National University of Science & Technology

MS Thesis Report

"Effect of Strain Rate & Welding Parameters on structural Performance of Butt Fusion Welds in HDPE"

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DEDICATION

To my family for supporting me during my studies and shouldering the extra burden

To my teachers for guiding me throughout the course work and thesis phase

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DECLARATION

None of the material contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institution of learning.

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ABSTRACT

Use of High Density Polyethylene (HDPE) material has increased extensively in last few decades. HDPE pipes are now frequently used to form long installation lengths for the construction of buried infrastructure such as water mains, sewers and gas pipelines. These pipes are available in standard length sections and joined together using fusion welding technique.

In the fusion joining process, welding surfaces of the two pipe segments are properly trimmed and prepared. Later these trimmed surfaces are heated using a heating plate and pressure is applied to complete the joint.

This thesis presents the effect of strain rate and fusion welding parameters i.e. heating temperature and heat soaking time on the structural performance of fusion joints in HDPE material. It also investigates the structural performance of fusion welds made between extruded HDPE pipes and injection molded HDPE fittings i.e. elbows, Tee-joints and close end cap connections. The research thesis also offer a comparative study related to the effect of strain rate on the performance of HDPE un-welded and fusion welded HDPE samples.

The fusion joints made between extruded-extruded HDPE were found to have high tensile strength and elongation at fracture as compared to injection molded HDPE material. The results of the study are significant in improving performance of composite wound HDPE storage tanks and pressure vessels i.e. type-IV CNG cylinders.

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LIST OF ABBREVIATION

HDPE	High Density Polyethylene
CNG	Compressed Natural Gas
DN	Nominal Diameter
PN	Nominal Pressure
TEB	Tensile Energy to Break
HAZ	Heat Affected Zone
AFM	Atomic Force Microscopy

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Chapter 1: Introduction

1. Introduction

The use of polymeric materials has widely increased due to their significance for light weight structures. High Density Polyethylene (HDPE) is one of the most common polymer material used widely across a variety of applications. One of the main uses of HDPE is to form long installation lengths for the construction of buried infrastructure such as water mains, sewers and gas pipelines. The popularity of HDPE is primarily due to its low initial material cost and excellent chemical resistance.

One of the most common methods to join HDPE pipe sections is through butt fusion welding where both pipe ends are heated and fused together. The presence of these welds affects the overall structural integrity of any pipeline system. This necessitates establishing reliable standard test procedures for evaluating the mechanical properties of welded joints. The understanding of weld joint is also important to confidently predict the service life of a pipe system. This becomes more important as industries move to more critical and challenging service conditions.

It has been studied that fusion welds are influenced by various parameters i.e. alignment of samples, heater plate temperature, heating time, heater plate removal time, joint cooling time [1, 2]. The values of these parameters may vary with material, diameter and pipe wall thickness [3, 4, 5]. It is established that joints made following standard procedures and in optimum environmental conditions have mechanical properties approximately as good as those of the parent pipe [6, 7]. However improperly fusion welded HDPE joints can be the weakest links in the pipelines [8, 9]. The quality of fusion joints becomes more important in high pressure applications i.e. type IV composite CNG cylinders [10]. These CNG cylinders use HDPE liner that is over wrapped with composite fiber.

Present studies cover a large number of mechanical test methods for evaluating the performance of fusion joints in extruded HDPE material. However, no work has been done to correlate results of fusion welded joints for extruded and injection molded HDPE samples. One of the most commonly used industry standard for evaluating the structural performance of fusion welds is tensile test. The present research uses standard tensile test to study the effect of changing welding parameters on fusion welds in HDPE samples. For this reason tensile test of extruded HDPE samples are used as a reference to estimate the weld quality.

Strain rate is also an important factor having significant effect on the structural properties of polymeric materials and becomes very important in engineering design. Hence designers need a complete understanding of material behavior at different strain rates according to their practical application [25]. The effect of strain rate is observed to be more significant at higher loading rates than during lower loading rates [25].

Studies have been done to investigate the effect of strain rate on tensile strength in HDPE material. However, there is no work published estimating tensile strength for fusion welded samples against changing strain rate. The research thesis aims to describe the effect of strain on the structural performance of fusion welded HDPE joints. The findings of the study are very important as the versatile use of HDPE has led to studies focusing on the deformation behavior of the materials at different loading rates.

1.1. Research Objectives

The main objectives of this research thesis are the following:

1. Experimentally evaluate the tensile strength of extruded HDPE material
2. Experimentally evaluate the tensile strength of injection molded HDPE material
3. Correlate the tensile test results of the extruded and injection molded HDPE samples
4. Experimentally evaluate the effect of changing welding parameters on the tensile strength of HDPE joints when made between;
    - Extruded – extruded HDPE samples
    - Extruded – injection molded HDPE samples
5. Experimentally evaluate the effect of changing strain rate on the tensile strength of the following:
    - Extruded HDPE material
    - Butt fusion welded HDPE samples
6. Correlate the strain rate effect on fusion welded and un-welded HDPE samples

The results of the study will help in improving the performance of fusion welds in HDPE material. The novelty of present work lies in the fact that it investigates the optimum fusion welding parameters for joints when made between extruded and injection molded HDPE samples. The findings of the research are important as all pipelines include elbows, Tee-joints and close end cap connections that are produced through injection molding technique, whereas the pipes are manufactured through extrusion process.

Another aspect of the research thesis is experimentally evaluating the effect of changing strain rate on fusion welds in HDPE material. The findings of the strain rate sensitivity analysis are very important for design engineers developing mathematical models using HDPE material. Mathematical models if developed using material properties against inappropriate strain rates may lead to product failure. The effect becomes more important for products subjected to higher loading rates i.e. CNG cylinders or pressure vessels.

Chapter 2: Literature Review

2. Literature Review

2.1. HDPE (High Density Polyethylene)

Polyethylene having the simplest molecular structure among all polymers is a thermoplastic material. The material is made from two and four atoms of carbon and hydrogen elements respectively. Polyethylene is made from polymerization of ethylene gas which is obtained from natural gas or crude oil. Linear polyethylene is obtained by lowering the temperature and pressure during polymerization process using an appropriate catalyst. Linearity of the material ensures that molecules are pack tightly and there are few branches in the polymeric chain.

High Density Polyethylene commonly known as HDPE is a type of linear polyethylene having density ranging from 0.94 to 0.96 g/cc. In comparison to other polymer material, HDPE offer higher strength and modulus properties and thus widely used for versatile applications. HDPE also has the ability to form thick sections and thus now days very popular material for manufacturing plastic pipes. Another major reason for popularity of HDPE is its exceptional chemical resistance.

2.1.1. HDPE Pipe

Conventional materials used for piping purposes include concrete and metals. Clay is one of the oldest piping material and polymers are the newest materials used in the piping industry. Plastic pipes have been used in pressure piping applications for many years. Sarkes and Smith [11] studied that since 1955 plastic pipes are in use by gas industry. In the early 1970s, plastic pipes started being used in highway drainage applications.

Because of its high strength and modulus properties, HDPE is the most widely used polymeric material for manufacturing plastic pipes. HDPE pipes are now installed more frequently than all other plastic pipes all combined. In last few decades, HDPE pipes have also been used for cables in segmental bridges as a safety layer by covering steel strings to avoid corrosion.

Figure 2.1: HDPE Pipe Samples

2.1.2. HDPE Fuel Cylinder

In past decades the utilization of natural gas has immensely increased as a fuel in automobiles. This quantity is growing at a very high rate particularly for Asian countries like Pakistan. Compressed natural gas commonly known as CNG and Hydrogen are the two main natural gases used as a fuel. CNG because of many advantages is more popular fuel than Hydrogen and most of the available vehicles use it.

CNG and hydrogen both are stored in cylindrical tanks when used in automobiles. These tanks are similar to standard pressure vessels and have four different types as discussed in Table 2.1. All types of cylinder are evenly safe and manufactured against proven international standards. This ensures that these cylinders fulfill the standard requirements and can be used anywhere in the world for storing fuel in automobiles. Although all type of cylinders are similar in terms safety, the choice of cylinder type depends on factors including weight, price, handling and filling process of the cylinder.

Type IV composite CNG cylinders as shown in Fig- 2.2 uses HDPE liner covered with glass/carbon/ Kevlar winding. Table 2.2 explains the minimum actual burst values and stress ratios for a type IV CNG cylinder. Type IV CNG cylinders are very light weight and offer better fuel economy than metallic or other type of CNG cylinders. Schematic of a type IV composite CNG cylinder is shown in Fig – 2.3.

The HDPE liners used in these CNG cylinders are manufactured by joining dome sections at the end of a pipe as shown in Fig – 2.4. Many welding methods are available for the joining of HDPE sections that include thermal, friction/mechanical and electromagnetic implementations. The joining of domes to HDPE pipe is done with butt fusion welding method and the process is similar to joining of HDPE pipes. Butt fusion welding is a very common method for welding HDPE sections and result in joints of high quality.

Table 2.1: Different Types of CNG Cylinders

Type	Construction	Characteristics	Storage Efficiency [*]
Type 1	All metallic (Aluminum or Steel)	• Cheap but heavy	0.90 -1.15 kg/L Lifetime 20 years
Type 2	Metal liner reinforced with hoop wound composite (glass, Kevlar or carbon fiber)	• Stress caused by internal pressure is shared b/w liner and composite fiber (Liner 50%, composite 50%) • Less heavy, but more costly	0.65 – 0.85 kg/L Lifetime 20 years
Type 3	Metal liner reinforced with full wrapped composite (glass, Kevlar or carbon fiber)	• Liner takes small amount of the stress • Light-weight, but expensive	0.30 -0.50 kg/L Lifetime 15 years
Type 4	Non-metallic plastic liner reinforced with fully wrapped composite (glass, Kevlar or carbon fiber)	• Entire strength of tank is composite reinforcement • Very Light-weight, but more expensive	0.25 -0.55 kg/L Lifetime 20 years

[*] Xperion ALPHA Composites GmbH @ 200 bar operation pressure

2.1.2.1. Butt Fusion Welding

Butt fusion welding is the very popular method used for joining HDPE pipe sections. It is necessary to join pipe sections for constructing long installation lengths required for water, sewerage and gas pipelines. The principle of butt fusion welding is heating the two surfaces to a selected temperature and then fusing them by application of a given pressure. The fusion joining process starts with facing the pipe ends to ensure clean and parallel mating surfaces. Once the joining surfaces are ready, the joint is completed following five steps [13].

1. heating the joining surface using heater plate
2. heat soaking
3. heater plate removal
4. joining surface under pressure
5. joint cooling

Fig – 2.5 shows the schematic of but fusion joint. For good fusion welds it is important that the joining ends are properly heated at the correct temperature. If the heat soaking time is too long the temperature of joining surfaces will considerably decrease and results in poor weld quality.

Table 2.2: Burst Pressure & Stress Ratios for Type IV CNG Cylinders [12]

Fiber Type	Burst Pressure (bar)	Stress Ratio
Glass	730	3,65
Kevlar/Aramid	620	3,10
Carbon	470	2,35

For all type IV CNG cylinders, the stress ratio is equal to the burst ratio

Some less evident factors resulting to poor weld quality include environmental elements such as dust, soil, water, and grease which are present on joining surfaces or heating plate. The environmental causes mainly effect fusion welds in outdoor construction sites but cannot be neglected for in-door sites. The occurrence of any foreign particles will lead to contamination at joining surfaces and thus affect the joint strength [14, 15]. Fig - 2.6 shows different components of a semi automatic butt fusion welding machine.

