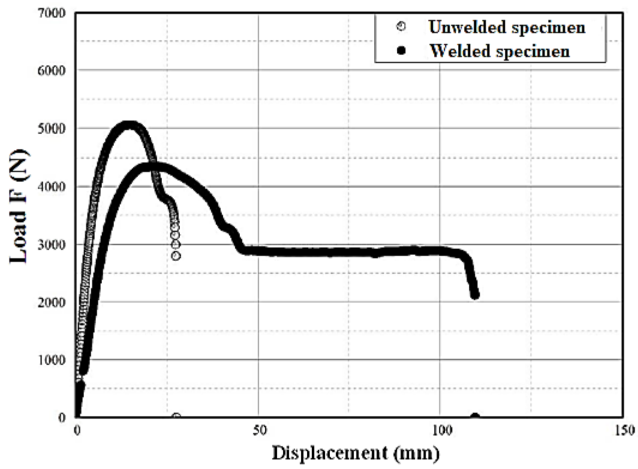

Figure 13 Load-displacement response of the Nol Ring tests, Ve=50mm/min.

The fragility revealed by a low value of the elongation at break corresponds to the corrugation of the inner wall of the tube between the zones.
So, with the test developed on the ring of Nol Ring, it is possible to establish a continuous range of degradation levels depending on the appearance of the sample.
These results show that the Ring test is more relevant for characterizing pipe damage than the standard tensile test.
The curves shown in (Figure 11) show the characterization of the damage of welded tubes at the melted part (weld bead). The results obtained show on the one hand the true mechanical properties of the weld bead and secondly the influence of the strain rate on the damage behavior on the weld bead.
From the curves shown in (Figures 10 and 11), we can describe the steps of the deformation. The first stage represents the reversible elastic deformation due to the amorphous phase of the material whose modulus of elasticity is lower than that of the crystalline phase.
The curve, initially linear, shows some non-linearity just before the top. Then, in the second stage the necking begins on both sides of the ring which corresponds to a heterogeneous deformation of the material which starts on a defect in the specimen, the necking is formed until stabilization.
And finally, the deformation becomes homogeneous thanks to a structural hardening linked to the orientation of the macromolecular chains in the direction of the stretch followed by a transition to a fibrillar structure.
The results of the Nol Ring test of healthy tubes were compared to those fused end-to-end (Figures 12 and 13). The results show that in the case of tests on a sound pipe (base material BM) the value of the elastic limit increases with the decrease of the deformation speed, whereas the deformation at break decreases with the decrease of the speed deformation.
We notice a significant drop in the deformation at break for the speed of 50 mm/min, concerning the case of welded pipe tests, the value of the yield strength and the Young's modulus increases with the decrease of the strain rate. In that case, the breaking strain decreases significantly with increasing solicitation speed. The influence of the speed of the deformation for the two cases compared shows that the cause of the rupture does not come from a defect but rather from the rise of the temperature within the material.

3.2. CRACKING TEST

Figures 14 and 15 respectively show the Load-Displacement responses of the cracked and uncracked specimens for two different strain rates (Ve), the results obtained show that the mechanical properties of the weld bead obtained for the two cases cracked and uncracked are different across the two deformation rates. From these results, we notice that the general shape of the Load-Displacement curve (Figure 14) shows a fragile behavior in the presence of a crack (a/t = 0.04) compared to that without crack which takes a ductile behavior.

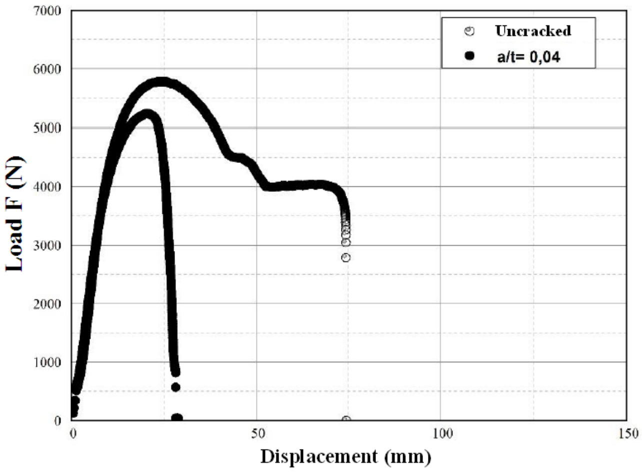

Figure 14 Load-displacement response of the Nol Ring tests, Ve=10mm/min.

