

**T.C.
ISTANBUL GEDİK UNIVERSITY
INSTITUTE OF GRADUATE STUDIES**



**DESIGNING AN AUTOMATED BUTT WELDING MACHINE FOR
WELDING HIGH-DENSITY POLYETHYLENE PIPES AND
INVESTIGATING BUTT WELDING PARAMETERS**

MASTER'S THESIS

Sangwani SINKALA

**Mechatronics Engineering Department
Mechatronics Engineering Master Program**

FEBRUARY 2022

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T.C.
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Enstitümüz, Mechatronics Engineering Department İngilizce Tezli Yüksek Lisans Programı 191203004 numaralı öğrencisi Sangwani Sinkala 'nın “Designing An Automated Butt Welding Machine for Welding High-Density Polyethylene Pipes and Investigating Butt Welding Parameters” adlı tez çalışması Enstitümüz Yönetim Kurulunun 10/02/2022 tarihinde oluşturduğu jüri tarafından *Oy Birliği* ile Yüksek Lisans tezi olarak *Kabul* edilmiştir.

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DECLARATION

I, Sangwani Sinkala, do hereby declare that this thesis titled as “Designing an Automated Butt Welding Machine for Welding High-Density Polyethylene Pipes and Investigating Butt Welding Parameters” is original work done by me for the award of the masters degree in the faculty of Mechatronics Engineering. I also declare that this thesis or any part of it has not been submitted and presented for any other degree or research paper in any other university or institution. (10/02/2022)

Sangwani SINKALA



I dedicate this work to my parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. Finally, I dedicate this work to my fiancé who has been a constant source of support and encouragement during the challenges of graduate school and life, I am truly thankful for having you in my life.

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LIST OF ABBREVIATIONS

UV	: Ultraviolet
CB	: Carbon black
NDT	: Non-destructive tests
PENT	: Pennsylvania edge-notched tensile
CNC	: Computer Numerical Control
T1	: Alignment period when initializing butt fusion welding
T2	: Heating-up period during butt fusion welding
T3	: Change over time during butt fusion welding
T4	: Build-up time in seconds specified during fusion for HDPE pipes
T5	: The Cooling period when the butt-fusion welding procedure is completed
ISO	: International Organization for Standardization
QFD	: Quality Function Deployment
H.O.Q	: House of Quality
HDPE	: High-Density Polyethylene
PLC	: Programmable Logic Controller
PID	: Proportional–Integral–Derivative
MFR	: Melt Flow Rate
AWWA	: American Water Works Association
PVC	: Polyvinyl Chloride
PP	: Polypropylene
P	: The applied pressure which is the ratio of the HDPE pipe’s cross-sectional area multiplied by the thrust coefficient of HDPE to the Cross-sectional area of the welding machine’s hydraulic cylinder, $P = A_P \cdot C_T / A_{HC}$
<i>P_{hs}</i>	: The operational pressure for the hydrostatic pressure test
<i>A_p</i>	: The pipe’s cross-sectional area
<i>C_T</i>	: The thrust coefficient for HDPE, 1.5 kg/cm ²
<i>A_{HC}</i>	: The cross-sectional area of the machine’s hydraulic cylinder, 14.13 cm ²
P1	: The welding pressure is defined as the sum of the drag pressure and applied pressure.
<i>P_d</i>	: The drag pressure. The force is required to overcome the internal friction of the equipment while moving the pipes.
P2	: Applied near-zero pressure during the continuous heating period.
P3	: $P3 = P1/2$, the second stage of the applied build-up pressure for a successful gradual application of welding pressure P1
HMI	: Human Machine Interface
ASTM	: American Society for Testing and Materials
PE	: Polyethylene
DVS	: Deutscher Verband für Schweißen (German Welding Society)

PPI TR-3	: Plastic Pipe Institute, Policies, and Procedures for Developing Hydrostatic Design Basis
CAD	: Computer-aided design
O.D	: HDPE pipe Outer diameter
Pwt	: HDPE pipe wall thickness
PTFE	: Poly-tetrafluoroethylene, trade name Teflon
d1-9	: Test specimens for determining carbon black dispersion
Th	: HDPE pipe wall thickness
RT	: Room temperature
Y1-3	: Butt fused samples performed by manual butt-fusion welding machine
W1-3	: Butt fused samples performed by semi-automatic butt-fusion welding machine
S1-3	: Un-welded pipe samples
HAZ	: Heat affected zone
ARC	: Area of a right cylinder. Which is defined when the axis (one of the sides of the rectangle) is perpendicular to the radius (r), then the cylinder, so formed, is called a right circular cylinder

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DESIGNING AN AUTOMATED BUTT WELDING MACHINE FOR WELDING HIGH-DENSITY POLYETHYLENE PIPES AND INVESTIGATING BUTT WELDING PARAMETERS

ABSTRACT

Due to the wide use of butt fusion (heated tool) welding in pipeline engineering and construction, butt-fused joints should be observed so that welding defects are reduced in projects. This study aimed at improving the heated tool welding method by designing a semi-automatic butt welding machine using ensured corrective quality improvement, the resulting butt-fused joints were per DVS 2207 international butt welding standard and eliminated welding defects that may result from mishandling of the welding equipment. A new welding algorithm that improved the resulting butt-fused joints in line with the recommended method described by the process in the literature was applied in the designed semi-automatic butt-fusion machine. The gradual application of the welding pressure parameter proposed in this research which directly affects the quality of the weld was applied linearly and continuously in the welding procedure proposed by the literature. However, it was observed that the result of linearly applying the welding pressure at T4 exposed the less heated surfaces of the heated zone on the welds which resulted in the formation of weak joints due to insufficient polymer diffusion during the fusion process. To overcome this, welding pressure was gradually increased when joining the HDPE pipes since the heated surfaces of the joints to be welded were not suddenly ejected; the resulting joint provided better mechanical, chemical, and performance properties. The identified series of defects in the literature and on-site experience included inadequate entanglement of HDPE molecular chains at the joint causing poor mechanical performance of the derived butt fused weld. When the welding pressure at build-up time T4 was linearly increased at once as described in the literature, the melted surfaces to be joined on either end of the pipe were easily displaced and in most instances overflow, hence exposing the unheated hard surfaces of the joints. This resulted in any or all of the three welding defects: cold welds, bead misalignment, and non-uniform penetration of polyethylene chains. This was because the hard unheated surfaces could not enhance the penetration of polyethylene chains, they lacked an even and homogenized distribution of melted PE material during the joining period and finally had poor intermolecular diffusion taking place from one pipe to the other which also affected the smooth distribution of carbon black (CB) to the butt fused joints. The identified defects can be avoided by either automating the system as proposed in this research, or by employing expensive professional experienced operators when welding HDPE pipes using the manual machine. This research tackled the common flaws by automating the machine and integrating it with a better welding algorithm, at T4 initial welding pressure is 0 N/mm^2 , build-up welding pressure was applied as follows, $(0 \text{ to } P2) \text{ N/mm}^2$, then finally $(P3 \text{ to } P1) \text{ N/mm}^2$ within 10 seconds. The mechanical properties, chemical properties, and performance of the fused joints were tested using the test method described in HDPE pipe technical standards. It was observed that the resulting joints

exerted identical mechanical properties to the parent pipe because the new welding algorithm integrated into the designed mechatronics system guaranteed that no exposure of the partially cooled melted PE chains had occurred before fusion during the pipe joining the stage at T4. This was successfully achieved by carefully optimizing a uniform force in this case welding pressure which was applied to facilitate the homogenous thermal movement of the melted material which was strategically adjusted to eliminate exposure of the cold zones during the fusion stage. Since a carefully optimized unvarying welding pressure was applied in the presence of heat during fusion at T4, such favorable conditions enhanced the dispersion of polyethylene chains throughout the material's matrix resulting in adequate meshing within the PE micro-structure chains.

The butt-fused samples from the semi-automatic welding machine were characterized by better mechanical strength, longer life span, and excellent performance compared to the butt fused samples from the manually operated welding machine which was characterized by poor mechanical strength and performance in some joints because the fused joints obtained from the manual welding machine had some welded pipe samples resulting in brittle failure mode when the tensile strength test was conducted, this meant that not all joints guaranteed a successful polyethylene entanglement during fusion at T4. The resistance to internal hydrostatic pressure at 80°C for 165 hours, under the pressure of 5.4 MPa for both machines' butt fused pipe samples was performed to evaluate a long-term internal pressure rating by investigating the material's enduring strength, functioning temperature, application settings, and pipe size, tests had shown that both the manual welding machine and automatic welding machine samples did not rupture or break after 165 hours. Also, the oxidation induction time (OIT) for both sample groups obtained by either manual butt fusion or automatic butt fusion was more than 20 minutes because the samples used were produced from the same batch of raw materials. Therefore, it was safe to say the method of fusion used had a negligible effect on the time it took for oxidation to occur on the welded pipe samples. However, it was observed that a nonhomogeneous distribution of CB in the PE matrix for samples performed by the manual welding machine had a significant effect on the resulting butt-fused joints' mechanical performance. This is why some of the resulting fused joints from the manual welding machine resulted in brittle failure mode during the tensile strength test.