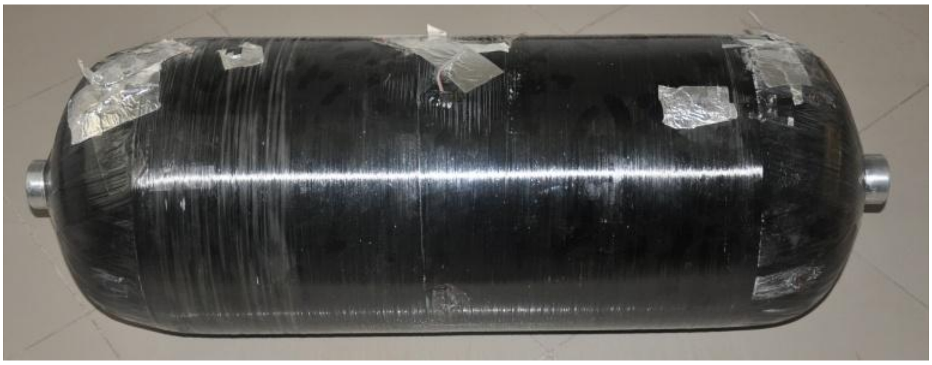

Figure 2.2: Type IV CNG Cylinder

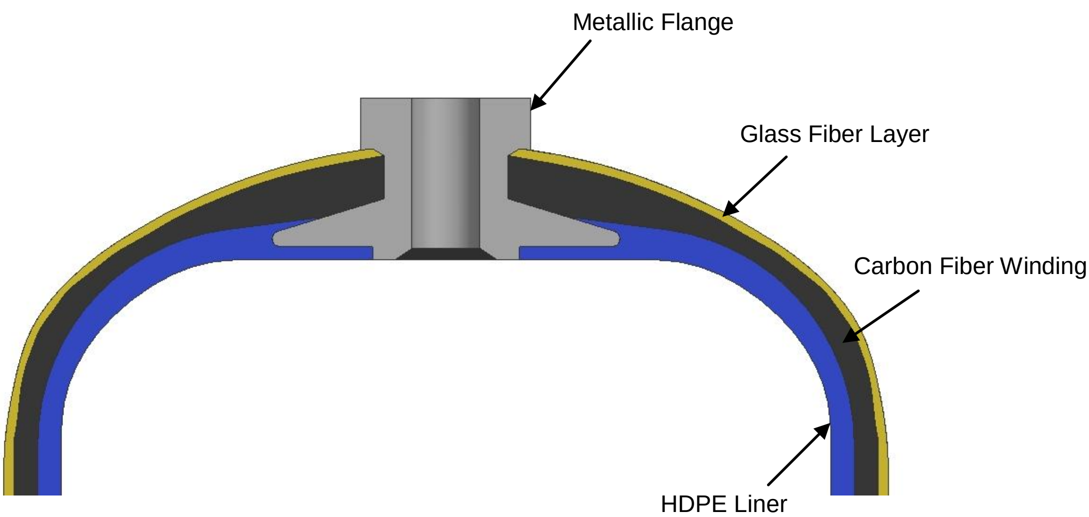

Figure 2.3: Schematic of a Type IV Composite CNG Cylinder

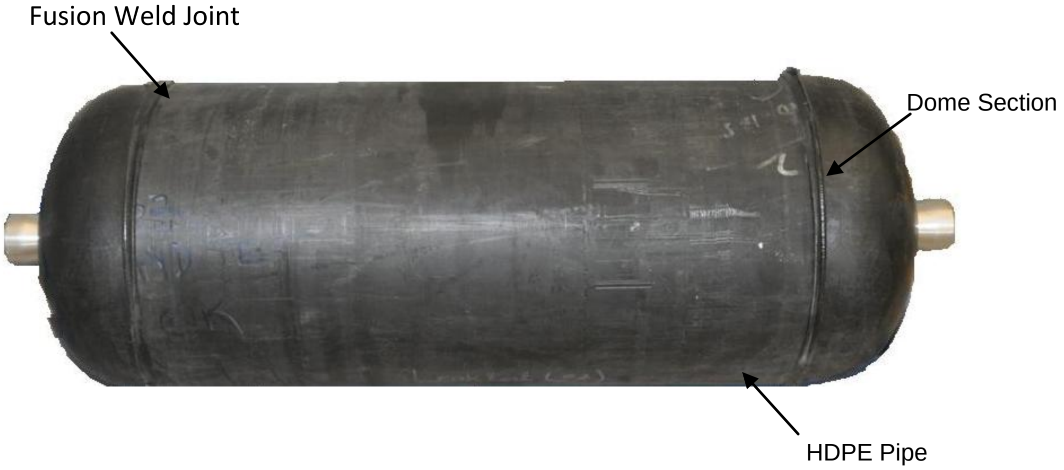

Figure 2.4: HDPE Liner

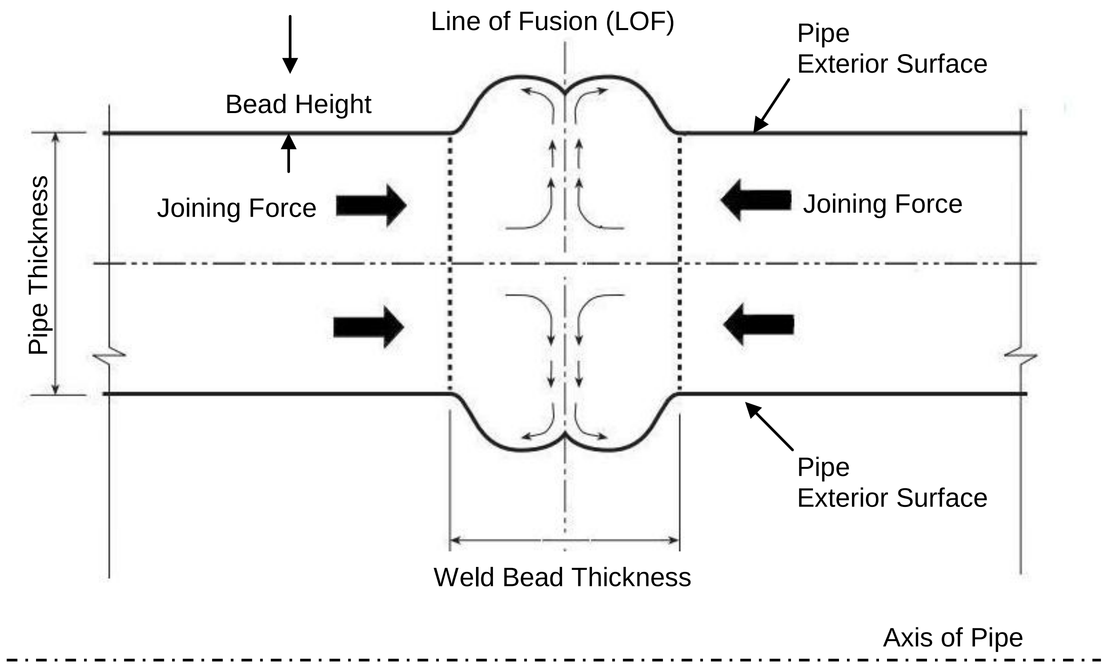

Figure 2.5: Schematic of Butt Fusion Joint

Studies also show that fusion joints made in ideal environmental conditions and following the recommended procedures have mechanical properties approximately as good as the parent material [6, 7,13]. It is established fact that the quality of fusion joint is not only dependent on the welding procedure but also affected by the environmental conditions. Cowley and Wylde studied that improperly-made butt fusion joints can be the weakest link in a pipeline and may result in considerable financial losses [8, 9, 16].

Studies describe that if the joint results in a concave weld bead the joint is of low quality and is a result of improper pressure applied during the heating process [17]. These joints are not acceptable and shall be redone to avoid any failure. It is studied that for proper fusion welded joints the weld beads are round and of uniform size across the weld length. For proper fusion welds the width of weld beads will be approximately 2-2 ½ times the bead height if measured from top of the pipe surface. It is also established that the v-groove formed between the weld beads shall have a depth of more than half of the bead height. Table 2.3 offer a general guide line for weld bead sizes resulting from fusion welding of HDPE pipes [17]. However these values may change depending upon the pipe thickness.

Studies have been done to estimate quality of fusion welds in HDPE material. These include quality estimation using different methods ranging from visual examination, destructive testing and non-destructive techniques [18].

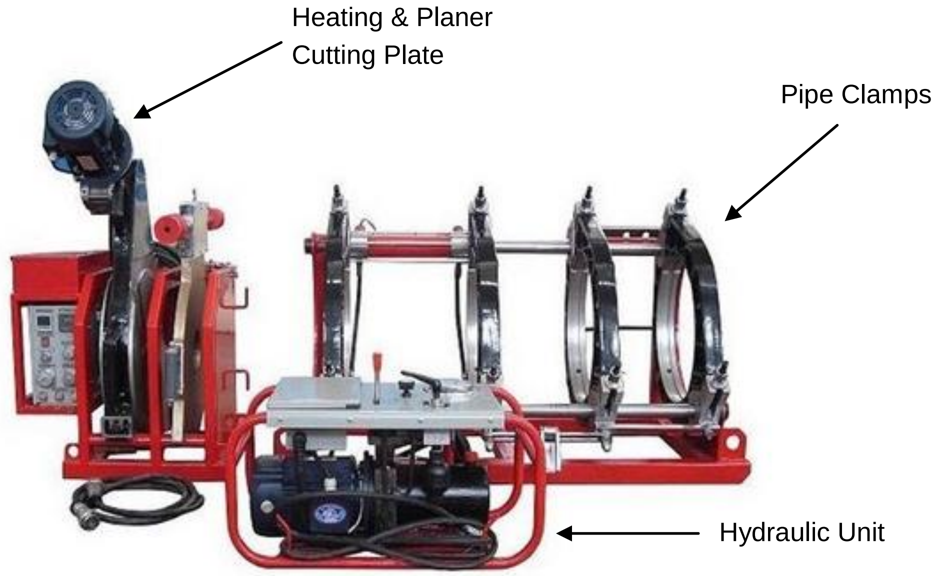

Figure 2.6: Semi Automatic Butt Fusion Welding Machine

Hinchcliff and Troughton established a destructive testing method for determining quality of fusion welds. According to this method joint samples across the pipe joint are cut and examined for any abnormalities [19]. Bowman claimed that burst testing of a standard pipe length can also be used to estimate the joint quality in HDPE pipes [6]. These types of destructive testing methods only offer a sign of the total joint performance. Munns and Georgiou studied non-destructive testing methods for determining the joint quality. These methods use ultrasonic and radiographic techniques but not very common in the industry [7].

Reynolds established a qualitative method known as “External Bead Test” to study the joint quality [20]. The test involves removing the weld bead and later bending and twisting the sample to visually identify joint slits or weak points. Reynolds with others also suggested that the height and shape of external beads can also be used as a quality indicator for fusion welds [18, 21].

Table 2.3: Approximate Weld Bead Size

Pipe Dia	Approximate Weld Bead Size
1 ¼” and smaller (40mm and smaller)	1/32” – 1/16” (1-2mm)
Above 1 ¼” through 3” (above 40mm-90mm)	About 1/16” (2mm)
Above 3” through 8” (above 90mm-225mm)	1/8”-3/16” (3-5mm)
Above 8” through 12” (above 225mm-315mm)	3/16”-1/4” (5-6mm)
Above 12” through 24” (above 315mm-630mm)	1/4”-7/16” (6-11mm)
Above 24” through 36” (above 630mm-915mm)	About 7/16” (11mm)
Above 36” through 63” (above 915mm-1600mm)	About 9/16” (14mm)

Pimputkar and Tappe further studied that the weld quality and bead geometry is affected by fusion parameters such as heating time, heating temperature and joining pressure [22, 23, 24]. The effect of these parameters become more prominent in case of products operated under high pressures i.e. CNG cylinders. Fig - 2.7 shows leakage in a type IV CNG cylinder due to improper joining parameters. Barber and Atkinson established that tensile test can be used for estimating the joint quality for butt fusion welds in HDPE material [3].

It is known that HDPE pipes are manufactured using extrusion process, where the molten polymer material is pushed against a die. After passing the die, material takes the shape of pipe and is then cooled to retain its shape. All pipe lines also involve fusion welding of pipe sections with fitting connections i.e. closed end caps, t-joints, elbows etc. These fitting connections are manufactured using the injection molding technique where molten polymer material is compressed in a mold using injection molding machines.

Figure 2.7: Leakage in Type IV CNG Cylinder

Studies have been made on determining the joint strength for fusion welded HDPE pipes manufactured using the extrusion process. However they do not discuss the effect when HDPE samples made from extrusion process are fusion welded with injection molded connections. Present research work aims to discuss the effect of welding parameters on the joint quality of extruded & injection molded samples.

Strain rate has high influence on the structural properties of materials. The effect of strain rate becomes more important in case of polymer materials as it greatly affect the deformation mechanisms. These changing deformation mechanisms help in characterizing the behavior of polymer materials, particularly semi-crystalline polymer materials [25]. Knowing the vast engineering applications of HDPE, it is important to understand the effect of changing strain rate on material deformation behavior.

Present studies do not discuss the strain rate dependence of fusion welded HDPE materials. The phenomena become very important as almost no application of HDPE is available without fusion welding. The present research aims to make a comparative examination of strain rate sensitivity for un-welded and fusion welded HDPE joints.

Chapter 3:

Experimental Procedure & Equipment

3.1. Research Methodology

The research involves estimating structural performance of fusion welded extruded and injection molded HDPE material. Standard tensile test is used for estimating the joint quality for fusion welded HDPE samples. In order to study the effect of welding parameters joints are made by changing parameters i.e. heating time and heating temperature. Changing the welding parameters for butt fusion welding requires developing a proper test setup. The welding setup must have the options for changing welding parameters i.e. heating temperature, joint alignment, heating time and if possible joining pressure. For the present study less prominent parameters i.e. joining pressure, environmental conditions and sample alignment are not considered as they do not contribute much towards the joint quality [8, 9, 16]. Tensile strength of fusion welded joints is compared against strength of un-welded HDPE samples for correlating the joint quality. Weld joints between extruded and injection molded HDPE material are also made with changing the welding parameters and the tensile test results are correlated against un-welded samples.

To study the effect of strain rate sensitivity on welded and un-welded HDPE samples, tensile tests are carried out by changing the displacement rate of machine. The results are further correlated to particle applications.

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3.2. Experimental Work

3.2.1 Butt Fusion Welding of HDPE

Flat strips of HDPE material are prepared by machining of HDPE pipe (PN8, DN: 355mm, Thickness: 16.9mm) as shown in Fig – 3.1. The machining of HDPE pipes is carried out in longitudinal direction and this direction is also the same in which these pipes are extruded. Flat strips obtained from these pipes are referred as *extruded HDPE strips*. The HDPE pipes used for machining are locally manufactured using HDPE grain (BroSafe HE3490-LS-H, also classified as PE100). The said HDPE grain material is produced by one of the leading polymer material manufacturer Borouge Pte Ltd. The manufacturer's data sheet of the HDPE grain material is given in Annex-A and the properties HDPE pipe are summarized in Table 3.1 [26].

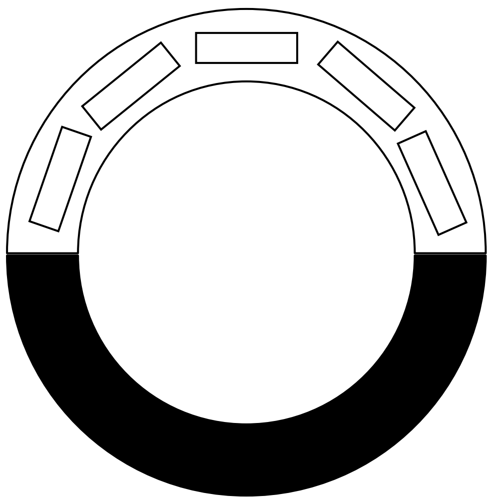


Figure 3.1: HDPE Pipe Section

During machining of HDPE pipe, it is ensured that the machined surfaces have good surface finish and no discontinuity is available on the machined surfaces. For this purpose the machining of the samples is done with a depth of cut less than 1mm and at very low feed rates [25]. The machined flat strips can now be fusion welded with the help of a welding fixture. To fulfill this purpose, an in-house butt fusion welding test setup is developed as shown in Fig – 3.2.