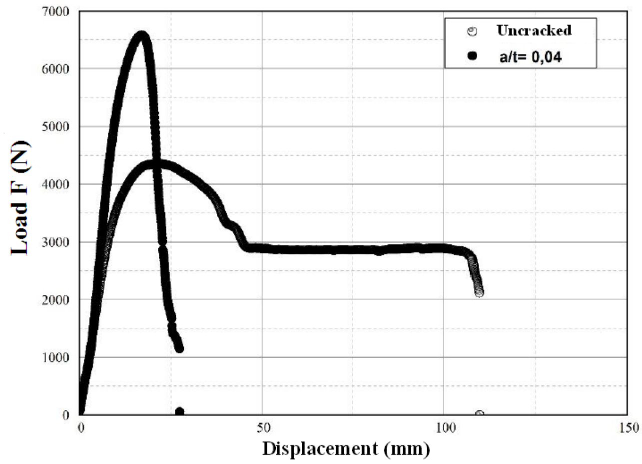

Figure 15 Load-displacement response of the Nol Ring tests, Ve=50mm/min.

Figures 16 and 17 shows a comparison between the base material BM and the welded part (bead) under different strain rates (Ve = 10 and 50 mm / min).
The results show that there is a remarkable decrease in the yield point for a low strain rate Ve= 10 mm/min and the base material (BM) is ductile. The crack, propagating in the longitudinal direction of the pipe thickness of the pipe shows that the rupture of the pipes occurs in the same direction. We notice that for the critical crack (a/t = 0.04) created in the sound test pipe depends on the rate of deformation. In fact, the increase in the rate of deformation increases the flow stress and leads to the breaking of the structure. To evaluate the influence of the critical crack on the strain rate (Ve) and the behavior of the weld bead, we carried out a series of cracking tests with two different deformation rates namely 10 mm / min and 50 mm / min on cracked rings and we determined the elastic limit and the deformation at break for each deformation rate (Ve).
Figure 15 illustrates the results obtained from the load-displacement curves.

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We observe that there is a significant influence of the biasing speed, for load levels lower than 3.5 KN. The tests are relatively non-reproducible. The behavior is relatively linear up to 3 KN for a strain rate Ve = 10mm / min and 5 KN for a strain rate Ve = 50mm / min. We reach two stress peaks at about 17% and 21% deformation since the final rupture of the test pieces will start at 28.12% and 27%, respectively. The rate of deformation (Ve) influences the behavior of the weld bead essentially on two aspects:

- The threshold of the viscoelastic-viscoplastic part;
- The limit at break decreases with the increase of the rate of deformation.

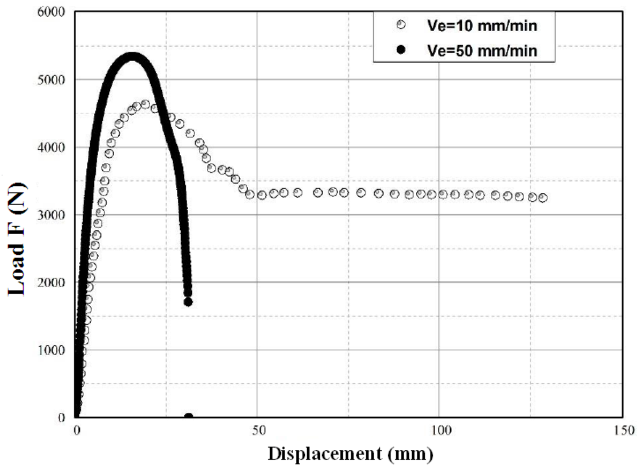

Figure 16 Load-displacement response of the Nol Ring tests, of base material (BM) (with a/t = 0.04).

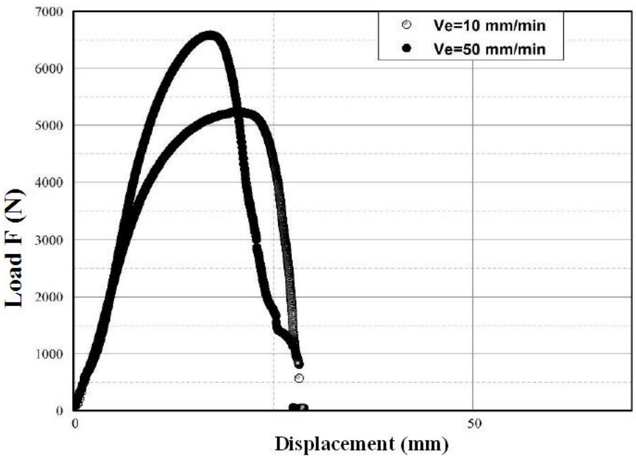

Figure 17 Load-displacement response of the Nol Ring tests, perded specimens (with a/t = 0.04)

3.3. HARDNESS SHORE D TESTS

The Δsh calculations for the two cases studied are given in tables 5 and 6. It is found that the resistance of the base material at the level of the plasticized zone is lower than the plastic zone of the weld bead.