Keywords: *Corrective Quality Improvement, Butt Fusion Machine, Cold Weld, Internal Hydrostatic Pressure, Oxidation Induction Time*

YÜKSEK YOĞUNLUKLU POLİETİLEN BORULARIN KAYNAĞI İÇİN OTOMATİK ALIN KAYNAK MAKİNESİ TASARIMI VE ALIN KAYNAK PARAMETRELERİNİN İNCELENMESİ

ÖZET

Alın kaynağının boru hattı ve yapımlarında yaygın olarak kullanılması nedeniyle, projelerde kaynak hatalarının azaltılması için alın kaynaklı bağlantılara dikkat edilmelidir. Bu çalışma, düzeltici kalite iyileştirme kullanılarak yarı otomatik bir alın kaynak makinesi tasarlanarak ısıtmalı kaynak yöntem proseslerini iyileştirmeyi amaçlamıştır. Tasarlanan makine, elde edilen alın kaynaklı bağlantıların DVS 2207 Uluslararası Alın Kaynak Standardına uygun olmasını sağlar ve kaynak ekipmanının yanlış kullanılmasından kaynaklanabilecek kaynak hatalarını ortadan kaldırır. Tasarlanan yarı otomatik alın kaynak makinesinde, alın kaynak standardı ve literatürde önerilen yöntem doğrultusunda elde edilen alın kaynaklı birleştirmeleri iyileştiren yeni bir kaynak algoritması uygulanmaktadır. Kaynak kalitesini doğrudan etkileyen bu araştırmada önerilen kaynak basıncı parametresinin kademeli uygulaması, literatürde önerilen kaynak prosedüründe doğrusal ve sürekli olarak uygulanmaktadır. Ancak, T4'te kaynak basıncının lineer olarak uygulanması sonucunun, kaynaklar üzerinde ısınan bölgenin daha az ısınan yüzeylerini açığa çıkardığı ve bunun sonucunda eritme işlemi sırasında yetersiz polimer difüzyonu nedeniyle zayıf bir bağlantının oluşmasına neden olduğu görülmüştür. Bunu aşmak için, HDPE boruların birleştirilmesi sırasında kaynak yapılacak bağlantıların ısınan yüzeyleri aniden dışarı çıkmadığından kaynak basıncı kademeli olarak uygulanmalıdır; ortaya çıkan kaynak daha iyi mekanik, kimyasal ve performans özellikleri sağlar. Literatürde ve saha deneyimlerinde tanımlanan kaynak hataları HDPE moleküler zincirlerinin yetersiz oluşmasının alın kaynaklı birleştirmede zayıf mekanik performansına neden olmasını içermektedir. Kaynak basıncı T4 literatürde anlatıldığı gibi bir kerede aniden uygulandığında, borunun her iki ucunda birleştirilecek olan erimiş yüzeyler kolayca yer değiştirmiş ve çoğu durumda taşmış, dolayısıyla kaynak yapılacak bağlantıları ısıtılmamış ve sert yüzeyleri açığa çıkarmıştır. Bu durum, üç hatadan herhangi birine veya tümüne neden olur; soğuk kaynak elde etmesi, yanlış hizalanma ve polietilen zincirlerin düzgün olmayan penetrasyonu. Bunun nedeni, ısıtılmamış sert yüzeylerin polietilen zincirlerinin penetrasyonunu artıramamasıydı, birleştirme süresi boyunca erimiş PE malzemesinin eşit ve homojen dağılımının olmamasındandır, ve son olarak bir borudan diğerine zayıf moleküller arası difüzyon meydana geldiğinden durum karbon siyahının (CB) alın kaynak bağlantılara düzgün dağılımını etkiler. Belirlenen kusurlar ve kaynak hataları, ya bu araştırmada önerildiği gibi sistemi otomatikleştirerek ya da HDPE boruları manuel makine kullanarak kaynak yaparken profesyonel deneyimli mühendisler ve teknisyenler çalıştırarak önlenabilir. Bu araştırmada, makineyi otomatikleştirerek ve daha iyi bir kaynak algoritması ile entegre ederek yaygın kaynak hataları ele alınmıştı, T4 başlangıç kaynak basıncı 0 N/mm^2 , kaynak basıncı oluşturma aşağıdaki gibi uygulandı, (0 to P2) N/mm^2 , ardından son olarak (P3 to P1) N/mm^2 , 10 saniye içinde. Kaynak bağlantılarının mekanik özellikleri, kimyasal özellikleri ve performansı, HDPE boru teknik standartlarında açıklanan test yöntemi kullanılarak test edilmiştir. Ortaya çıkan bağlantıların ana boruya aynı

mekanik özellikleri uyguladığı gözlemlendi, çünkü tasarlanan mekatronik sistemine entegre edilen yeni kaynak algoritması, T4'te boru birleştirme aşaması sırasında füzyondan önce kısmen soğutulmuş erimiş PE zincirlerinin maruz kalmamasını garanti eder. Bu, ergimiş malzemenin homojen termal hareketini kolaylaştırmak için uygulanan ve füzyon aşaması sırasında soğuk bölgelerin maruz kalmasını ortadan kaldırmak için stratejik olarak ayarlanan kaynak basıncının bu durumda düzgün bir kuvvetin dikkatlice optimize edilmesiyle başarılı bir şekilde elde edilmiştir. T4'te füzyon sırasında ısı mevcudiyetinde dikkatle optimize edilmiş değişmeyen bir kaynak basıncı uygulandığından, bu tür uygun koşullar, polietilen zincirlerinin malzemenin matrisi boyunca dağılımını artırarak, PE mikro yapı zincirleri içinde yeterli bağlantı oluşumuna neden olmuştur. Yarı otomatik kaynak makinesinden alınan alın kaynaklı numuneler, manuel olarak çalıştırılan kaynak makinesinden alınan alın kaynaklı numunelere kıyasla daha iyi mekanik mukavemet, daha uzun ömür ve mükemmel performans ile karakterize edilmiştir. Manuel kaynak makinesinden T4'te füzyon sırasında elde edilen erimiş bağlantıların bazı kaynaklı boru numuneler sahip olması nedeniyle, bazı bağlantılarda zayıf mekanik dayanım ve performans ile karakterize edilen, çekme dayanımı testi yapıldığında gevrek arıza moduna neden olmuştur. Bu, tüm bağlantıların başarılı bir polietilen garanti etmediği anlamına gelir. Her iki makinenin alın kaynaklı boru numuneleri için 80°C, 165 saat içerisinde 5,4 MPa basınç altında dahili hidrostatik basınca direnç, malzemenin dayanıklılık, çalışma sıcaklığı ve uygulama ayarlarını inceleyerek uzun vadeli bir iç basınç derecesini değerlendirmek için gerçekleştirilmiştir. Boru boyutu, testler, hem manuel kaynak makinesi hem de otomatik kaynak makinesi numunelerinin 165 saat sonra yırtılmadığını veya kırılmadığını göstermiştir. Ayrıca, manuel kaynak makinesi veya otomatik kaynak makinesi ile elde edilen her iki numune grubu için oksidasyon indüksiyon süresi (OIT), kullanılan numuneler aynı hammadde partisinden üretildiği için, oksidasyon indüksiyon süresi 20 dakikadan fazlaydı. Bu nedenle, kullanılan kaynak makinesi kaynaklı boru numunelerinde oksidasyonun meydana gelmesi için geçen süre üzerinde ihmal edilebilir bir etkiye sahip olduğunu söylemek güvenlidir. Ama, manuel kaynak makinesi tarafından gerçekleştirilen numuneler için PE matrisinde CB'nin homojen olmayan bir dağılımının, elde edilen alın kaynaklı bağlantıların mekanik performansı üzerinde önemli bir etkiye sahip olduğu gözlenmiştir. Bu nedenle, manuel kaynak makinesinden kaynaklanan bazı kaynak bağlantıların çekme mukavemeti testi sırasında gevrek davranış gösterdiği tespit edilmiştir.

Anahtar Kelimeler: *Düzeltilici Kalite İyileştirme, Alın Kaynak Makinesi, Soğuk Kaynak, İç Basınç Direnci Tayini, Oksidasyon Indüksiyon Süresi*

1. INTRODUCTION

1.1 Research Topic

In butt fusion welding, the joining pressure parameter at T4 which directly affects the quality of the weld was applied linearly and continuously in the welding procedure described by the literature. However, it was observed that the result of linearly applying the joining pressure at T4 not only exposes the less heated surfaces of the heated zone on the welds but also contributes to the non-homogenous displacement of CB in the PE matrix. CB compound is a widely used additive in the production of pipe grade HDPE, besides offering protection from UV rays exposure to the material it also contributes to its mechanical performance. The identified series of defects resulting from linearly applying the joining pressure during the fusion process at T4 causes the formation of a weak joint which is characterized by insufficient polymer diffusion and a non-homogenous distribution of CB in the PE microstructure, hence significantly reducing the mechanical performance of the fused joint. To overcome this, during fusion the joining pressure at T4 should be gradually applied. In this research, the gradual application of joining pressure at T4 was achieved by developing a new welding algorithm that was integrated into the existing butt welding machine manufactured by Turan Makina Borfit.

Figure 1.1 shows the new welding algorithm developed for this research including all welding parameters.