Table 3.1: Properties of HDPE Pipe [26]

Property	Value	Standard
Density	959 kg/m^3	ISO 1183/ISO 1872-2B
Tensile Stress @ yield (50mm/min)	25 MPa	ISO 527-2
Elongation @ Break	>600%	ISO 527-2
Hardness, Shore D	60 - 70	ISO 868
Carbon Black Content	>2%	ASTM D 1603

The test setup consists of a heating plate having three heating elements and a clamping fixture. The temperature of heating plate is adjustable using a microcontroller that can operate with a tolerance of $\pm$1 ^{0}C. The presence of microcontroller will ensure accurate heating of plate and the same setup will be used for changing weld parameter study. Joining force required for fusion welding is applied manually with the help of a lead screw that is mounted on the welding fixture. The developed fusion welding fixture is very similar to the standard butt fusion welding machines used for joining of HDPE pipes as shown in Fig – 3.2.

Once the flat HDPE strips are machined and the welding fixture is available. Fusion joints can be made between the machined *extruded HDPE strips* by varying welding parameters (heating temperature and heat soaking time). The reason for considering only these two parameters into consideration is based on the already done research that explains that these two parameters mostly affect the quality of weld in a fusion joint [14, 15]. It is also assumed that since the joints are being made in a laboratory so no environmental effects i.e. dust contamination will affect the quality of welds.

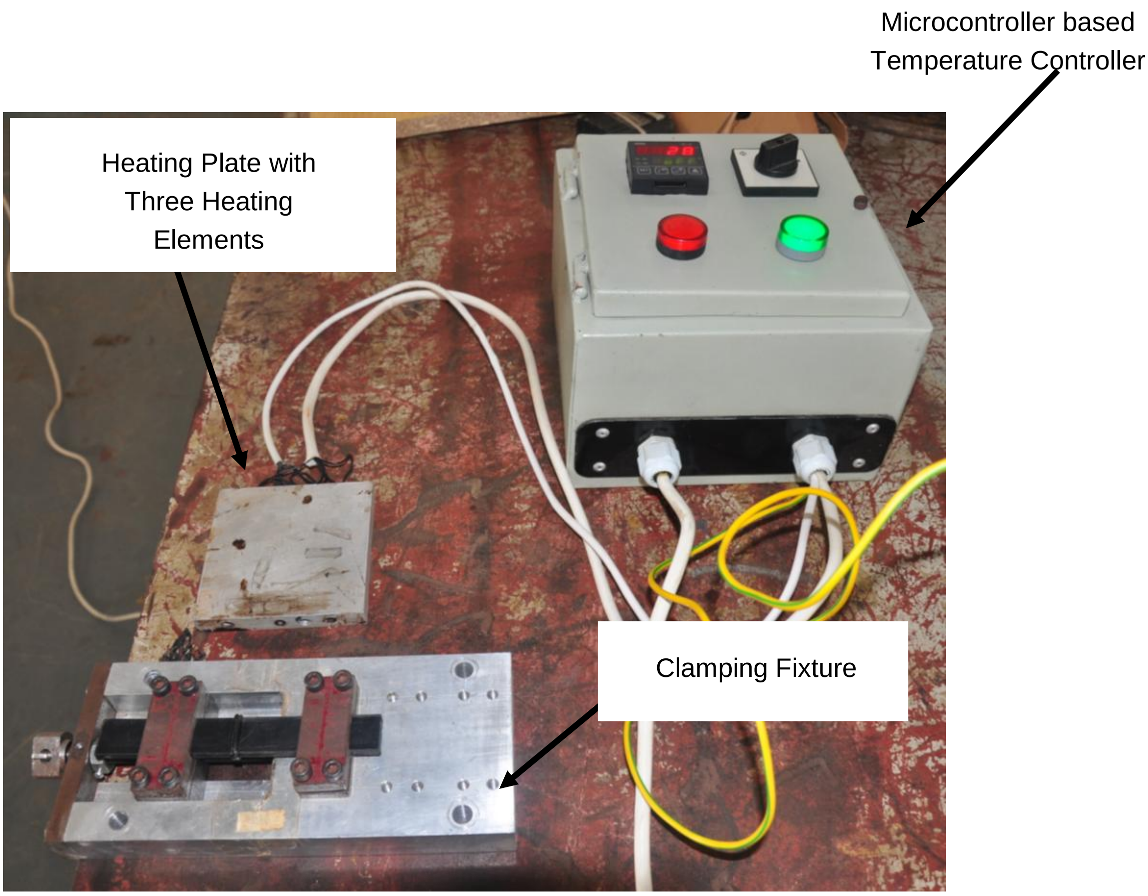


Figure 3.2: Developed Fusion Welding Fixture

The research thesis also aims to study fusion joints made between extruded and injection molded HDPE samples. For this purpose flat HDPE strips are obtained through machining of injection molded HDPE end caps as shown in Fig 3.3.

The end caps used for the study are locally manufactured using the HDPE grain (BroSafe HE3490-LS, also classified as PE100) that is produced by Borouge Pte Ltd. This HDPE grain material used for injection molding is compatible for fusion welding with the extruded HDPE Pipes (Annex-B). Still it will be very interesting to study the joint quality when these two dissimilarly manufactured materials are joined through fusion welding. The manufacturer's data sheet of the injection molded HDPE grain material is given in Annex-B.

Figure 3.3: HDPE Fittings & End Cap Connections

Chapter 4:

Effect of Welding Parameters on Structural Performance of HDPE Joints

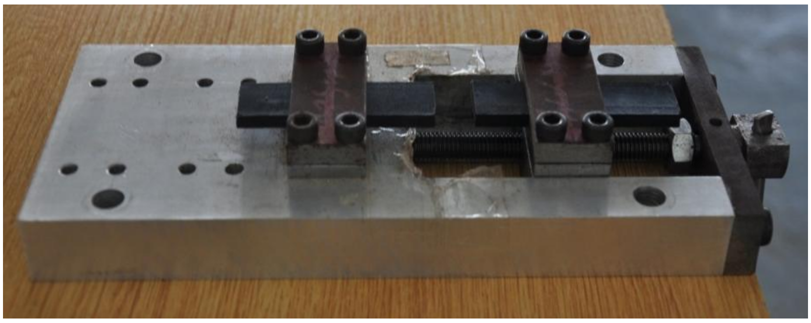
4.1. Changing Fusion Welding Parameters

As discussed, the research thesis aims to study the effect of changing welding parameters on structural performance of HDPE joints. For this purpose, joints are made by changing the welding parameters for both (extruded-extruded) and (extruded-injection molded) HDPE strips. It has been established from the literature survey that two parameters *heating plate temperature and heating soaking time,* mainly affect the structural performance of fusion welded HDPE joints [14, 15]. Understanding the fact, only these two parameters are changed during the present research and their values are as follows:

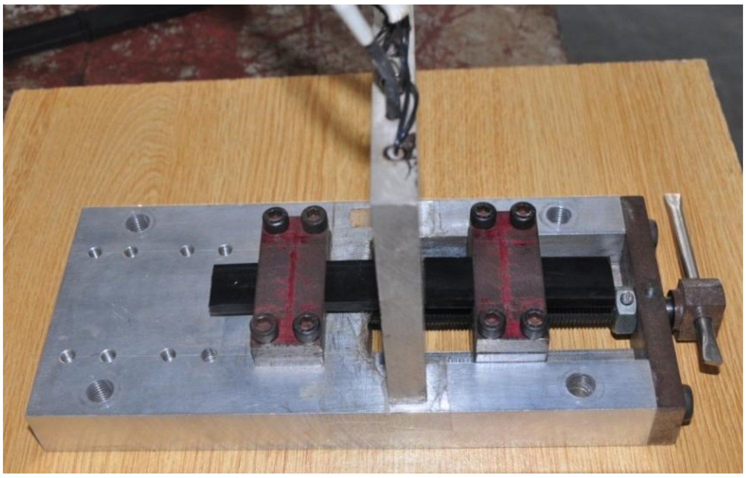
- Heater plate temperature: (150 ^{0}C – 350 ^{0}C)
- Heat soaking time: (1min – 5 min)
- Applied joining pressure: 2.5 turns (kept constant, as applied through the lead screw installed on the developed fusion welding fixture)

The fusion joining of machined HDPE strips is carried out in a workshop at room temperature (28 ^{0}C) using the developed fusion welding setup and the process of fusion joining is explained in Fig – 4.1 (a, b, c, d). Since the joints are obtained in a workshop hence the environmental effects i.e. dust contamination can be ignored. A good joint requires proper alignment of the joining samples, to ensure sample alignment, flat HDPE strips are properly clamped and joining force is applied gradually during the fusion welding process. Fig – 4.2 shows fusion welded HDPE strips by using the developed welding fixture. It is observed that no joint is made at temerature of 150 ^{0}C understanding the fact that the melting temperature of the HDPE material is above 150 ^{0}C. However for the same temperature at high heat soaking times the fusion joint is obtained which can be used for further testing.

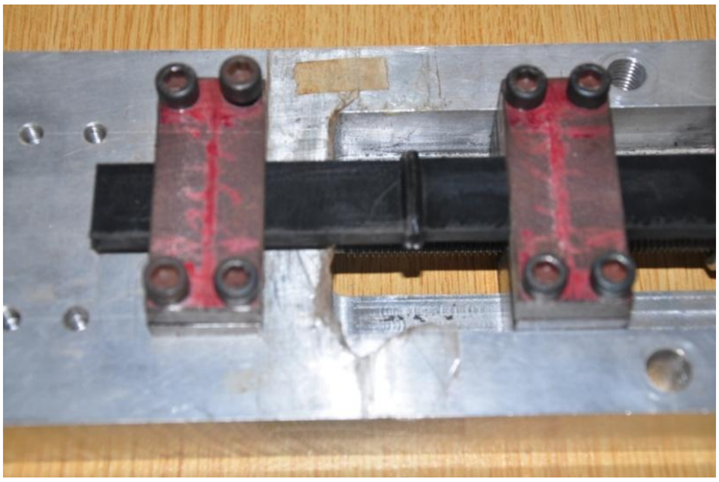
Once the fusion joints are made from the machined HDPE strips, the joints are inspected for any abnormality. Sizes of weld beads are measured to check how it can correlate the performance of fusion joint and reported in next chapters. The welded flat strips are then machined in standard ASTM tensile bars (ASTM D638) having the joint in middle of gauge length, as shown in Fig - 4.3.



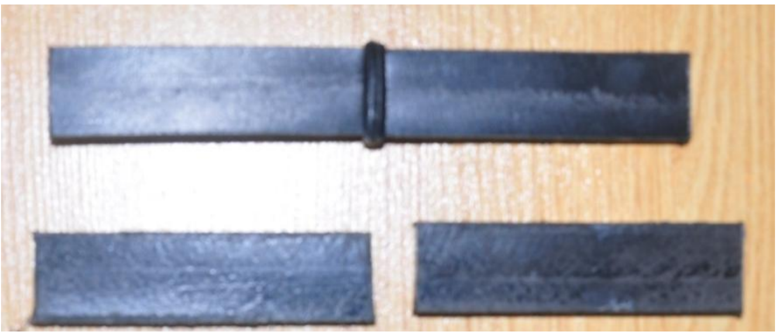
(a) Clamping of HDPE strips



(b) Heatinig Ends of HDPE Strips



(c) Joining of Heated HDPE Strips



(d) Welded & Un-Welded HDPE strips

Figure 4.1: Fusion Joining Using Developed Welding Fixture

The machining of strips removed weld beads from the tensile samples and weld joint line is exposed. Since any discontinuity available on the tensile sample may result in stress concentration at that point and will lead towards misleading results. It is ensured that during machining no discontinuities are available on the tensile samples particularly at the joining location. Later the samples are prepared for microscopy using sand paper of sizes 1, 2, 3 respectively. Microscopy of the tensile samples over the weld line is carried out to find out any lack of fusion at the joining line. The tensile samples are later tested in uni-axial direction at room temperature (25 ^{0}C) using a computerized MTS 210 tensile testing machine with extensometer having a gauge length of 25 mm. The displacement rate for this testing is kept constant as 50mm/min (ASTM D638).

Figure 4.2: Fusion Welded HDPE Strips

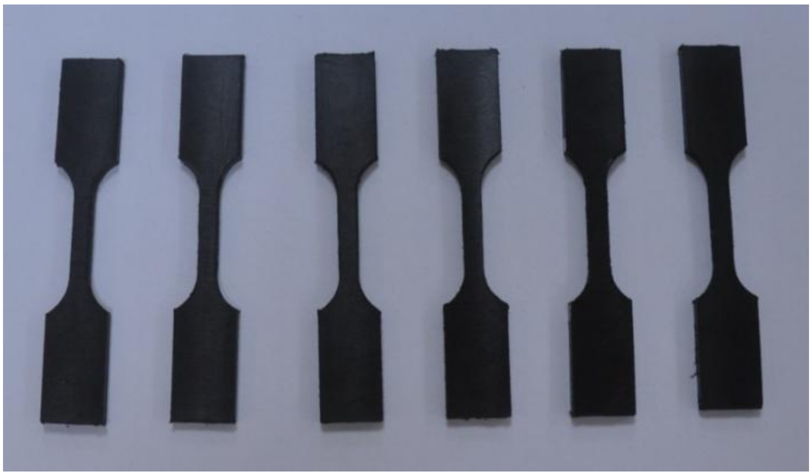


Figure 4.3: Machined Fusion Weld Tensile Samples

The tensile specimens are held between the fixed and movable grips. The samples are aligned to ensure that the long axis of the test specimen coincides with the direction of applied displacement and no slippage occurs at the grips. At least three specimens are tested for each combination of welding parameters. The tensile testing machine used has a constant rate of crosshead movement with fixed and moveable grips. The process is repeated for all test cases and results are listed in next pages.