This means that the contact plane melting fields and the temperature at the interface are independent of the time at the beginning of the heating phase.

Figure 18 shows the microscopic images of the plastic zone (PZ). According to these results, tells us that there are small, noticeable variations of the plastic zone.

In this zone, the mechanical properties are determined in pixels in a very small range. These results have a very reliable ductility at the ambient temperature used.

The mechanical properties of the weld bead strongly depend on the parameters of the microstructure.

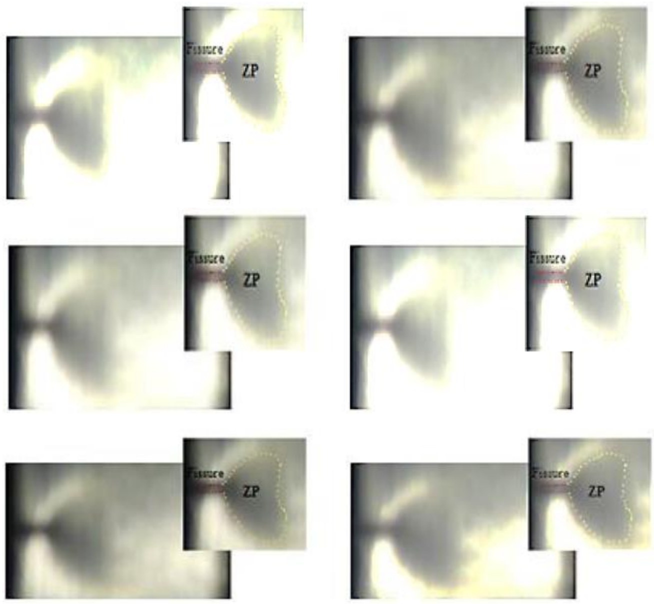

Figure 18 Illustration of the plastic zone (PZ) at the end of crack.

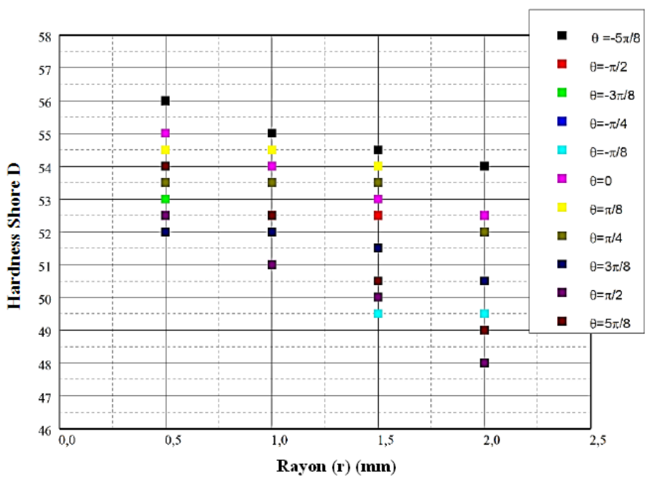

Figure 19 Hardness profile at the head of a crack of a healthy ring specimen

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 23, No. 01, 2022

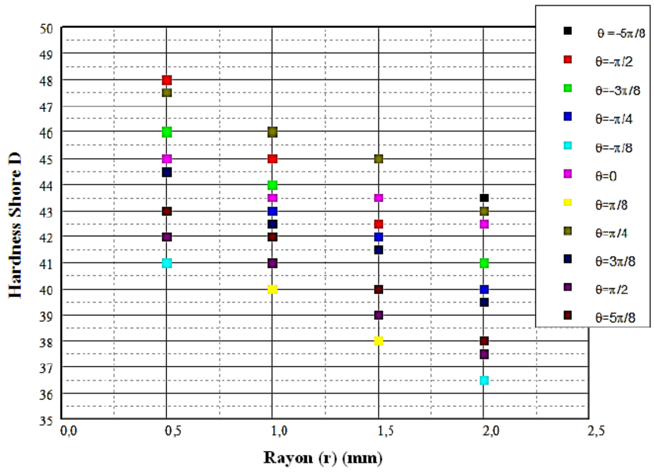

Figure 20 Hardness profile at the head of a crack at the weld bead

Table V - Results Shore D hardness and Δsh D as a function of (r) and (θ) of a healthy part

radius (r)	θ=−5π/8		θ=−π/2		θ=−3π/8		θ=−π/4		θ=−π/8	
	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D
2,00	43,50	/	41,00	/	41,00	/	40,00	/	36,50	/
1,50	43,50	/	42,50	1,50	42,00	1,00	42,00	2,00	38,00	1,50
1,00	44,00	0,50	45,00	4,00	44,00	3,00	43,00	3,00	40,00	3,50
0,50	44,50	1,00	48,00	7,00	46,00	5,00	45,00	5,00	41,00	4,50