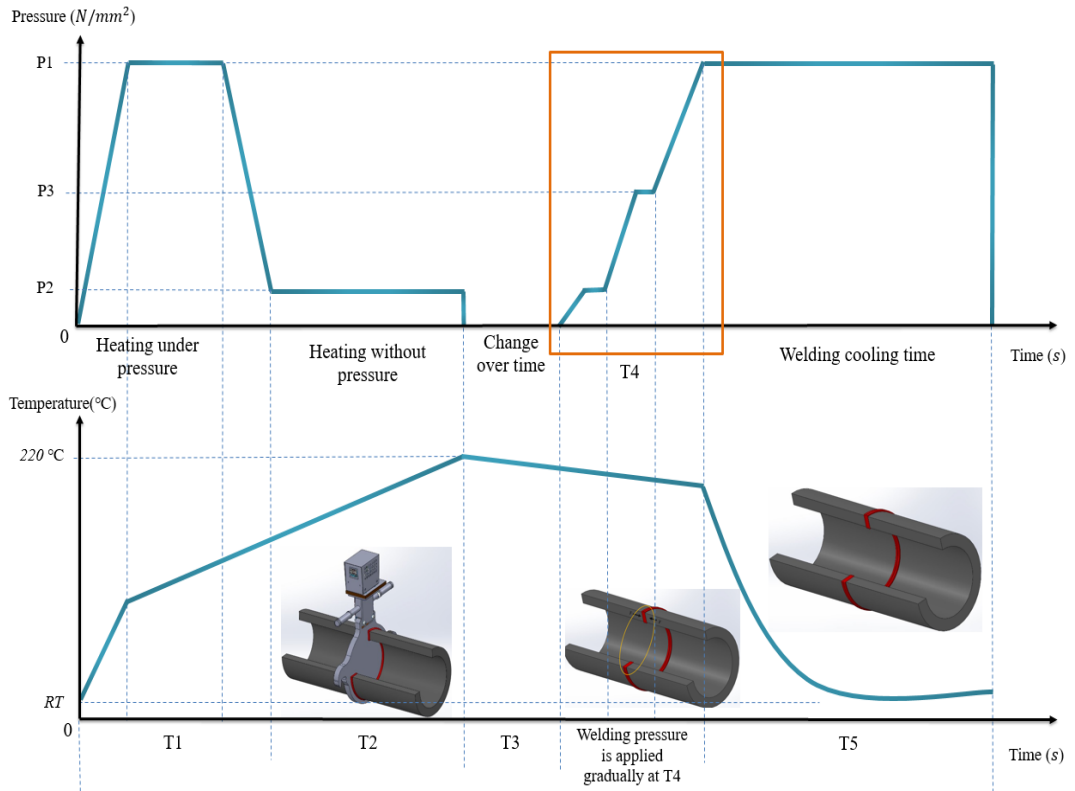


Figure 1.1: Hypothesis and research topic

With the new welding algorithm integrated into the PLC program, the semi-automatic welding machine ensured that;

- i. The less heated surfaces of the joints to be welded were not exposed or suddenly ejected when applying joining/welding pressure at T4.
- ii. The homogenous distribution of CB in the PE microstructure was successful.

Successfully implementing the above solutions in the mechatronic system produced joints that provided better mechanical and chemical performance properties. The mechanical performance and chemical properties of the fused joints were tested using the test method described in HDPE pipe technical standards then the obtained results were compared to the literature.

1.2 Objective

The main objective of this study was to improve the heated tool welding method by modifying the design of an existing semi-automatic butt welding machine using corrective quality improvement, ensuring that the resulting butt-fused joints are as per DVS 2207 international butt welding standard while eliminating welding errors

that may result from mishandling of the welding equipment. A new welding algorithm that improves the resulting butt-fused joints in line with the recommended method described by the butt welding standard and literature is applied in the designed semi-automatic butt-fusion machine

The manual and automated butt welding machines have been used and designed by many industries in this field. To come up with a unique design that tackles most of the challenges faced by consumers can be challenging. Nevertheless, with research, technical experience, and reference to the literature, this research came up with a solution to the challenges which were then implemented in the designed automatic butt fusion machine. As a result, the better design features integrated customer requirements and product developments which lead to a successful mechatronics system design.

The identified series of flaws in the literature and on-site experience may include inadequate entanglement of HDPE molecular chains at the joint causing poor mechanical performance of the derived butt fused weld. When the joining pressure at T4 is applied linearly as shown in the literature, the melted surfaces to be joined on either end of the pipe can be easily displaced and in most instances spill out, hence exposing the unheated hard surfaces of the joints. This will result in any or all of the three errors: cold welds, bead misalignment, and non-uniform penetration of polyethylene chains. This is because the hard unheated surfaces cannot enhance the penetration of polyethylene chains, they lack an even and homogenized distribution of melted PE material during the joining period, and finally have poor intermolecular diffusion taking place from one pipe to the other which can also affect the homogenous distribution of carbon black (CB) to the butt fused joint.

These defects can be avoided by either automating the system as proposed in this research, or by employing expensive skilled engineers or technicians when welding HDPE pipes using the manual machine. This research tackled the common flaws by automating the machine.

Details can be seen on the welding chart shown in Figure 1 adapted for this paper, at T4 when welding pressure is 0 N/mm^2 , joining or welding pressure should be applied as follows;

$(0\text{ N/mm}^2), (0\text{ to P2})\text{ N/mm}^2, (P3\text{ to P1})\text{ N/mm}^2$, within 10 seconds, the

resulting joint exerts similar properties to the parent pipe.

The designed mechatronics system guaranteed that no exposure of the partially cooled melted PE chains before fusion occurred during welding at T4, because a carefully optimized uniform force, in this case, joining pressure was applied to facilitate the homogenous thermal movement of the melted material which was strategically adjusted to eliminate exposure of the cold zones during the fusion stage. Since a carefully optimized unvarying welding pressure was applied in the presence of heat during fusion at T4, such favorable conditions enhanced the dispersion of polyethylene chains throughout the material's matrix resulting in adequate meshing within the PE micro-structure chains.

The designed mechatronics system was used to eliminate the major challenges currently being faced by engineers and technicians during pipe installation and servicing. The method used to design the machine, and the applied computer algorithm implemented to completely remove cold welds, bead misalignment, and non-uniform penetration of polyethylene chains will be discussed in the chapters to follow.

2. LITERATURE REVIEW

2.1 High-Density Polyethylene (HDPE) in Pipe Systems

Plastic is obtained by the chemical processing of natural materials such as crude oil, natural gas, coal, and cellulose. To obtain plastic raw material, unit cells called monomer derivatives are obtained by chemically treating ethylene products obtained from the distillation of crude oil. Then, consisting of the same type of single-molecule, the monomer derivative is treated via the process called polymerization, millions of these unit cells are bonded to each other forming vast and long molecular chains, i.e. plastic raw materials. In other words, polymerization is the process of forming vast and very long molecular chains by bonding monomer unit cells consisting of only a single molecule using chemical catalysts. An ethylene monomer, a crude oil derivative is processed by polymerization to produce polyethylene raw material. Semi-crystalline thermoplastics are structures consisting of only hydrogen and carbon atoms. Their molecular structures consist of partly amorphous bonds and partly crystalline bonds. Example; polyethylene, polypropylene.

To design an efficient HDPE piping system with optimum performance, an essential understanding of the material's properties and characteristics is a significant part of the design process for any piping system. Having a great understanding of the material results in a successful design and project. HDPE is a polymeric material also known as thermoplastic. Thermoplastics are materials with a structure of fibrous bonds which are branched or unbranched. They are divided into two groups; amorphous thermoplastics (PVC, polystyrene) and semi-crystalline thermoplastics (polyethylene, polypropylene). Thermoplastic materials can be softened and molded into useful shapes when heat and pressure are applied to them. Engineering Properties of Polyethylene (AWWA, 2005) defines semi-crystalline thermoplastics as materials prepared by the polymerization of at least 85 percent ethylene and at least 95 percent of total olefins by weight with an addition of compounding components which can include carbon black. The manufacturing method of pipes from semi-crystalline thermoplastics is usually through extrusion and molding.

HDPE and polypropylene (PP) are part of the polyolefins group. These materials form flexible but tough products which normally possess low water absorption, very little to moderate gas permeability, decent toughness, and elasticity at low temperatures, with fairly low heat resistance, and excellent resistance to many chemicals.

In this research, our interest in PE is in pipe systems application specifically for HDPE. For HDPE to be applied in modern piping systems, its performance capability is determined by three main parameters; density, molecular weight, and molecular weight distribution. Engineers and technicians should always take note that each of these polymer properties affects the physical overall performance of the resulting piping system (AWWA, 2005).

Semi-crystalline polymers such as HDPE comprise long, chain-like molecules of varying sizes and quantities of lateral branches. When the sum of lateral branches escalates, both polymer crystallinity and density decrease since the molecules cannot pack as thoroughly together. **Figure 2.1** shows the polymerization of ethylene and resulting HDPE raw material (Turan Makina, Technical Catalogue, 2017).

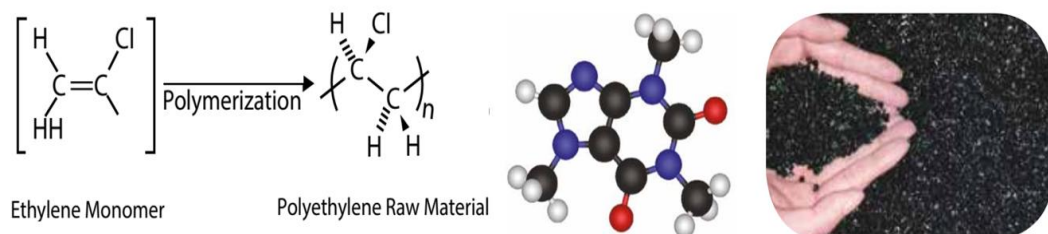


Figure 2.1: Polymerization of ethylene and resulting HDPE raw material

Source: Turan Makina, Technical Catalogue. (2017).

The performance of the finished pipe greatly depends on its density and polymer distribution. Pipe designers should be informed that physical properties like stress crack resistance, tensile strength, and stiffness are all affected by the base resin density of the polymer.