4.1.1. Experimental Results - Changing Fusion Welding Parameters

The resulting stress – strain curve for both types (extruded-extruded & extruded-injection molded) fusion welded tensile samples are presented in Fig – 4.5 (a, b). Studies show that the mechanical properties of a good fusion joint are as good as of the parent material [6, 7, 13]. To compare the results of fusion welded HDPE joints, tensile samples of the parent HDPE material are tested and the resulting stress strain curve is presented in Fig – 4.4. Like any stress strain curve, the stress-strain plots for HDPE material can also be divided in four distinct regions as explained in Fig – 4.4.

a) Region 1: Elastic region where stress linearly increases with strain
b) Region 2: Yield point that is also the maximum value on stress strain graph
c) Region 3: Continuation of yielding where stress drops causing less change in strain
d) Region 4: also known as cold drawing where stress is almost constant and strain increases

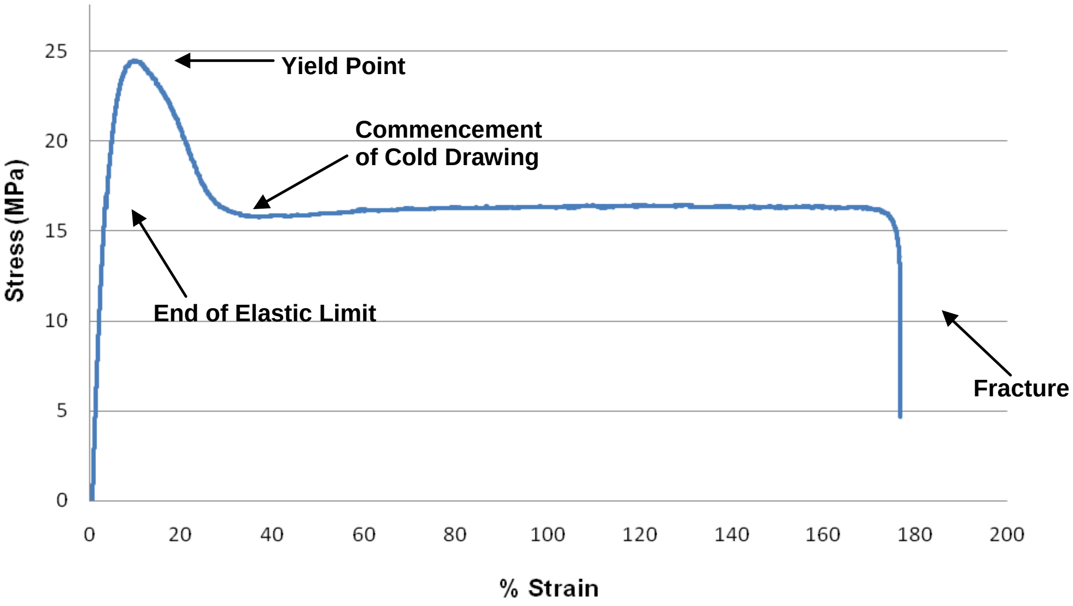


Figure 4.4: Stress-Strain curve for HDPE material

Fig – 4.5 (a, b) shows that stress strain curve for both types of samples (extruded-extruded & extruded-injection molded) show identical behavior, however the resulting values for tensile strength and % elongation at fracture are different for both these types.

Studies suggest that if fusion joint results in a concave weld bead the joint will be of low quality. These low quality fusion joints are a result of improper applied pressure during the heating process [17]. The resulting weld beads for all the samples during present research work are convex, thus all the joints can be termed as good quality joints. Studies have also shown that for proper fusion welded joints the weld beads are round and of uniform sizes across the weld length [17]. The assumption is only valid only for fusion joints made between similar materials. In case of fusion welds between dissimilar materials, the hypothesis does not hold true i.e. fusion joints made between materials that are produced through different manufacturing process. Examining the resulting weld beads the same phenomenon is observed with uniform weld bead sizes for extruded-extruded samples and non-uniform weld bead sizes for extruded-injection molded samples.

To study the effect of changing welding parameters on the weld bead sizes (thickness and height) the values are listed in Table 4.1 (a, b). It is observed that the weld bead sizes for different welding parameters are different.

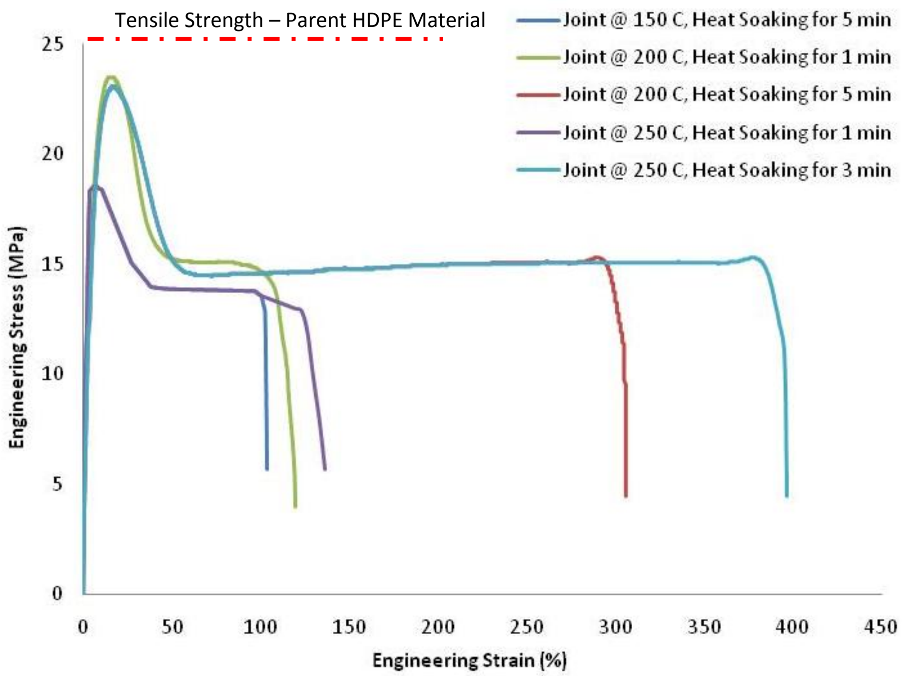


Figure 4.5 (a): Stress – Strain Curve (extruded-extruded Joints)

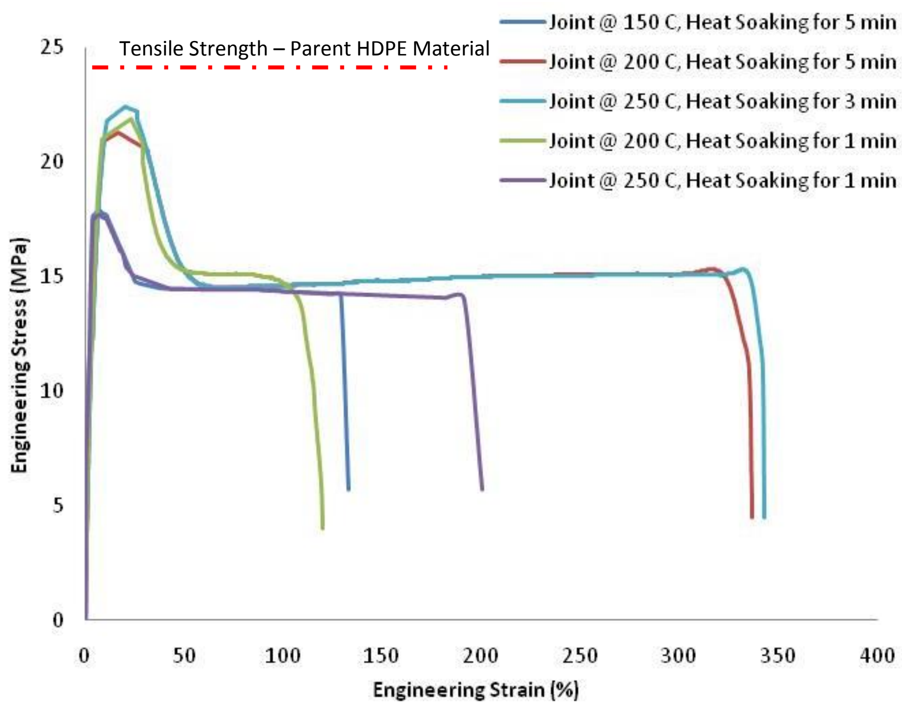


Figure 4.5 (b): Stress – Strain Curve (extruded-injection molded Joints)

Table 4.1 (a): Fusion Weld Results (Extruded – Extruded HDPE samples)

	Heating Temperature (^0C)	Heat Soaking Time (min)	Weld Bead Size (mm)		Tensile Strength (Mpa)
			Thickness	Height	
Extruded – Extruded	100	1	…..	…..	…..
		3	…..	…..	…..
		5	…..	…..	…..
	150	1	…..	…..	…..
		3	…..	…..	…..
		5	13.4	5.1	24.3
	200	1	9.4	4	17.8
		3	12.5	4.5	23.1
		5	13.8	5.2	23.5
	250	1	9.5	4.3	19.5
		3	12.3	5.4	24.5
		5	13.5	5.4	24.8
	300	1	9.8	4.5	20.1
		3	13.2	5.4	23.5
		5	13.9	5.3	24
	350	1	9.5	5.1	20
		3	13.2	5.1	18.5
		5	14.3	5.4	22.4

(**…..**) No melting of the joining faces is observed which does not result in a weld joint.

Table 4.1 (b): Fusion Weld Results (Extruded – Injection Molded HDPE samples)

	Heating Temperature (^0C)	Heat Soaking Time (min)	Weld Bead Size (mm)		Tensile Strength (Mpa)
			Thickness	Height	
Extruded – Injection Molded	100	1	…..	…..	…..
		3	…..	…..	…..
		5	…..	…..	…..
	150	1	…..	…..	…..
		3	…..	…..	…..
		5	11.9	5.1	17.7
	200	1	8.2	4.3	16.6
		3	11.4	4.9	21.3
		5	12.3	5.3	21.1
	250	1	8.6	4.5	17.2
		3	11.9	5.1	22.2
		5	12.5	5.6	21.4
	300	1	8.8	4.8	17.7
		3	12.0	5.5	21.7
		5	12.6	5.2	20.9
	350	1	8.7	5	18.1
		3	12.2	5.3	19.5
		5	12.8	5.3	20.1

(**…..**) No melting of the joining faces is observed which does not result in a weld joint.

4.1.2. Results Analysis - Changing Fusion Welding Parameters

To study the effect of changing welding parameters the results obtained from the experimental work are plotted in next sections. Fig – 4.6 (a, b, c, d) shows the effect of weld parameters on the weld bead thickness for joints made between extruded-extruded and extruded-injection molded materials respectively. It is observed that the weld bead thickness shows a linearly increasing trend for all weld parameters in case of fusion joints made between extruded-injection molded samples. However for extruded-extruded joint samples the weld bead thickness remains approximately the same even with a change in the welding parameters. The values of weld bead height however remains almost the same for both types of samples (extruded-extruded & extruded-injection molded) showing a zero slope.

ASTM F2620-06 defines that for proper fusion weld PE joints the thickness of the weld beads will be approximately 2-2 ½ times the bead height [27]. Fig – 4.7 shows the dimensional guideline for measuring the weld bead sizes.

Comparing the obtained values of weld bead sizes as plotted in Fig – 4.6 (a, b, c, d) against the definition of ASTM F2620-06 regarding a proper fusion weld, it is observed that all the welds made between extruded-extruded samples fulfill this criteria. The resulting weld bead thickness of the weld beads for extruded-extruded samples is greater than 2 times the bead height. However for few joints made between extruded-injection molded samples the weld bead thickness is less than 2 times of the bead height and these joints are termed as improper weld joints [ASTM F2620-06].

Estimating the joint quality on the basis of weld bead sizes as suggested by ASTM F2620-06 show that all the joints are of good quality having no major influence of weld parameters.