θ= 0		θ= π/8		θ= π/4		θ=3π/8		θ= π/2		θ=5π/8	
hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D
42,50	/	37,50	/	43,00	/	39,50	/	37,50	/	38,00	/
43,50	1,00	38,00	1,50	45,00	2,00	41,50	2,00	39,00	1,50	40,00	2,00
43,50	1,00	40,00	3,50	46,00	3,00	42,50	3,00	41,00	3,50	42,00	4,00
45,00	2,50	42,00	5,50	47,50	4,50	44,50	5,00	42,00	4,50	43,00	5,00

The results obtained, measurements of the Shore D hardness as a function of the radius (r) for the different values of (θ), are shown in tables 5 and 6. The evolutions of the Shore D hardness for the different directions are illustrated in (Figures 19 and 20).

For each case we calculated the average value of the hardness far from the crack:

- Unwelded specimen hardness measurement
  sh moy = 52,2
- Welded specimen hardness measurement (weld bead)
  sh moy = 42,1

4 CONCLUSIONS

In this work, we studied the degradation pipe influence of stretching speed (Ve) and strain rate (ε) on the behavior of the welded tube at the proposed conditions, which is a widely used material in industrial field, namely high-density polyethylene (HDPE).

The main objective of this experimental work is to study the mechanical behavior under static loading of the two types of unwelded high density polyethylene (HDPE) pipe and pipe welded by the butt fusion procedure, to characterize the fused part (bead) and to make a comparison and an estimate of the durability of the contact surface of the two assembled pipes. To do this, we propose to realize this part in three parts. The first part focuses mainly on the welding technique used, the selected welding conditions and parameters as well as the verification of the occurrence of a welding bead at the welding plane resulting from the lateral ejection of the melt formed at the end of the pipes whose shape is generally used to provide a first visual indication of the quality of the butt fusion weld.

The second part is devoted to the characterization of the mechanical behavior of unwelded high density polyethylene (HDPE) pipe and pipe welded by the butt fusion process: two sets of tests are studied, a series in tension under uniaxial solicitations and another called Nol Ring test, as an example of the hydrostatic pressure test capable of reproducing circumferential stresses such as those encountered under service conditions.

And in the third part we evaluated the resistance of the plastic zone of the welding bead using tests of hardness shore D. The results presented experimentally make it possible to conclude that the mechanisms of deformation are mainly governed by the different rates of deformation.

The experimental study allowed us to study:

1. Breaking of the welding bead portion;
2. Cracking of the welding bead part;
3. The plastic zone resistance of the welding bead part.

The molten material exhibits good behavior during melting. This made it possible to obtain consolidated materials with good mechanical properties due to residual stresses.

Table VI - Results Shore D hardness and Δsh D as a function of (r) and (θ) of weld bead

radius (r)	θ=−5π/8		θ=−π/2		θ=−3π/8		θ=−π/4		θ=−π/8	
	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D
2,00	54,00	/	52,00	/	50,50	/	48,00	/	49,50	/
1,50	54,50	0,50	52,50	0,50	50,50	/	50,00	2,00	49,50	/
1,00	55,00	1,00	53,50	1,50	52,00	1,50	51,00	3,00	51,00	1,00
0,50	56,00	2,00	54,00	2,00	53,00	2,50	52,50	4,50	52,00	2,00
radius (r)	θ=−5π/8		θ=−π/2		θ=−3π/8		θ=−π/4		θ=−π/8	
	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D	hardness Sh D	ΔSh D
2,00	54,00	/	52,00	/	50,50	/	48,00	/	49,50	/
1,50	54,50	0,50	52,50	0,50	50,50	/	50,00	2,00	49,50	/
1,00	55,00	1,00	53,50	1,50	52,00	1,50	51,00	3,00	51,00	1,00
0,50	56,00	2,00	54,00	2,00	53,00	2,50	52,50	4,50	52,00	2,00

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