In recent years the use of HDPE pipes and fittings for the distribution of water and gas has increased rapidly. Compared to PVC, steel, iron e.t.c. HDPE is gaining more popularity due to its versatile use in piping systems and applications. The HDPE pipe currently being installed all over the world for gas and water applications range from

16 to 2300 mm. **Figure 2.2** shows HDPE pipe installation and butt fusion welding (Turan Makina, Technical Catalogue, 2017).



Figure 2.2: HDPE pipe installation and butt fusion welding

Source: Turan Makina, Technical Catalogue. (2017).

The major advantage of HDPE pipes and fittings compared to their steel, iron and other metal counterparts in pipework for engineering projects is that they can be used in a wide series of pipe systems and applications. Despite the material being plastic, it offers the same service or even better compared to pipes made from metal elements and alloys which are usually difficult to maintain. For example, metallic pipes corrode under seawater conditions, they are rigid, heavy, and expensive. Therefore, the use of plastic pipes has increased for applications like distribution of potable water, discharge of wastewater, transport of gas, and intake and discharge of seawater. In seawater applications, HDPE-LS 4984 is considered to be the most appropriate material due to its resistance to corrosion, resistance to UV radiation, lightweight, high flexibility, and good strength to withstand erection loads (Yadavalli, Harinath & Mohan, 2016). Today in many nuclear power plants, cast iron tertiary cooling pipework is being replaced by HDPE as an alternative material for designing and erecting cooling pipework (Maclennan, Pettigrew & Colin, 2010).

This paper explored the major attractive feature of HDPE pipe materials, which is the method in which they can be joined to a network of HDPE pipes and HDPE fittings

in engineering projects using the butt fusion welding technique. The butt welding technique is a welding method used to join HDPE pipes by heating the pipe ends to be joined using a heated tool (heated mirror) with a temperature between 200-220 °C which is greater than the melting temperature of the HDPE pipe material. In various applications the upper-temperature limit (220 °C) is used when welding pipes with smaller wall thickness, then the lower temperature limit(200 °C) for bigger ones, **Figure 2.3** process and steps of butt welding (DVS 2207, 2010).

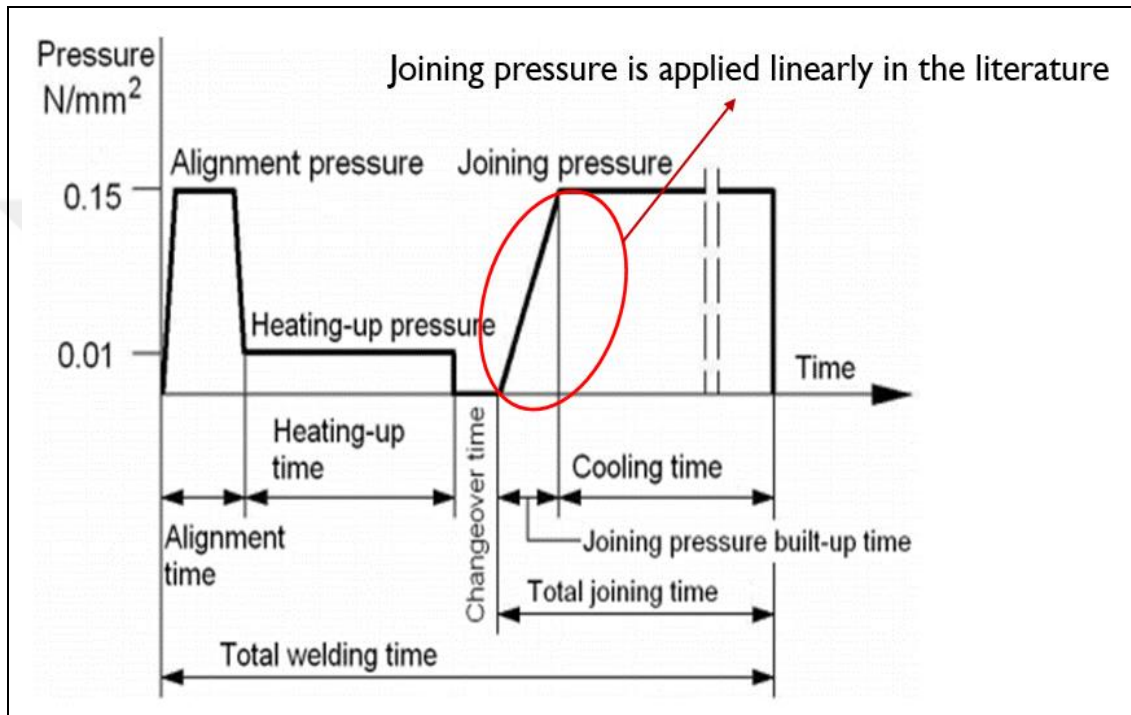


Figure 2.3: Process steps of heated tool butt welding

Source: DVS 2207. (2010)

2.2 The Butt Welding Procedure for HDPE Pipes Applied in This Research

During butt fusion welding, the pipe pieces to be welded were placed and clamped firmly between the clamps of the machine, then pushed against the heating tool by moving the hydraulic pistons with a calculated drag pressure (P_d). Afterwards, the trimmer was placed between the two pipe pieces. Tips of the pipes to be welded were trimmed until 100% contact was achieved before withdrawing the trimmer.

- a. When the PID controller had shown 220 °C, the heating tool was carefully placed between the pipes as shown in Figure 2.4. To equalize the temperature of both tips of the pipes, initially, they were pushed against the heating tool

by moving the hydraulic pistons with a calculated welding pressure (P_1) for a short period. Note that since the welding pressure (P_1) is the sum of the drag pressure (P_d) and the applied pressure (P), P_1 varied depending on the pipe's wall thickness, length, and outer diameter.

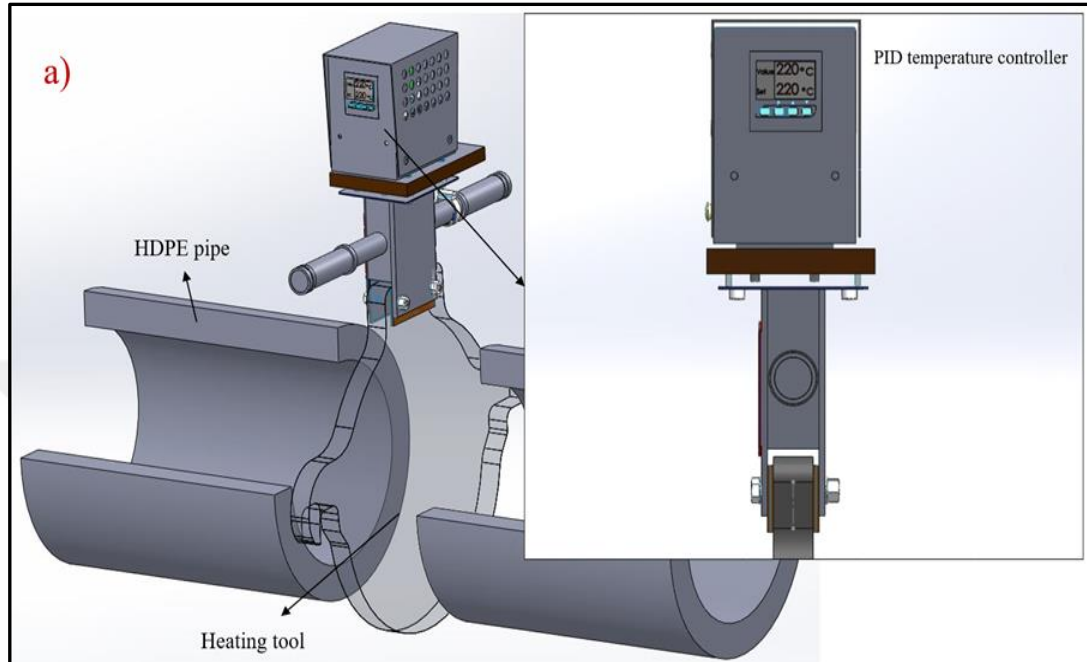


Figure 2.4: Initializing the butt fusion process

- b. During the temperature equalizing period, note that P_1 was maintained until a visible weld bead was formed on both tips of the pipes that were in contact with the heating tool. The weld bead varied depending on the size of the pipe, refer to Table 2.1 for details. Once the temperature equalizing period was finished (this was determined by observing and achieving the desired weld bead size), the tips of the pipes were continuously heated at the same temperature while the heating tool was still in between with a near-zero welding pressure for T_2 seconds. This stage is known as the heating up period or heat-soak stage, the welding pressure (P_1) had to be reduced to a near-zero pressure such as 0.01 N/mm^2 (or zero drag pressure), this pressure drop was observed on the machine's manometer. T_2 was calculated using Formula 2.1

$$T_{2_{minutes}} = [11_{seconds} \cdot \text{pipe's wall thickness } (P_{wt})] \pm 5_{seconds} \quad (2.1)$$