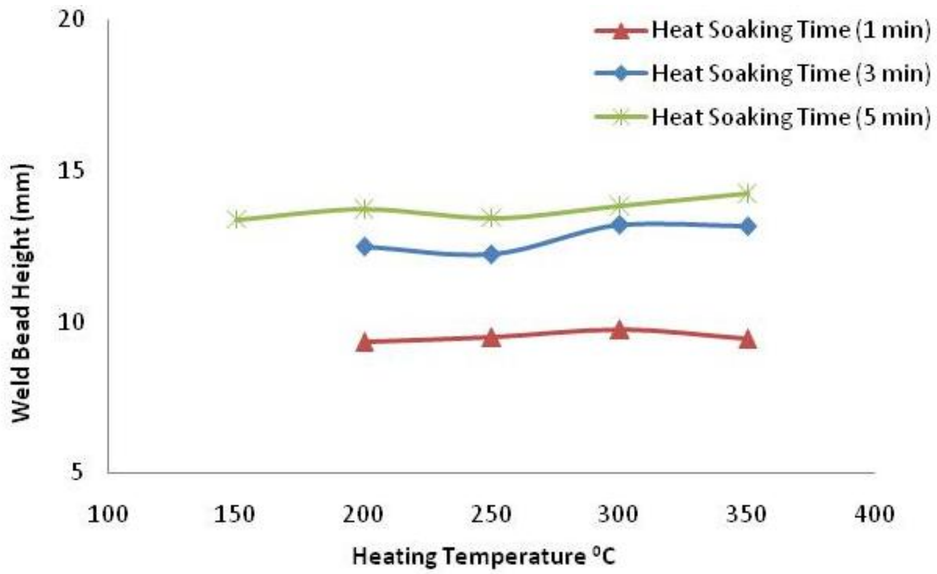


Figure 4.6 (a): Effect on Weld Bead Height (Extruded – Extruded Joint)

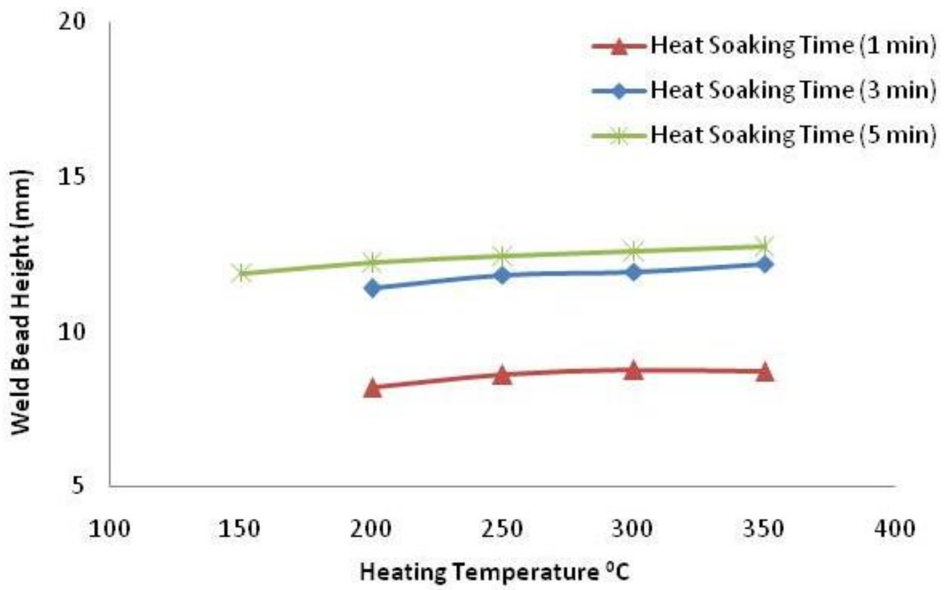


Figure 4.6 (b): Effect on Weld Bead Height (Extruded – Injection Molded Joint)

Figure 4.9: Effect of Weld Parameters on Fusion Joints

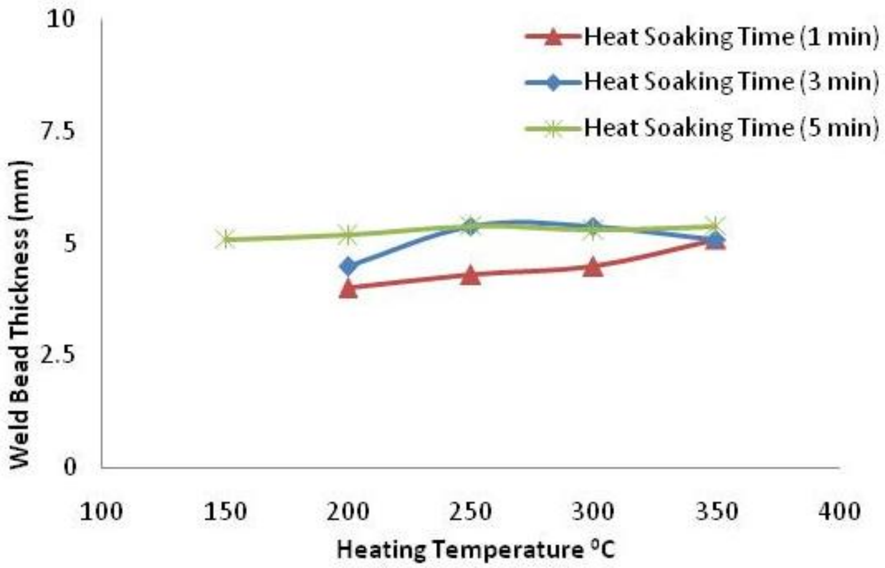


Figure 4.6 (c): Effect on Weld Bead Thickness (Extruded – Extruded Joint)

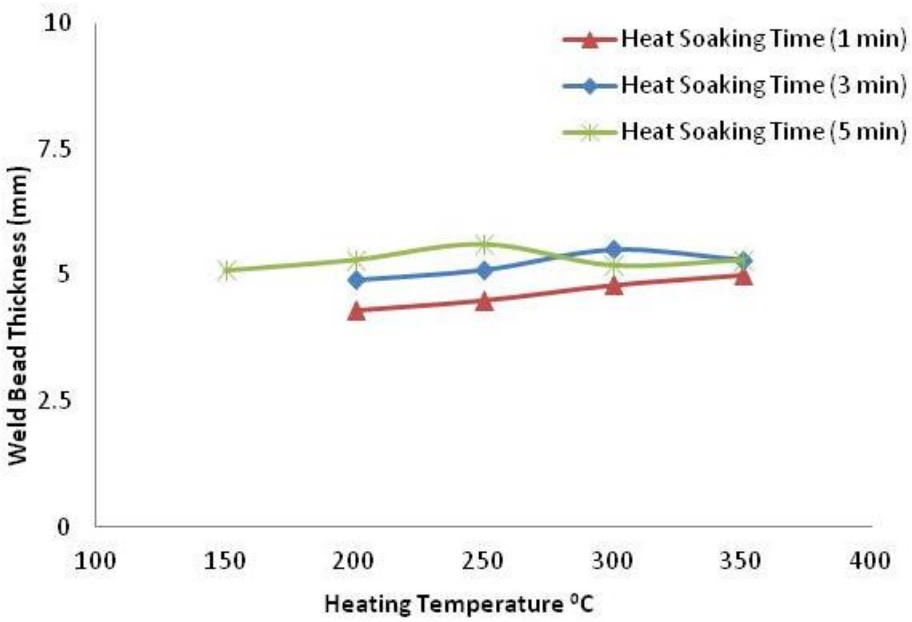


Figure 4.6 (d): Effect on Weld Bead Thickness (Extruded – Injection Molded Joint)

Figure 4.9: Effect of Weld Parameters on Fusion Joints

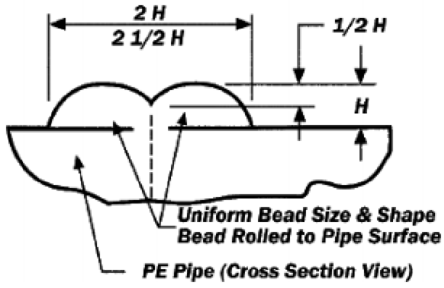


Figure 4.7: Butt Fusion Bead Dimensional Guideline (ASTM F2620-06)

Studies have shown that tensile energy to break (TEB) and maximum strain observed during tensile test of a fusion joint are considered the most acceptable parameters for distinguishing between joints of different qualities [2, 27]. Since the thickness of weld beads for all the fusion joints made is approximately 2 times the bead height, based on the hypothesis suggested by ASTM F2620-06 the values of tensile energy to break (TEB) and maximum strain shall be identical for all these weld samples. For such comparison the values of tensile strength and total elongation at fracture obtained trough experimentation are plotted in Fig – 4.8 and Fig – 4.9 respectively. Fig – 4.8 (a, b) shows that tensile strength changes like a bell curve with changing weld parameters. The behavior is almost identical for both types of weld samples (extruded-extruded and extruded-injection molded), however the resulting values of tensile strength are not the same for both sample types.

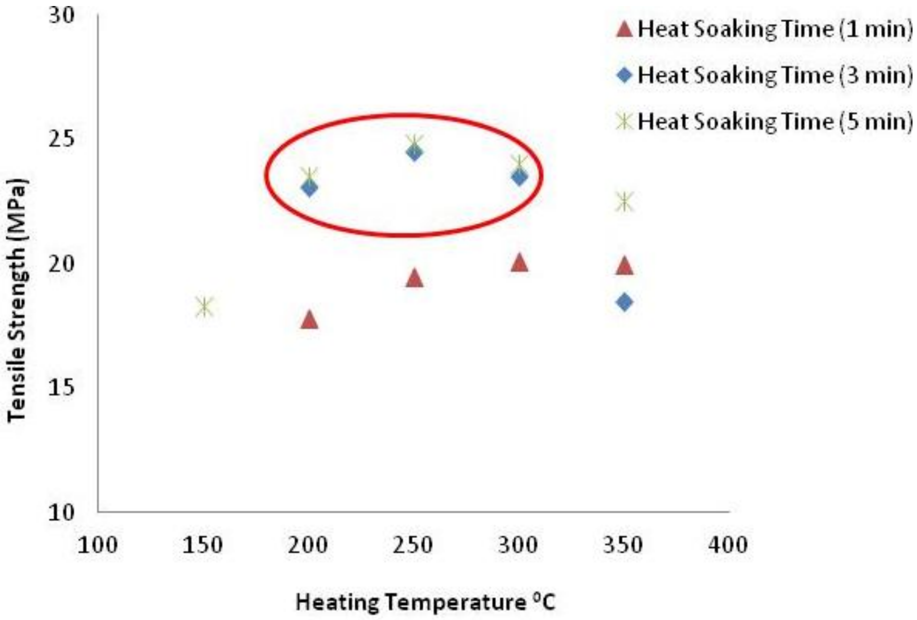


Figure 4.8 (a): Effect of Weld Parameters on Tensile Strength (Extruded – Extruded Joint)

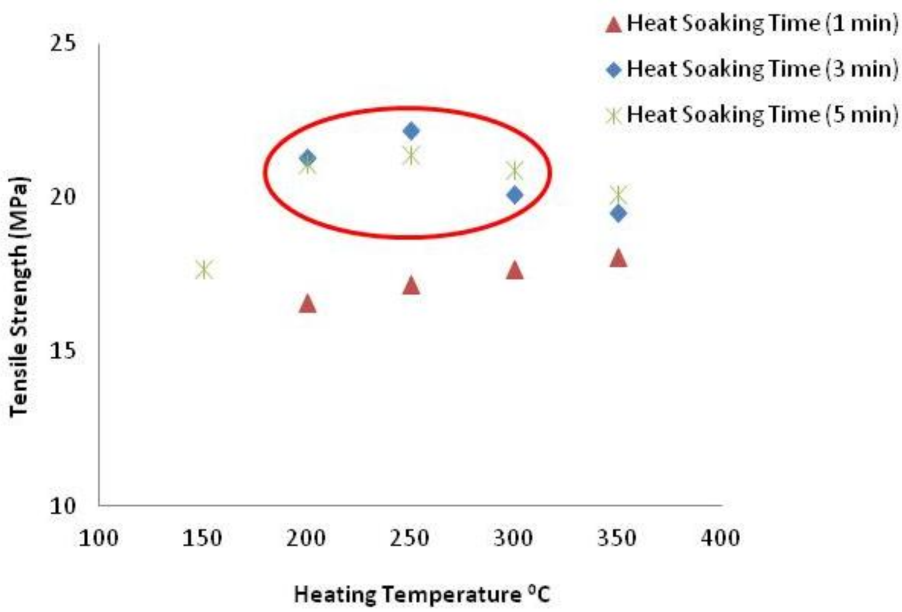


Figure 4.8 (b): Effect of Weld Parameters on Tensile Strength (Extruded – Injection Molded Joint)

Figure 4.8: Effect of Weld Parameters on Tensile Strength

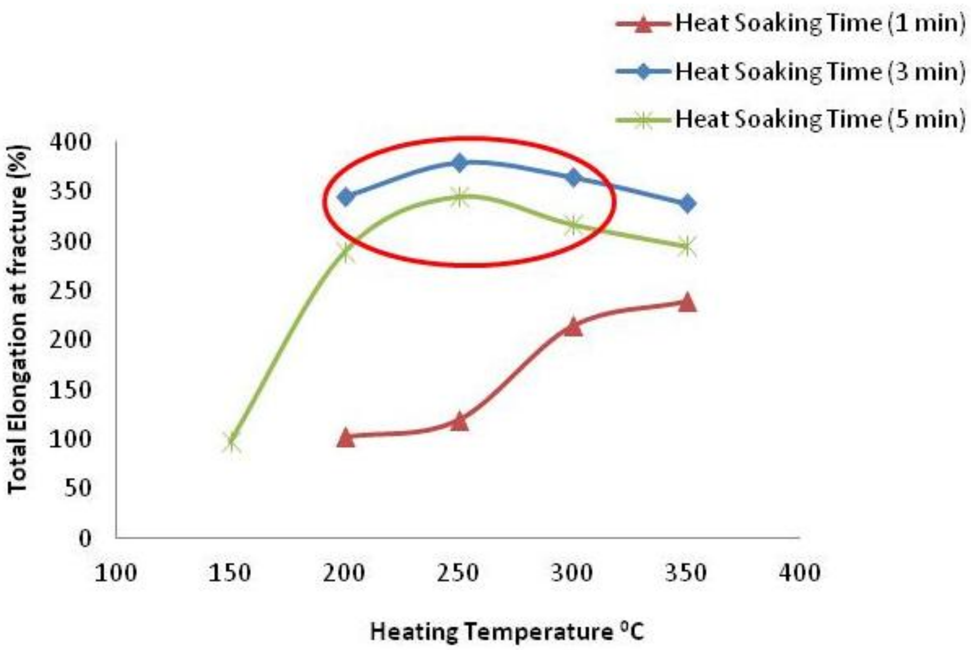


Figure 4.9 (a): Effect of Weld Parameters on % Elongation (Extruded – Extruded Joint)

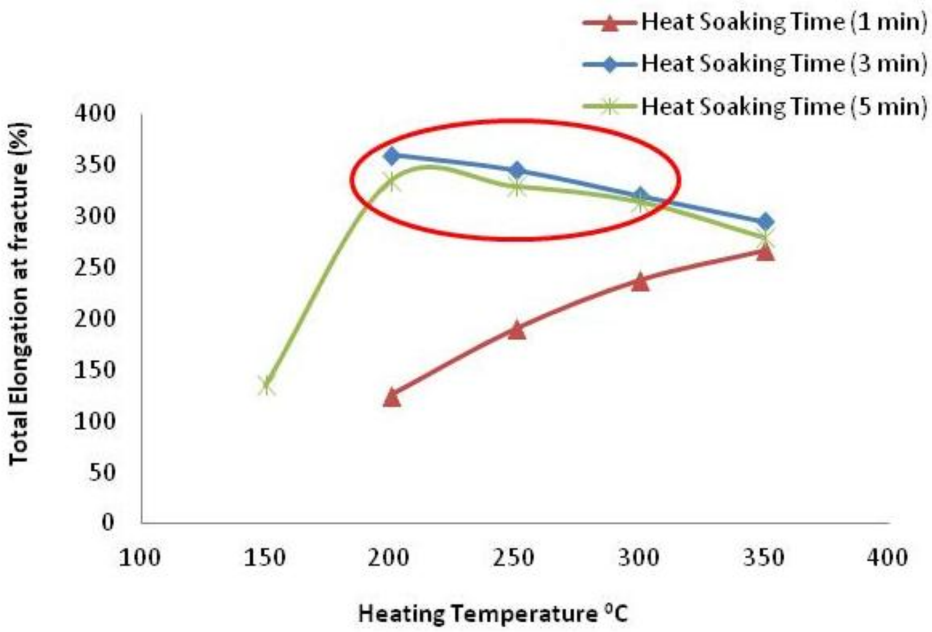


Figure 4.9 (b): Effect of Weld Parameters on % Elongation (Extruded – Injection Molded Joint)

Figure 4.9: Effect of Weld Parameters on % Elongation

From the plots of Fig – 4.8 (a, b), it is observed that the values of tensile strength do not change significantly for heat soaking time of 3 & 5 minutes at corresponding heating temperatures. This observation holds valid for both type of fusion joints (extruded-extruded and extruded-injection molded). On the other hand for heat soaking times less than 3 minutes the fusion weld results in a poor quality of joints having lower structural strengths. The reduction in tensile strength is because of improper heating of joining surfaces that consequently result in lack of fusion.