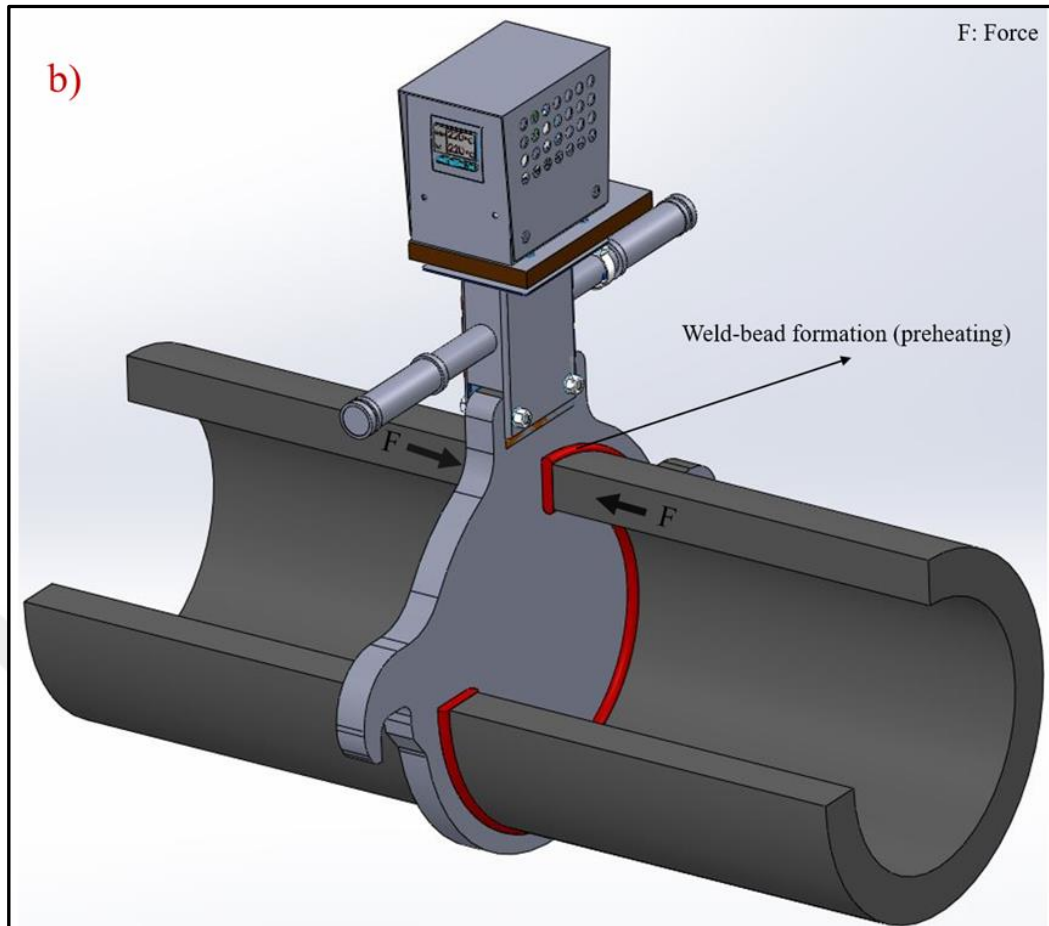


Figure 2.5: The heating up period or heat-soak stage at T2 during the butt-fusion process

Table 2.1: Butt fusion welding parameters for HDPE

Material: HDPE (PE100) SDR 11 PN 16								
Area for the machine's hydraulic cylinder (A_{HC}): 14.13 CM^2								
The thrust coefficient for HDPE (C_T): 1.5 kg/cm^2								
Outer Diameter (O.D) mm	Wall Thickness (P_{wt}) mm	The applied pressure (P) (N/mm^2)	Lip Thickness (mm)	T2 (min)	T3 (sec)	T4 (sec)	T5 (min)	Total (min)
75	6,8	0.2	1,2	1,25 min	5-6	10	10	12
90	8,2	0.3	1,3	1,5 min	6-8	10	12	14
110	10	0.4	1,5	2 min	6-8	10	15	17
125	11,4	0.5	1,6	2,2 min	6-8	10	17	20
140	12,7	0.6	1,8	2,35 min	8-10	10	19	22
160	14,6	0.7	2	3 min	8-10	10	22	25

- c. Once the unpressurized heating period was completed, the heating tool was removed, then the areas to be welded were joined by gradually building and

applying the demanded joining pressure in three intervals ($0 N/mm^2$), (0 to P_2) N/mm^2 , (P_3 to P_1) N/mm^2 within 10-12 seconds. Figure 2.6 shows the heating tool which was withdrawn in preparation for fusion.

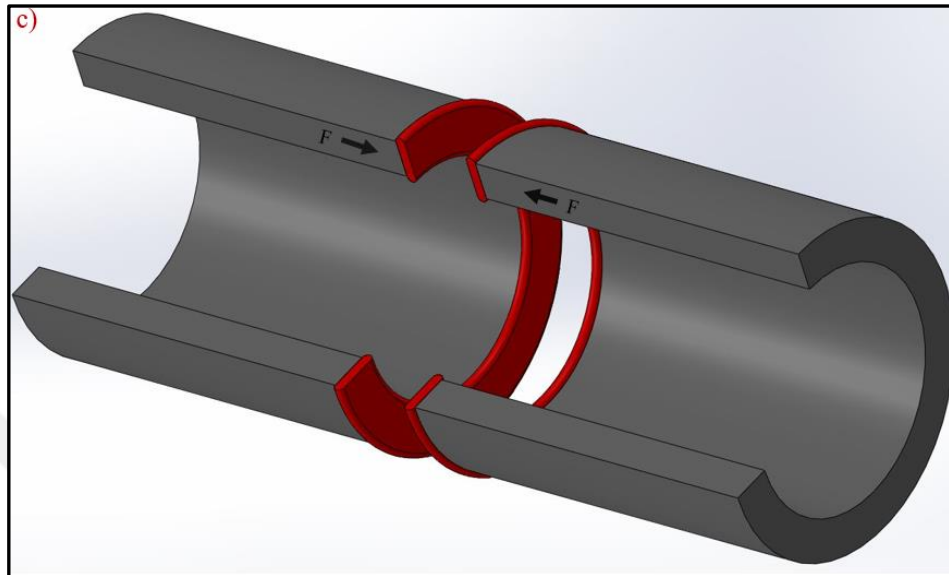


Figure 2.6: The heating tool was withdrawn in preparation for fusion

- d. The welding pressure was kept constant throughout the cooling time at ambient temperature. Figure 2.7 shows the joining stage, the cooling time (T_5) was calculated using Formula 2.2.

$$T_{5_{minutes}} = \left(\frac{90_{seconds} \cdot pipe's \ wall \ thickness \ (P_{wt})}{60_{seconds}} \right) \pm 5_{seconds} \quad (2.2)$$

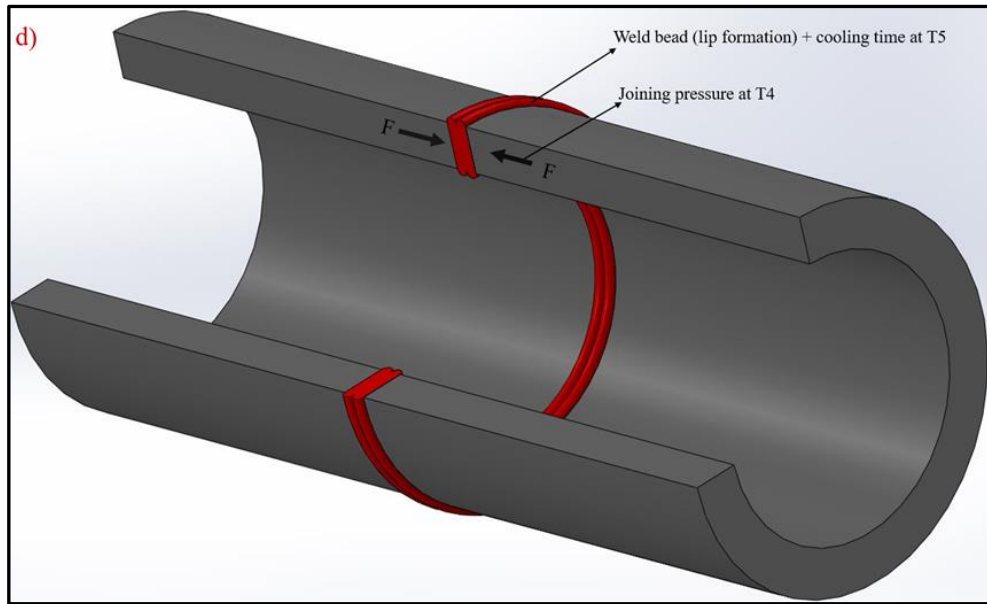


Figure 2.7: The joining stage

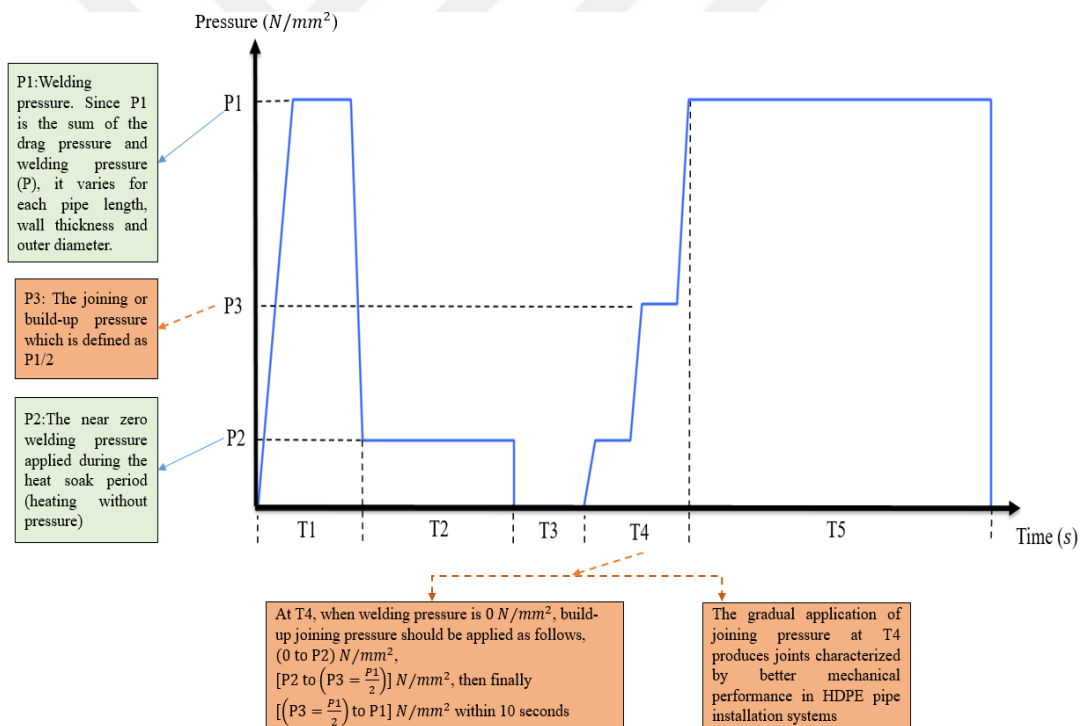


Figure 2.8: The applied butt-fusion welding procedure for this research

The butt welding procedure was summarised above from sections a to d. At T4, note that the butt fusion welding procedure in the literature specifies that the joining pressure is applied linearly and not gradually as described above. Figure 2.8 shows the applied butt-fusion welding procedure for this research.

2.2.1 Hypothesis

The literature describes in detail stages involved in butt fusion, in the literature it was observed that the joining pressure of the joints to be welded were applied and built linearly. The method of applying the joining pressure exposes the less heated surfaces in the heated zone and most cases form a weak joint. The outer and innermost joined welded layers may show bad-quality welds because imperfections at the joint area can enhance stresses due to cold weld problems (Deveci, 2019).

The melt flow rate (MFR)-range and melted surface/welded surface distribution of HDPE were also important parameters to discuss because carbon black is added to HDPE to ensure that the material is protected from UV rays from the sun. UV rays are capable of speeding up the degradation of HDPE chemical structure if exposed for a long time to the sun. A welded joint with poor carbon black distribution might risk degradation if not properly joined, AWWA_C906_PE emphasizes that HDPE material to be used in piping systems should comprise of minimum 2 percent carbon black which is evenly distributed in the PE micro-structure. In today's HDPE piping systems carbon black acts as both a colorant and a fundamental UV stabilizer. Tests were performed on the resulting welded joints and carbon black content was investigated for each butt fused joint obtained using the proposed welding method in this paper. The obtained results were then compared to the welded joints acquired from the joints using the standard welding procedure performed by a manual butt fusion machine as described in the literature.

In the literature, the butt welding procedure was performed by heating the heating tool to $210 \pm 5^\circ\text{C}$, which is about 30°C higher than the melting temperature of most commercial HDPE pipe material. To perform a butt-fused joint, the pipes were dragged to make their ends to be welded press against the heated tool from each side of the heated mirror and were kept firmly pressed by a hydraulic unit at a defined pressure (P) which is carefully calculated and defined for the introduction and realization of the weld bead for at T1. The defined duration is carefully selected depending on the pipe size and working conditions on-site of each project, this step is also called the bead formation step.

Pressure applied (P) was calculated using the following equation: (Equation 2.3) (Mohan, 2016)

$$P = \frac{\text{Pipe Cross Sectional Area} \cdot \text{Material Thrust Coefficient}}{\text{Cross Sectional Area of Machine Hydraulic Cylinder}} \quad (2.3)$$

In the literature, to define P and execute the equation shown above, the material thrust coefficient for HDPE was defined as 1.5 kg/cm^2 , and the cross-sectional area of the machine hydraulic cylinder that was given by the equipment manufacturer was 14.13 cm^2 was calculated as 30 kg/cm^2 .

In butt-fusion, calculating P alone is not sufficient to perform the weld, the drag pressure should be defined, recorded, and added to the applied pressure P. Drag pressure corresponds to the force required to overcome the internal friction of the equipment while moving the pipes. The equipment used for the literature had a drag pressure of 10 kg/cm^2 .

In the designed semi-automatic butt-fusion machine for this research, the drag pressure is automatically determined and stored by the machine. Using a PLC microcontroller, the applied pressure (P) defined in formula (2.3) is then calculated and added to the drag pressure to obtain the welding pressure P1 (2.4).

$$P1 = \text{drag pressure}(P_d) + \text{applied pressure}(P) \quad (2.4)$$

All processes above were automatically executed by the designed machine to ensure that no errors occur during the initiation and completion of the welding process.

Similar to the welding procedure described by DVS 2207. After obtaining a bead size of 2.5–3 mm (0.1–0.12 in.), typically for pipes of 355-mm (14-in.) O.D, during the welding process, the welding pressure P1 (30 kg/cm^2) to P2 (4 kg/cm^2). Then the heating was continued for 420 s (T2), during the soaking period, and the continual heating step.

In the literature, the melted pipe faces were quickly inspected to ensure that they were flat. If they were curved in shape, it meant that there was inadequate pressure during heating and this weld would be unacceptable. To correct this, the pipe ends would have to be trimmed and heated again. For this paper, the designed semi-automatic welding machine automatically regulates the pressure at this stage to

ensure that the correct bead formation and sufficient heating of the pipe surfaces to be joined are assured.

Bead formation and bead height were not an issue to be addressed during this research because studies have shown that the double formation of the bead on the inner and outer layer of the pipe during butt-fusion have very little effect on the hydraulic flow and are negligible. For this reason, even internal bead removal is not necessary for butt-fused pipes. Hydraulic studies show that the movement disruption effect of HDPE butt-fused welds is negligible and that the Hazen Williams flow coefficient for butt-fused HDPE pipes is about 155 (AWWA_C906, 2005).

After confirming flat pipe end surfaces, both pipe ends were drawn towards and beside each other. This was defined as the changeover step, and had occurred within a limited duration (T3), and is critical to obtaining a good weld joint. This duration (T3) was 7 s and is given by seconds.

Then finally, by applying welding pressure (P1), the pipe ends were then pressed against each other. This is called the pressure building step and must be completed within 12 s (T4) to obtain a good joint. During this step, intermolecular diffusion takes place from one pipe to another across the welding surface zone. As the pressure continues, with the increase in time, the bead size rises gradually and, simultaneously, the molten HDPE material solidifies while the joint cools.

From this section as described by literature, during the pressure build-up process (T4) intermolecular diffusion takes place from one pipe to another this stage is critical to ensure that the resulting welded joint is successful, in this research applying P1 at T4 for 10-12s in three gradual intervals while waiting for at least 2s at each stage guarantees a successful intermolecular diffusion. The resulting joint exerts similar properties to the parent pipe. To better compare mechanical, chemical, and performance properties of the joint to the mother pipe, tensile tests for butt fusion (ISO 13953, 2001), carbon black test (ISO 6964, 1986), and hydrostatic pressure tests (ISO 1167-3, 2007) were performed on samples obtained from the pipe and joint. Figure 2.9 shows the gradual application of pressure (P1) at T4 improves the resulting welded joints.

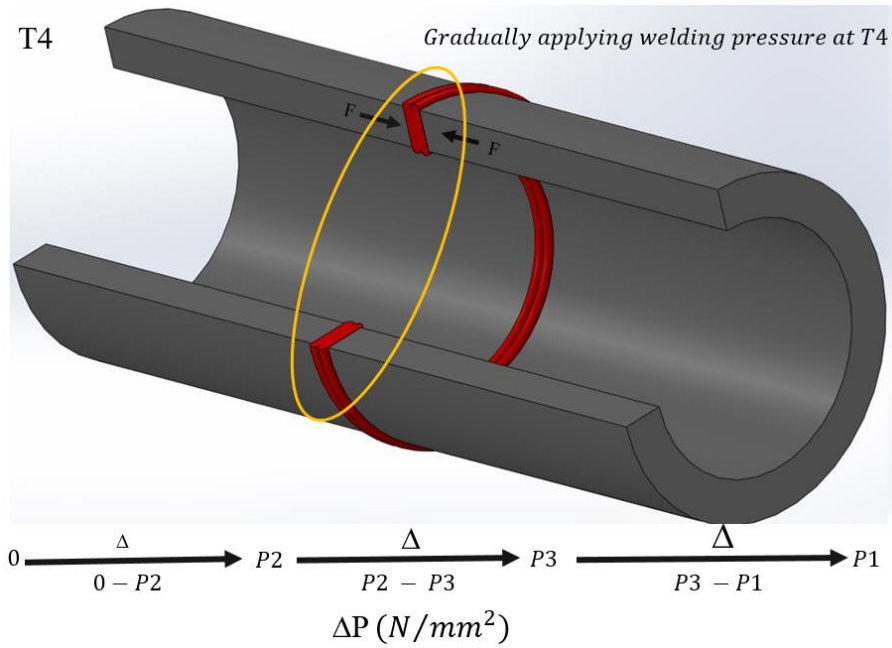


Figure 2.9: The gradual application of pressure (P1) at T4 improves the resulting welded joints

Details can be seen on the welding chart adapted for this paper at T4 when welding pressure is $0 N/mm^2$, build-up welding pressure should be applied as follows,

$$(0 - P2) N/mm^2 \quad (2.5)$$

$$[P2 - (P3 = \frac{P1}{2})] N/mm^2 \quad (2.6)$$

then finally

$$[(P3 = \frac{P1}{2}) - P1] N/mm^2 \quad (2.7)$$

within 10 seconds, the resulting joint exerts similar properties to the parent pipe.