Although the joints made at high heating temperatures exhibit considerably good structural strength, the resulting weld beads show signs of burning of the HDPE material. The same observation is also evident from the results of microscopic examination as presented in Fig – 4.11.

The plots presented in Fig – 4.8 & Fig – 4.9 show that maximum strength and % elongation at fracture for both type of weld joints (extruded-extruded and extruded-injection molded) is obtained at heating temperature of 250^0C for a heat soaking time of 3 minutes. The resulting values of tensile strength for extruded-extruded fusion joints are comparably high as compared to the tensile strength of extruded-injection molded fusion weld samples. However the values of % elongation at fracture remains almost identical against the maximum tensile strength values obtained with changing weld parameters.

Comparing the tensile strength values obtained for both types of fusion joints (extruded-extruded & extruded-injection molded) against the parent HDPE material, it is observed that extruded-extruded fusion welds exhibit less reduction in tensile strength. Fig – 4.10 shows % reduction in tensile strength for both types of fusion welds. The reduction in tensile strength is due to stress concentration at the joining line and residual stresses induced in the heat affected zone (HAZ) while heating of joining surfaces. It is because of this stress concentration that all the tensile samples fail near the weld joint.

During this research work, microscopic examination of the weld surfaces is also carried out. The images of the joint section are obtained using microscope at 10x sizes and presented in Fig – 4.11. It is evident from the microscopic images that extruded – injection molded weld samples show an increased lack of fusion as compared to extruded – extruded weld samples. It is because of this lack of fusion that the structural performance of extruded-injection molded joint samples is lower than extruded-extruded joint samples for same welding parameters.

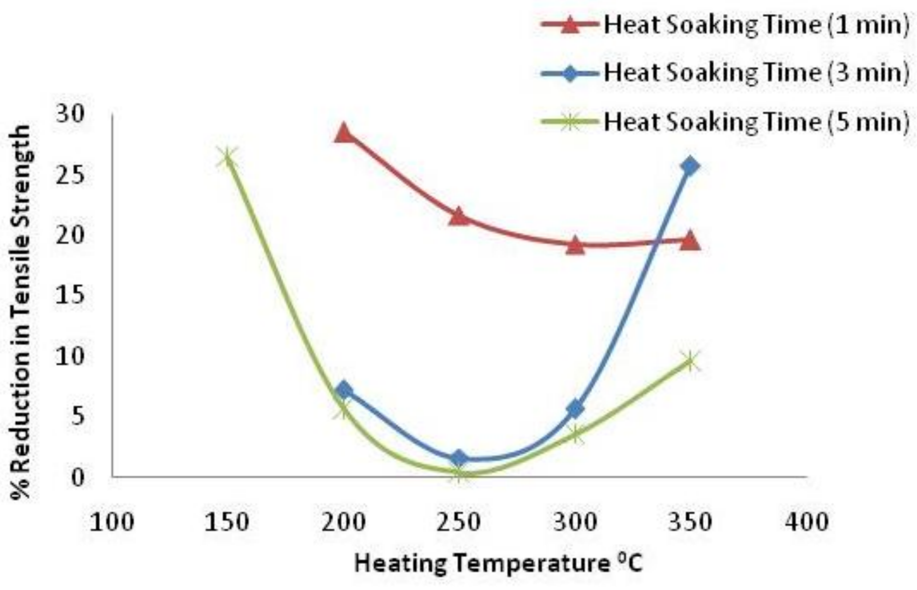


Figure 4.10 (a): % Reduction of Tensile Strength (Extruded – Extruded Joint)

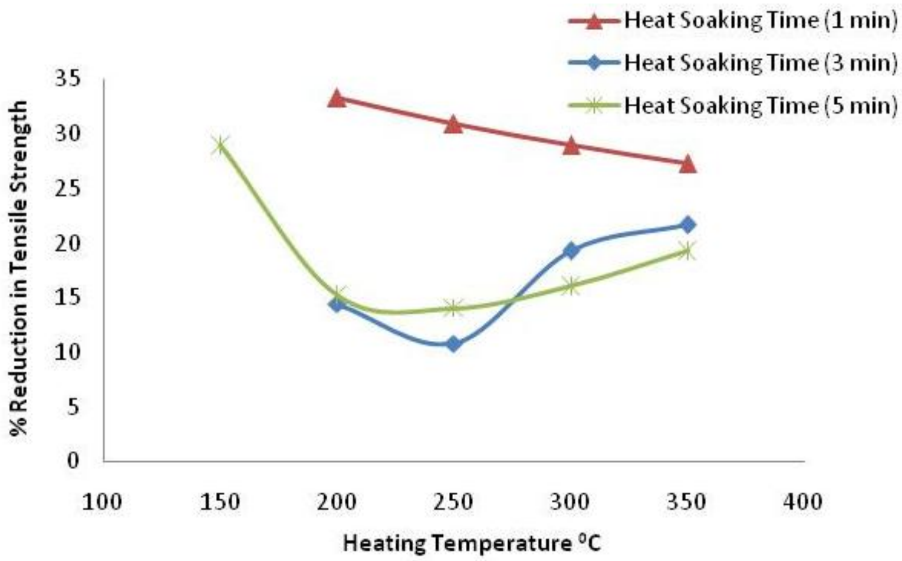


Figure 4.10 (b): % Reduction of Tensile Strength (Extruded – Injection Molded Joint)

Figure 4.10: % Reduction of Tensile Strength

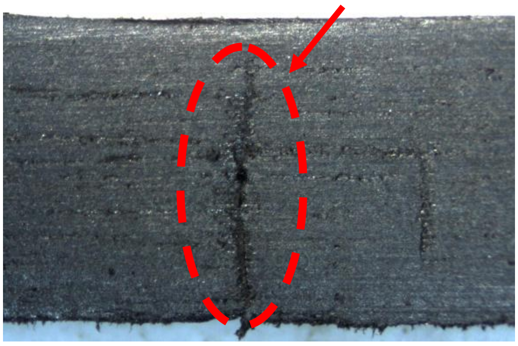
Based on the research work it is now known that structural performance of fusion welds in HDPE is highly affected by the weld parameters. The effect becomes more prominent in case of joints made between extruded and injection molded HDPE materials. Considering the tensile strength of parent HDPE material for designing any HDPE structure may lead to design failures. Since the structural performance of HDPE is affected by the presence of fusion welds, engineers must consider this fact while designing any HDPE infrastructure. Based on present research it is known that joint strength for HDPE material is weakest between extruded and injection molded weld samples, this value of tensile strength can serve as a failure criteria while designing any HDPE installation involving fittings or connections.

Fusion Joint made @ 200 ^{0}C & 3 min
(extruded – extruded)

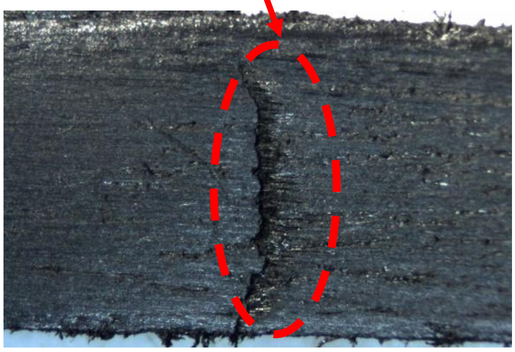
Fusion Joint made @ 200 ^{0}C & 3 min
(extruded – injection molded)

Fusion Joint made @ 250 ^{0}C & 3 min
(extruded – extruded)

Fusion Joint made @ 250 ^{0}C & 3 min
(extruded – injection molded)



Fusion Joint made @ 350 ^{0}C & 3 min
(extruded – extruded)



Fusion Joint made @ 350 ^{0}C & 3 min
(extruded – injection molded)

Figure 4.11: Microscopic View of Fusion Welded Surfaces (Extruded - extruded & extruded - injection molded joints)

5.1. Changing Strain Rate

The structural performance and deformation behaviors of polymeric materials are in-general dependent on strain rates [29]. The main purpose of studying the deformation behavior with changing strain rates is to help design engineers with reliable data related to practical applications. The effect of strain rate becomes more important in case of applications involving higher loading rates [25]. Rate dependent deformation behaviors are important to study as they are used to characterize the behavior of polymeric materials. The effect becomes more significant in case of semi-crystalline polymers such as polyethylene, polypropylene, and ethylene/propylene copolymers [25, 28].

The scope of present research work covers studying the strain rate sensitivity of HDPE material and fusion joints made between HDPE samples. Available research does not study the effect of strain rate sensitivity on fusion welded HDPE samples. The present research work also provides a comparative study on the strain rate sensitivity for both un-welded & fusion welded HDPE samples..

To study the effect of strain rate sensitivity on the structural performance of HDPE material, flat strips are machined from HDPE pipes similar to the weld parameter study. It is ensured with care that machining process does not leave any discontinuity on the HDPE samples that may lead to miss leading results. For this reason HDPE strips are machined with a low depth of cut and high feed rates. These machined flat strips are later cut into standard tensile bars (ASTM D638) and tested against varying displacement rates ranging from 1 – 400 mm/min.

As no pipe line or structure having HDPE pipes is complete without the presence of fusion welds. It is important to study and compare the strain rate sensitivity of extruded (un-welded) and fusion welded HDPE samples. For this purpose fusion joints between the machined HDPE strips are made as discussed in previous chapters at optimum welding parameters suggested in this research work (heat soaking time: 3 min, heating temperature: 250 ^{0}C). These fusion welded HDPE strips are machined to remove the weld beads and later cut into standard tensile bars (ASTM D638). The fusion welded tensile bars then tested against varying displacement rates ranging from 1 – 400 mm/min).

The tensile samples are tested in uni-axial direction at room temperature (25 ^{0}C) using a computerized MTS 210 tensile testing machine with extensometer having a gauge length of 25 mm. The tensile specimens are held between the fixed and movable grips. The samples are aligned properly to ensure that the long axis of the test specimen coincides with the direction of applied displacement and no slippage occurs at the grips. At least three specimens are tested for each value of displacement rates. The tensile testing machine used has a constant rate of crosshead movement with fixed and moveable grips. The process is repeated for all displacement rates and samples (welded & un-welded both) and results are available in next chapters.

Engineering stress/strain curves for HDPE (welded & un-welded samples) at the selected displacement rates of 1 – 400 mm/min are presented in Fig – 5.1 (a, b). Each stress-strain graph shows a different behavior with varying values for tensile strength, total elongation, and elongation at yield etc. As explained earlier that stress strain plot for HDPE can be divided in four distinct regions.

a) Region 1: Elastic region where stress linearly increases with strain

b) Region 2: Yield point that is also the maximum value on stress strain graph

c) Region 3: Continuation of yielding where stress drops causing less change in strain

d) Region 4: also known as cold drawing where stress is almost constant and strain increases

The graphs at varying strain rates show different values of these regions for both types of HDPE samples (welded & un-welded samples). The graphs presented in Fig – 5.1 (a, b) show that for high strain rates HDPE samples do not offer any visible localized neck formation. However for lower values of strain rates, the tensile samples show well developed plastic deformation having visible neck propagation along the entire gauge length.