From the equations, after the heating tool is withdrawn the welding pressure is at $0 N/mm^2$ then slowly built to achieve P2 (2.5). The next pressure stage is built from P2 to P3 (2.6). The final stage is achieved by building the pressure from P3 to P1 (2.7).

By utilizing the collected data from previous research in the literature below, carefully studying the butt fusion welding procedure, and considering all the processes involved, this information was used to design a semi-automated butt welding machine a mechatronics system.

2.3 Similar Research and Background

Bagory, Sallam & Younan (2014) investigated the influence of strain speed, sample width, and butt-fusion on the fracture strength for the samples made from HDPE. To examine the mechanical properties of the butt-fused and unfused samples, tensile tests were performed at different crosshead speeds. This study revealed that the breakage strength is more for un-welded than welded specimens.

In similar research, specimens were fused under identical pressure settings to analyze the resulting quality of the weld and its mechanical characteristics. In all the welded samples, the standard tension test results were found to be nearly the same as that of the parent pipe. Nevertheless, the identified toughness or mechanical strength for welded samples was lower than the toughness of the mother pipe (Riahi et al, 2011).

Another study investigated the impact of using dual-pressure welding procedures on small-scale pipes made of PE 100 and PE 100 RC materials. Special attention was given to mechanical and also fracture-mechanical short- and long-term properties of the welded areas and their surroundings. It was concluded that higher degrees of crystallinity due to welding can benefit the mechanical properties of welds (Arbeiter et al. 2013).

In previous research, it was shown that tensile strength and strain were the most satisfactory parameters for differentiating between diverse qualities of butt fused welds compared to yield stress, yield strain, and modulus of elasticity. Likewise, it was concluded that if the butt welding procedure is correctly performed, the quality of welded joints is as decent as that of the mother pipe (Jack et al. 2002).

In a recent study, the mechanical characteristics of butt-fused joints were investigated by performing the bending test, while the microstructure of the welded joints was observed by an electron microscope (SEM). The research concluded that to obtain the required weld a 0.2 MPa of welding pressure and a range of 210 °C to 230 °C welding temperature need to be applied (Cai et al. 2018).

In a different study, the outcome of inadequate homogenization of HDPE resin during butt fusion of PE in pipe applications was observed. It was found that inadequate homogenization resulted in scarce distribution and spreading of carbon black in the HDPE pipes. Tensile tests performed on welded pipe joint samples with insufficient carbon black distribution resulted in weak butt fused joints which were

characterized by brittle failure modes when subjected to the tensile strength tests, Figure 2.10 shows the average energy that was required to break 5 butt fused welds and Figure 2.11 shows the average extension that was required to break 5 butt fused welds (Yu et al. 2020).

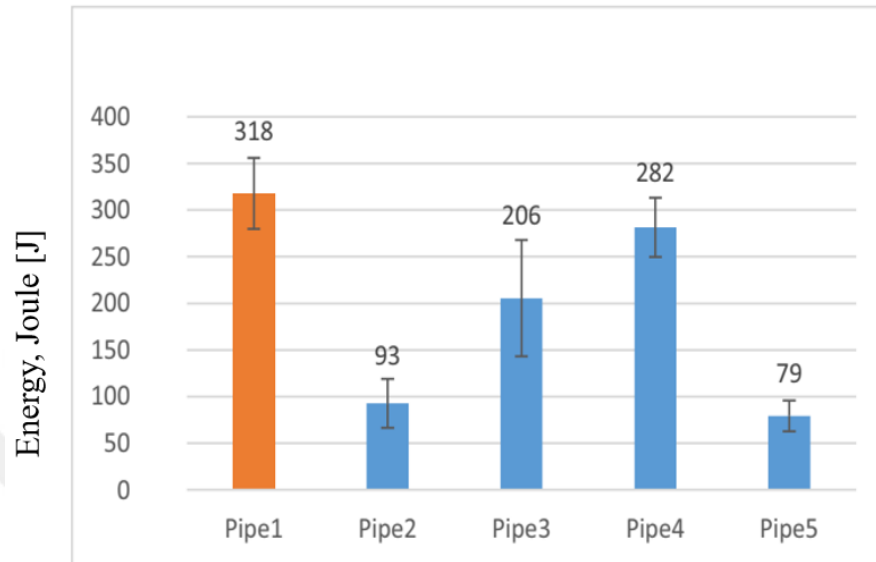


Figure 2.10: The average energy that was required to break 5 butt fused welds

Source: Yu et al. (2020).

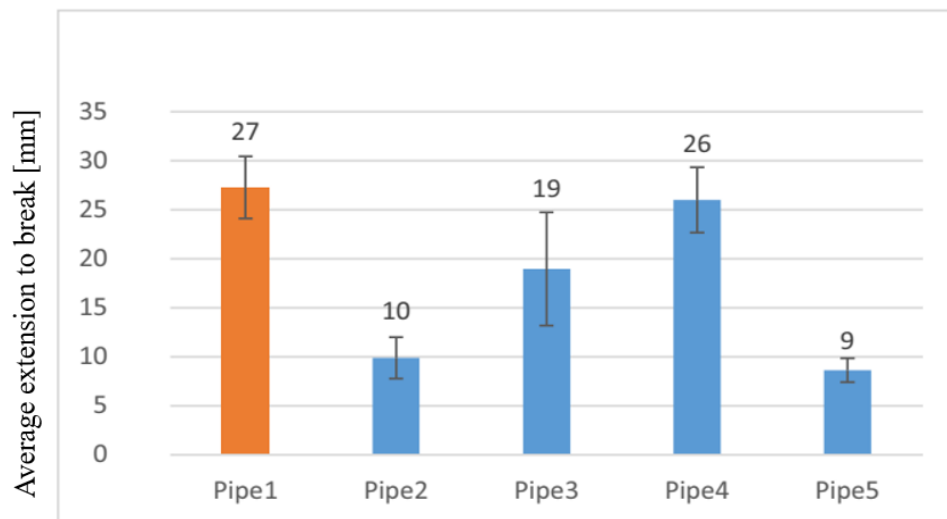


Figure 2.11: The average extension that was required to break 5 butt fused welds

Source: Yu et al. (2020).

2.3.1 The effect of carbon black content in pipe grade HDPE

Carbon black (CB) is a commonly used additive in the manufacturing of HDPE pipes to offer resistance against thermal and photo-degradation of HDPE pipes by

absorbing ultraviolet (UV) radiation and providing adequate UV protection, provided that CB has a homogenous distribution in the PE matrix.

Several possible reasons affect and reduce the mechanical characteristics of butt-fused joints in HDPE piping systems having inadequate homogenization when joining the heated zones. Some of these reasons include a strain accumulation positioned in the zones without CB, weak areas consisting of elevated levels of CB concentration. To overcome most of these errors resulting from insufficient homogenization that affect the mechanical properties and performance of the butt-fused joints, engineers or pipe installers need to ensure that throughout the butt welding process of HDPE fittings and pipes the heated and melted areas to be fused have an even and homogenized distribution during joining period to avoid creating more windows which affect the integrity of the butt fused joint. The gradual application of welding pressure at T4 ensures that the melted surfaces of the pipes to be joined are evenly distributed because welding pressure is applied in intervals ensuring that the microstructural chains at melted heated zones warrant the thermal movement of HDPE material. When a stable force in this case pressure is applied, polyethylene, being a semi-crystalline thermoplastic, enhances the saturation of heated HDPE chains into the PE matrix ensuring abundant entanglement within the molecular chains of the material. The series of changes in the molecular chains result in polymer distortion or deformation which produces a material with greater strength because the entangled chains in the microstructure have similar characteristics to the crystalline state of HDPE. From the literature, we have seen that the intermolecular bonding in the crystalline stage is more significant compared to the amorphous state. This is because, in the crystalline state, PE offers better mechanical performance.

ASTM standard describes the heat soak period (T2) according to the size of the resulting melt-bead, then the DVS standard refers to the heat soak based on time.

To investigate the distribution of carbon black for the butt-fused joints welded according to this research, quantification of CB will be carried out by performing tests as described by ISO 6964 then image samples and data will be collected from the welded joints. In the literature, a related image analysis technique to count windows and not CB for HDPE pipes were performed (Yu et al. 2020). The samples tested were ribbons that were obtained when trimming the pipe joints before the butt-fusion procedure and used a continuous greyscale for each image.

Sorin et al. (2020) defined the mechanical performance of HDPE pipes manufactured and installed for water supply, however, the study only looked into the effects of stress on installed HDPE pipes and fittings. There was no data on the effects of stress on fused joints. Nevertheless, the results obtained from this research can be beneficial to a designer or pipe installer when installing a water supply system.

In an alternative paper, the two common procedures used to fuse HDPE pipes were compared and analyzed. Results of the tests had shown that electro-fusion welding was a more ideal method for welding pipes up to a certain diameter. Nevertheless, for main transmission line pipes with larger diameters, heated tool butt welding proved to be a better option (Akkurt, 2013). This study just like the other literature shows how significant the butt-fusion welding process is in a wide range of pipework and engineering projects. Despite electro-fusion welding having more advantages, it cannot replace the use of butt welding in projects. For this reason, special care has to be given to the designed systems and equipment during the butt-welding procedure due to the fact this welding procedure will be used for a long period in pipework design involving HDPE pipes and fittings.