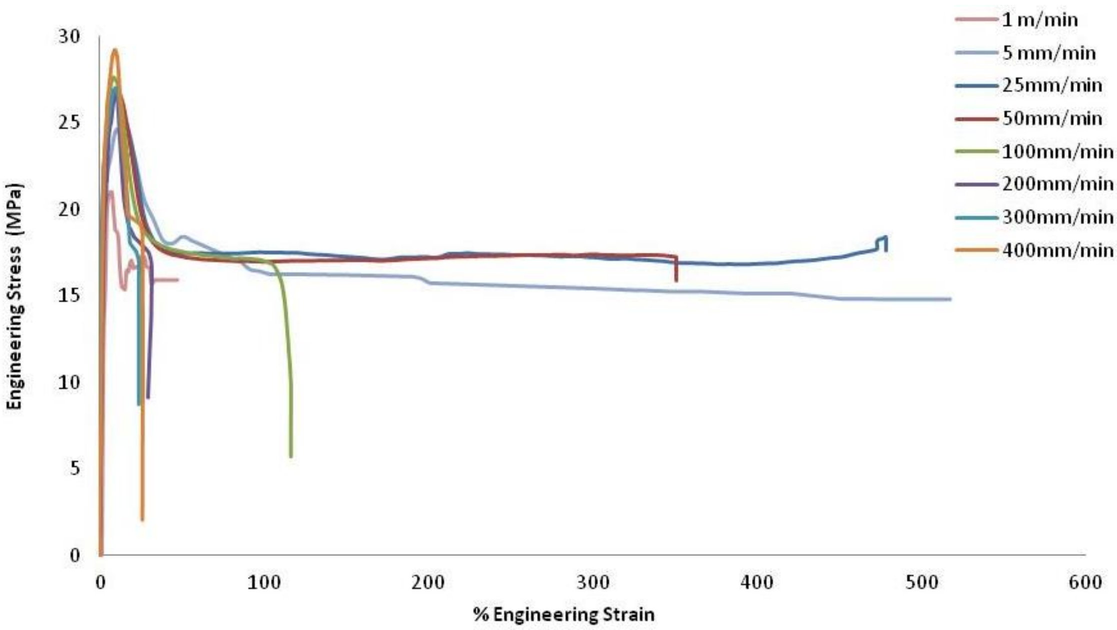


Figure 5.1 (a): Engineering Stress – Strain Curve (Un-Welded HDPE Sample)

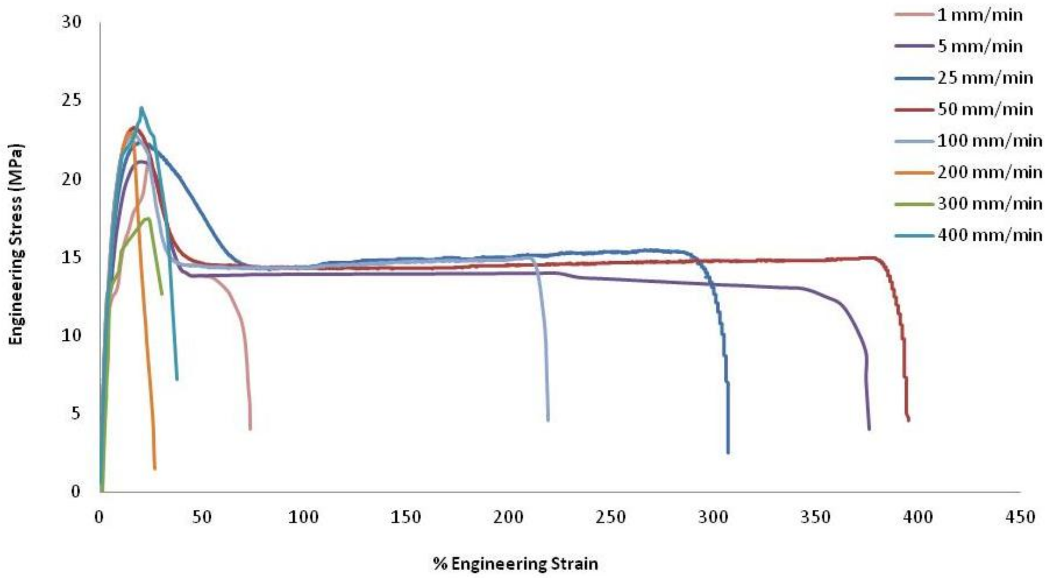


Figure 5.1 (b): Engineering Stress – Strain Curve (Fusion Welded HDPE Sample)

5.1.1. Results Analysis - Changing Strain Rate

Comparison of total elongation-at-fracture for un-welded and fusion welded HDPE samples is presented in Fig – 5.2. The results show that for un-welded and fusion welded HDPE samples the maximum strain-to-fracture is observed at a displacement speed of 5 mm/min, however the values of maximum strain-to-fracture are different for both these sample types. The maximum elongation is 520% for un-welded and 380% for welded HDPE samples. The test data shows that for any particular displacement rates of the tensile test maximum elongation is obtained in un-welded HDPE samples. It is also evident from Fig – 4.16 that for strain rates lower than 200 mm/min, the un-welded HDPE samples offer approx. 27% increase in elongation-at-fracture as compared to fusion welded HDPE samples. The higher values of strain-to-fracture are because of the fact that cold drawing is predominant at lower strain rates. The effect of cold drawing is more in un-welded HDPE samples as they have homogenous material throughout the gauge length without having any stress concentrations. The absence of any stress concentration led to proper material flow during the tensile test and ultimately resulted in an increased elongation at fracture.

The test data also predict (as encircled in Fig – 5.2) that compared to welded samples, un-welded HDPE samples are prone to an increased cold drawing phenomenon. The reason is that for such un-welded HDPE samples the plastic deformation resulted in a well-developed and visible neck at the gauge length. However the effect of cold drawing/neck formation was more dominant at lower strain rates for each type of welded or un-welded HDPE samples.

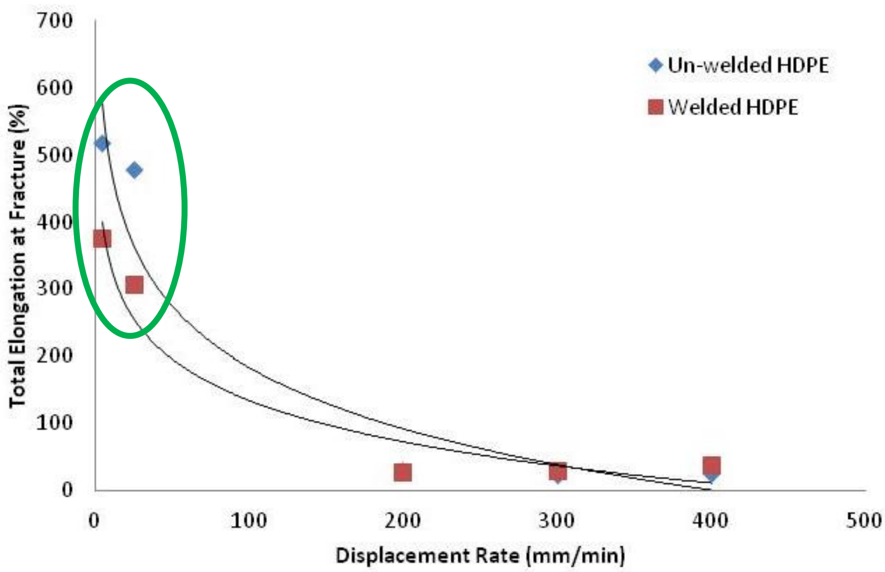


Figure 5.2: Elongation at Fracture vs. Displacement Rate (un-welded/welded HDPE Sample)

As expected, yield stress increases with an increase in strain rate as shown in Fig – 5.3. The reason for this increase in yield stress is because of an increase in strain hardening that requires an additional force against the flow of material. Fig – 5.3 shows that the value of yield stress for un-welded HDPE samples is higher at all strain rates as compared to welded HDPE samples. The reason for a lower yield stress in welded HDPE samples is stress concentration available at the weld region that is in middle of the tensile sample gauge length. During fusion welding of samples, the heat affected zone (HAZ) produces residual stresses near and across the weld area that resulted in lowering the yield strength of welded HDPE samples.

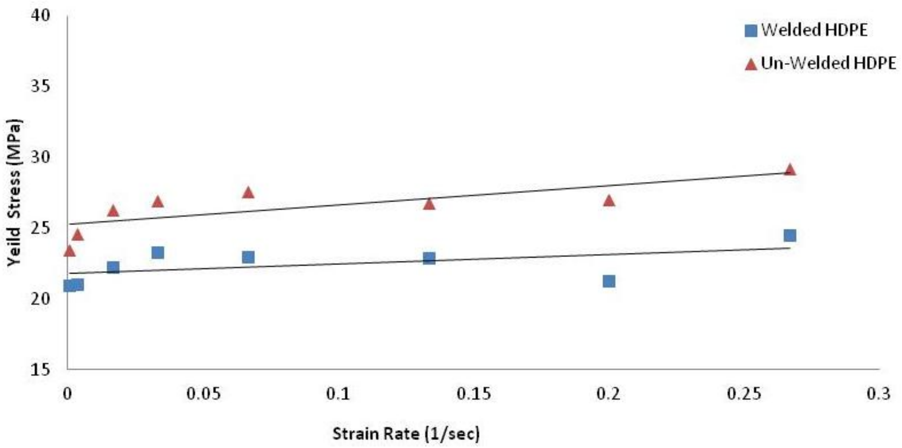


Figure 5.3: Yield Stress vs. Strain Rate (un-welded/welded HDPE Sample)

Due to the in-homogeneous nature of deformation behavior particularly during necking, engineering stress – strain curves can not fully explain the deformation behavior of polymeric materials [25, 29]. In order to have a better understanding of the physical events that happened during the tensile test, values of true stress – strain are plotted in Fig – 5.4 (a, b). The true stress – strain plots are based on constant volume conditions. The true stress – strain plots offer an improved visualization of the mechanical stress response of the micro structural transformation process during deformation. Comparing the true stress – strain plots as shown in Fig – 5.4 (a, b), it is noted that un-welded HDPE samples have greater resistance to failure as compared to welded HDPE samples. The greater resistance to failure offered by un-welded HDPE samples is due to an increased flow stress during the cold drawing range against the welded HDPE samples.

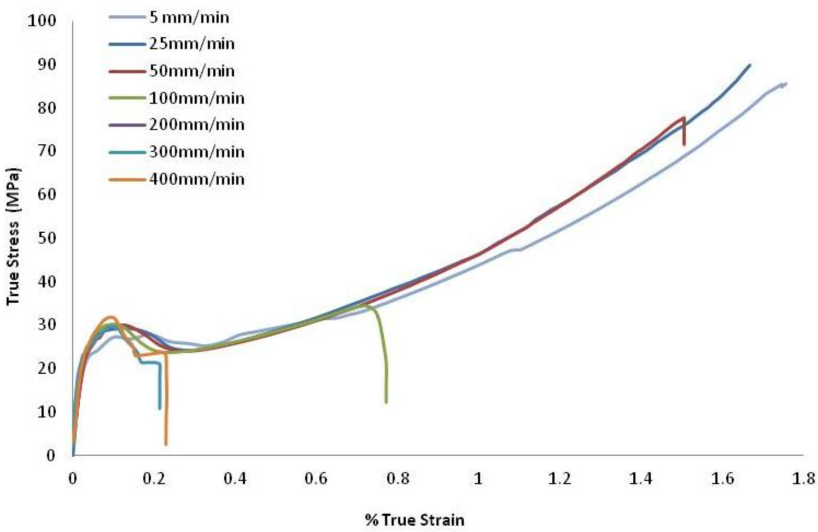


Figure 5.4 (a): True Stress – Strain Curve (Un-Welded HDPE Sample)

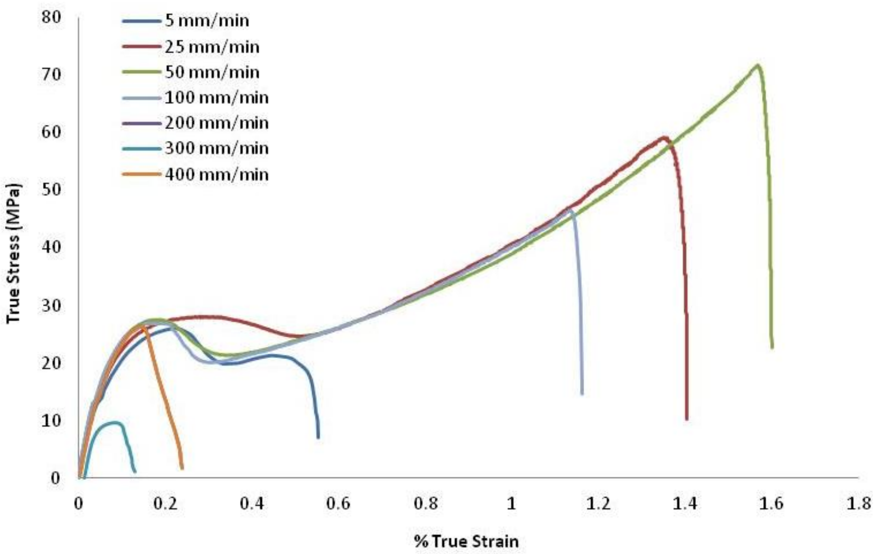


Figure 5.4 (b): True Stress – Strain Curve (Fusion Welded HDPE Sample)

5.1.2. Strain Rate Sensitivity Index

The structural properties of polymeric materials are immensely affected by the formation of neck along the longitudinal direction. The strain rate sensitivity index is defined as a tensile ductility offered by polymeric materials during the propagation of neck where engineering stress does not change much but strain varies greatly. Strain rate sensitivity index denoted by "m" is defined as a slope of ln (true stress) and ln (strain rate). Higher values of strain rate sensitivity index for any material predicts that the material will exhibit high ductility during deformation process [25].

The values of ln(true stress) are obtained at fixed strain levels for both welded & un-welded HDPE samples and plotted against strain rate. Fig – 5.5 (a, b) shows that both welded and un-welded HDPE samples are strain rate sensitive and the behavior for these samples is linear at different strain rates. The values of strain rate sensitivity index for welded and un-welded samples are plotted in Fig – 5.6. The plot of strain rate sensitivity is divided into two strain regimes as indicated in Fig – 5.6. The 1st strain regime refers to low strain levels from end of elastic limit to the start of plastic deformation. The values of strain rate sensitivity index (m) for this regime refers to materials resistance against the development of necking. The values of 'm' in the low strain regime for un-welded and welded HDPE samples are 0.052 and 0.014 respectively. The higher value of 'm' for un-welded HDPE samples suggest that these samples offer maximum resistance to necking. It is observed from Fig – 5.6 that for all strain rate levels, the values of strain rate sensitivity index (m) are high for un-welded HDPE samples.

Regime 2 as indicated in the Fig – 5.6 refers to high strain levels consisting of regions from continuation and end of yielding and further transition to cold drawing. During regime 2 a sharp decrease in the value of ‘m’ is observed that is correlated to the transition from low to high strain rate levels. In regime 2, the values of ‘m’ for un-welded and welded HDPE samples are 0.027 and 0.012 respectively representing materials resistance to necking and increased vulnerability to greater plastic flow during cold drawing process.

The high value of strain rate sensitivity index (m) for un-welded HDPE samples is consistent with the observation that these samples exhibit delayed tensile failure at all strain levels as compared to fusion welded HDPE samples.

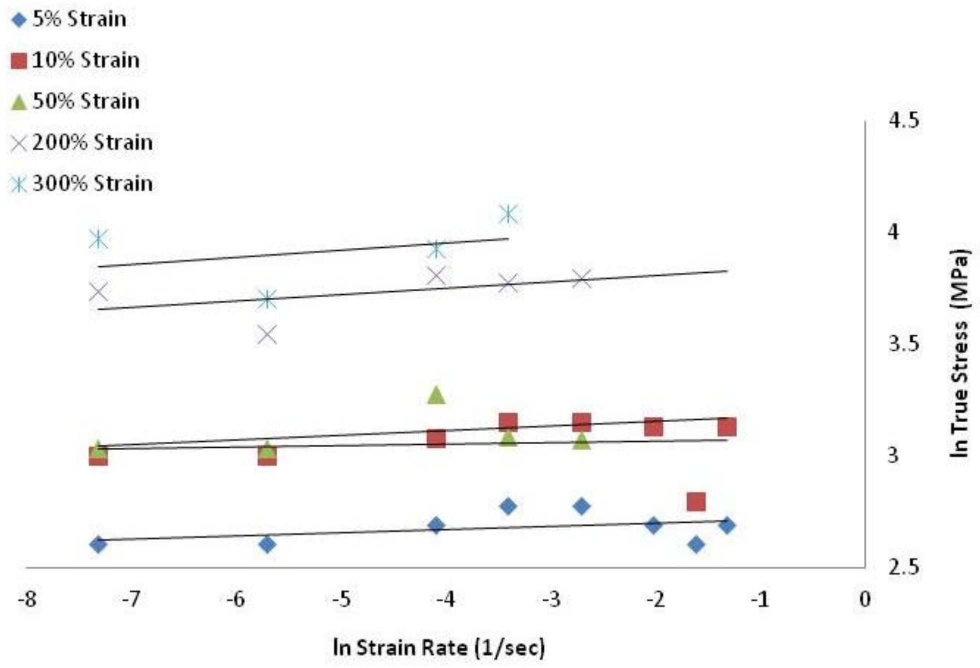


Figure 5.5 (a): ln (true stress) – ln (strain rate) for Fusion Welded HDPE samples

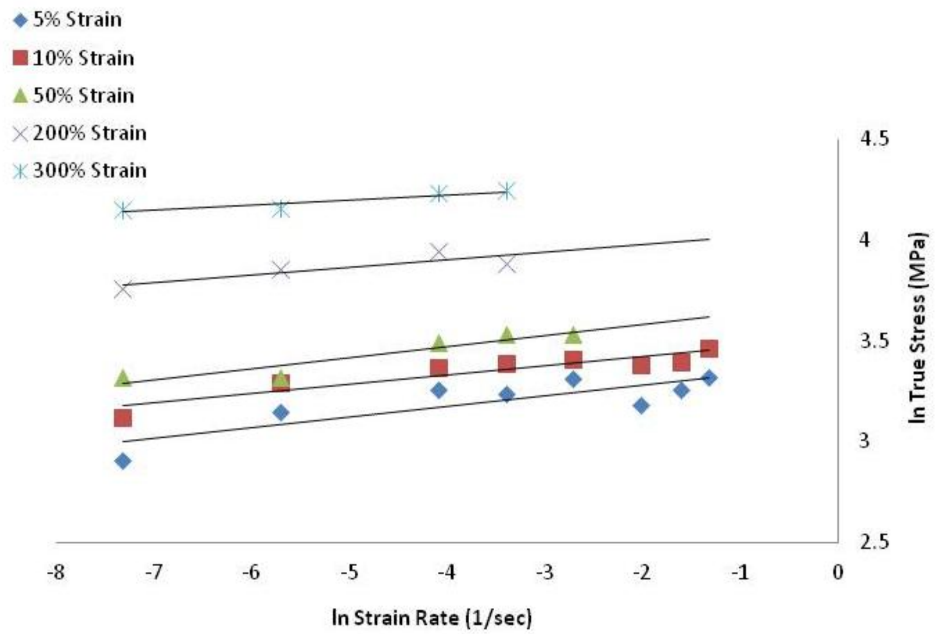


Figure 5.5 (b): ln (true stress) – ln (strain rate) for Un-Welded HDPE samples

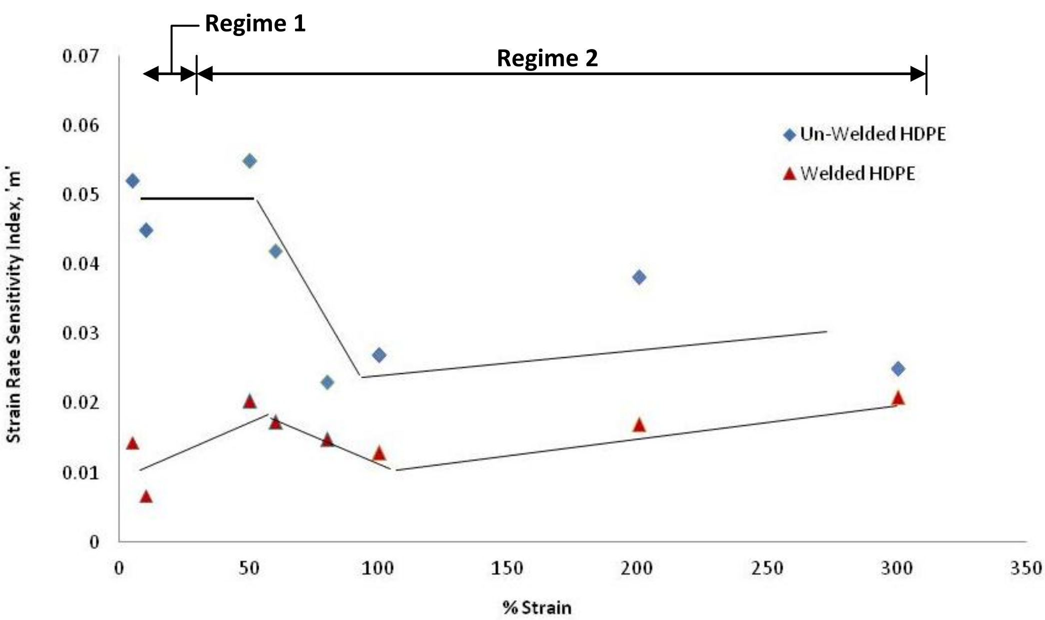


Figure 5.6: Strain Rate Sensitivity Index (m) as a Function of Strain (Un-Welded & Welded HDPE Samples)

5.1.3. Micro-Structural Evaluation

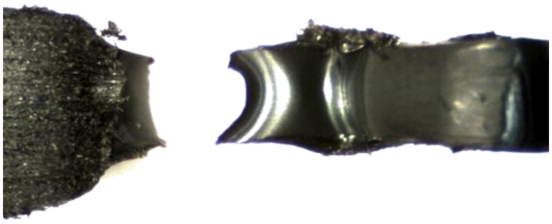
Microscopy of tensile samples is performed and the fracture surfaces of HDPE welded & un-welded are studied for comparison. It was observed that fracture surfaces of welded HDPE samples show almost 100% ductile nature by causing material flow in the direction of applied loadings. Understanding that the inherent stress concentration is expected to be high for welded HDPE samples the fracture surfaces show sudden sample failure without or little neck formation. The microscopic images (at 10x magnification) of fracture surfaces obtained are presented in Fig – 5.7.

Un-Welded HDPE Tensile Samples

Tensile test @ strain rate 25mm/min

Tensile test @ strain rate 50mm/min

Fusion Welded HDPE Tensile Samples



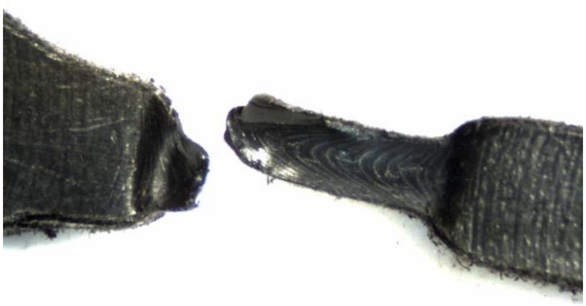
Tensile test @ strain rate 25mm/min

Tensile test @ strain rate 50mm/min

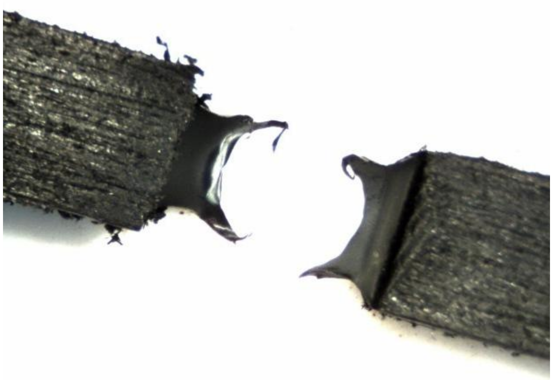
Un-welded HDPE Tensile Samples | **Fusion Welded HDPE Tensile Samples**

Tensile test @ strain rate 100mm/min

Tensile test @ strain rate 100mm/min

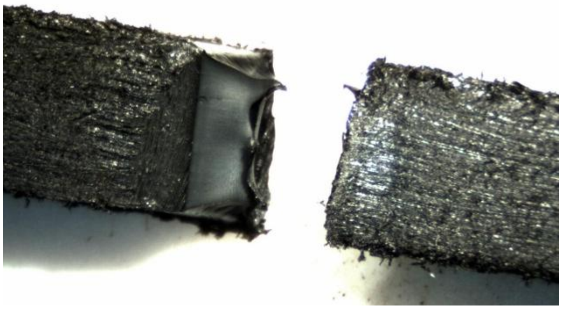


Tensile test @ strain rate 200mm/min



Tensile test @ strain rate 200mm/min

Tensile test @ strain rate 300mm/min



Tensile test @ strain rate 300mm/min

Figure 5.7: Microscopic Images of Fracture Surfaces

6.1. Research Findings

- Tensile strength of available extruded HDPE material is experimentally calculated as 25 MPa.
- Tensile strength of available injection molded HDPE material is experimentally calculated as 24.5 MPa
- The tensile test results show that extruded HDPE samples have an almost equal tensile strength as compared to injection molded HDPE material.

6.1.1. Effect of Fusion Welding Parameters on Structural Performance

- For HDPE material, the structural performance of fusion welds is highly affected by weld parameters. The tensile strength may decrease upto 31% for fusion joints made using inappropriate weld parameters.
- The optimum weld parameters do not greatly differ for fusion joints if made between extruded-extruded and extruded-injection molded HDPE samples. However the values of tensile strength are different for both types of fusion joints.
- Weld bead size estimation does not completely represent the quality of a fusion welded joint. Tensile test serves a better parameter quantifying the structural performance of fusion weld in HDPE.
- At corresponding optimum weld parameters, the fusion joints made between extruded-extruded HDPE samples offer 13% increased tensile

strength and 11% increased elongation at fracture when compared to injection molded HDPE material.

6.1.2. Effect of Strain Rate on Structural Performance

- For HDPE material, the initial and post yielding behavior is highly sensitive to changing strain rates.
- The mechanical properties and deformation mechanisms for both un-welded and welded HDPE samples are strain rate dependent.
- Un-welded HDPE samples offer better resistance against neck formation as compared to welded HDPE samples. Due to this effect un-welded HDPE samples exhibit 20% increased yield strength at same rate levels.
- Un-welded HDPE samples have higher flow stress thus offer increased time to tensile failure and exhibit more strain rate hardening than the welded HDPE samples. The effect is more prominent at low strain rate levels where the un-welded HDPE samples results in approx. 27% increased elongation at fracture as compare to fusion welded HDPE samples.
- The values of strain rate sensitivity index for Un-welded and fusion welded HDPE samples are in the range of (0.055 – 0.026) and (0.005 - 0.02) respectively.

6.2. Conclusion

The structural performance of HDPE is affected by changing welding parameters and the presence of fusion welds in the infrastructure. Design engineers must consider this factor into consideration as using the tensile strength of parent HDPE material in designing may lead to design failures. The joint strength for HDPE material is weakest between extruded and injection molded weld samples, hence this value of tensile strength can serve as a failure criteria while designing any HDPE installation involving fittings or connections.

Accurate engineering designs also require the study of deformation behavior at different strain rates as the mechanical properties and deformation mechanisms are greatly dependent on the applied strain rates. Strain rate sensitivity index is a good pointer explaining the nature of deformation process and also helps in comparing deformation resistance of different polymeric materials. Un-welded HDPE samples having high strain rate sensitivity index (m) are more vulnerable to mechanically induced damage.

6.3. Future Work

During the thesis, analysis was undertaken to study the structural performance of butt fusion welds against varying weld parameters and strain rates. Following future work can be carried as an extension of this research thesis and is recommended:

a) Effect of fatigue or cyclic loadings on butt fusion welds in HDPE

b) Characterization of fusion welds using Atomic Force Microscopy (AFM)

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