In new research, the mechanical characteristics of HDPE microstructures joined using the butt-fusion process were investigated then subjected to tensile testing. It was concluded that the butt-fusion conditions and parameters have a direct effect on the microstructure of the bead formed and weld quality (Belaziz & Mazari, 2018). This research ensured that the heat-affected zone (HAZ) is carefully addressed to obtain a successful welded joint with excellent mechanical characteristics. The gradual application of the welding pressure as proposed in this research, which directly affects the quality of the weld was applied linearly and continuously in the welding procedure proposed by the literature. This study has shown that applying the welding pressure at T4 linearly has a negative effect on the performance and quality of the resulting butt-fused joint.

Recent research performed several mechanical tests including Pennsylvania edge notch tensile (PENT) to observe the effect of heated tool welding procedure on the fused joint's long-term performance in buried HDPE piping systems. It was concluded that the tensile test procedure with notched samples was the most favorable test (Kim et al. 2019). Some of the mechanical tests performed by this literature were adapted for this research. However, the described test methods by this literature limit a depth understanding of the behavior of butt-fused joints.

Concentrating on mechanical properties alone does not give a better insight into how butt-fused joints perform and respond to the wide range of elements in piping systems once installed. For this reason, our research included several other tests including the investigation of thermal stability in HDPE using the oxidation induction time (OIT) test (ISO 11357, 2009), quantifying CB content using calcination & pyrolysis, and hydrostatic pressure test of butt fused samples.

Slimane et al. (2018) listed out the effects of cold welds on the resulting butt-fused joints by comparing the stress-strain characteristics of butt-fused and unfused pipes. The usual stress-strain characteristics observed in semi-crystalline materials were maintained in the butt-fused and unfused samples though with slight and distinctive limits with each sample group. Inner layers of the fused joint revealed lesser values of yield, failure stresses, and elastic modulus, though, in the outer layers of the fused joints, the opposite was observed.

In similar research involving cold welds, the mechanical characteristics and microstructures of the welded joints in HDPE pipes obtained from performing cold butt fusion welds in HDPE pipes were evaluated. Inadequate inter-molecular dispersal of PE chain fragments initiated the deficient polymer entanglement of the resulting welded joints. The research revealed that the butt-fusion setting and conditions affected the mechanical characteristics of the welded joints (Pokharel et al, 2016).

From the above literature, we concluded that the mechanical characteristics and performance of HDPE are governed by crystallinity, polymer chain meshing, bond molecule mass, and structure. These parameters are all dependent and influenced by the heating conditions during the extrusion process when manufacturing and butt-fusion welding when joints are heated.

The Figures 2.12, 2.13 and 2.14 below show the microstructure changes observed during butt fusion when heated molecular chains diffuse across the weld margin (Pokharel et al, 2016)..

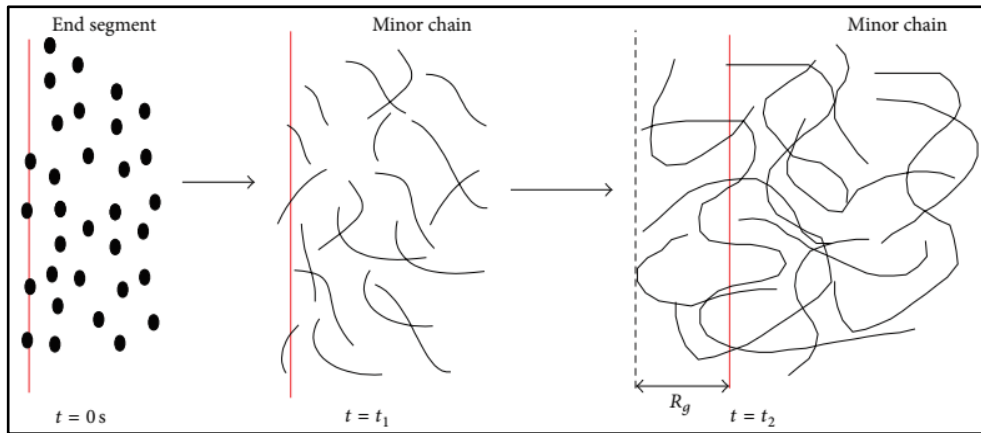


Figure 2.12: Distribution of PE meshes across the weld margin during a typical welding condition

Source: Pokharel, Kim & Choi. (2016).

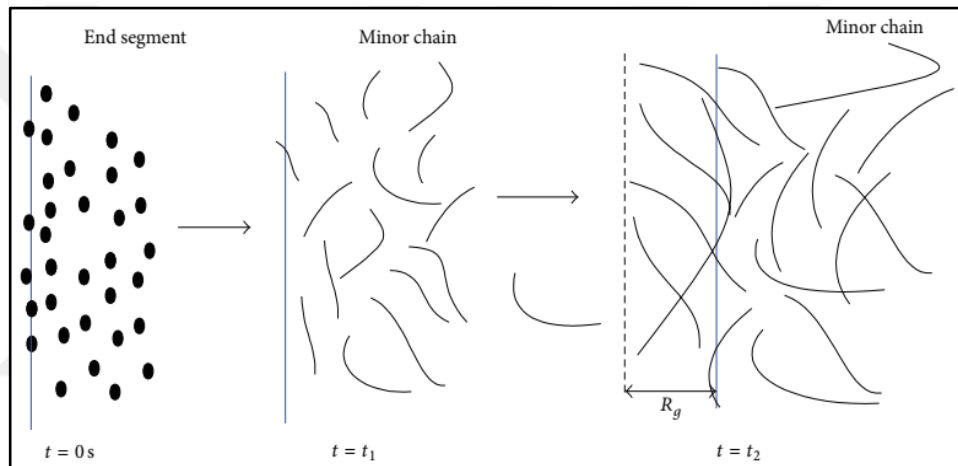


Figure 2.13: Partial distribution of polyethylene chains across the weld margin during cold fusion

Source: Pokharel, & Choi. (2016).

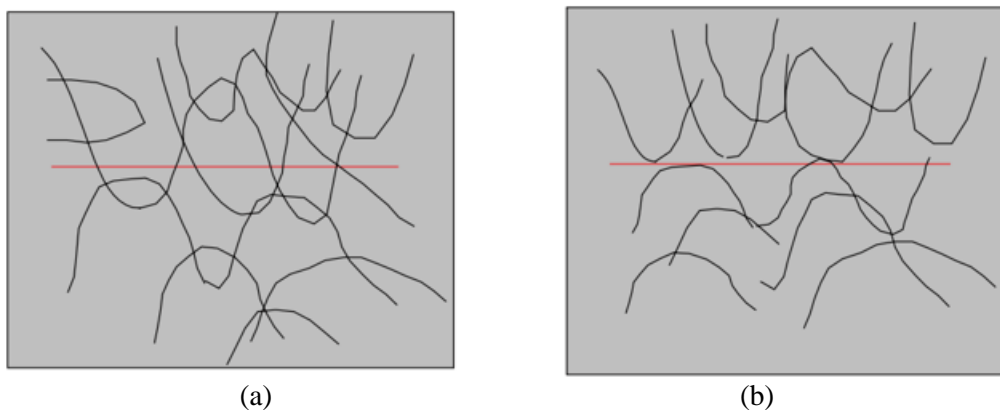


Figure 2.14: (a) Melted microstructure nest/web illustration of the butt-fusion zone at standard welding condition. (b) Melted microstructure nest/web illustration of the butt-fusion zone at cold butt-fusion

Source: Pokharel et al, (2016).

Using the butt fusion process with the finite element method, another study modeled the heated polymer pipe deformation properties under loading and applied the joining of plastic pipes. The information from the analysis was used to identify the heat material characteristics of HDPE (Shillitoe et al, 1990). A simulation procedure can be applied to observe the characteristics of the material, results obtained are only approximations, it is critical to perform actual experiments to get a real insight of what happens during the butt-fusion process, all the experiments and data collected for this research was done in on physical samples.

2.4 Research Review and Summary

Using the butt welding method to join HDPE pipes offers a wide range of advantages compared to other welding methods. The butt fusion process involves fairly simple tools as seen from the literature. For a pipe installer to complete projects involving pipes with large diameters, the fusion welding method guarantees resulting welds with mechanical properties similar to those of the parent pipe as was proved in this research. The literature proved that the inadequate meshing or webbing of polyethylene molecular chains is the major cause of producing cold fusion defects at the butt-fused joint causing poor mechanical performance of the joints.

The main weakness of this procedure is the time consumed per weld cycle. Fusion cycles can range between 10 to 25 seconds for small pipe diameters. However, this process can last as long as an hour plus for larger diameter pipes e.g.; 630 mm PN 16 wall thickness of 57.2 mm which takes 98 minutes to complete. The duration at each stage of the welding procedure can be decreased by automating the technique. Automating the butt fusion process not only saves on time but also benefits the complete dismissal of human error giving better regularity in the quality of the fused joints. According to previous research, increasing efficiency by manually modifying the butt-fusion parameters is challenging because of the demanding skills required and the long working duration. For this reason, human error is inevitable as the procedure has shown to be prominently full of mistakes.

The above points strictly promote the method and approach we used in this research and experiment, all the necessary welding parameters were automatically pre-optimized and easily modified in the designed machine during this research.

By utilizing the collected data from previous research in the above literature, carefully studying the butt fusion welding procedure, and considering all the processes involved, this information was used to design a semi-automated butt welding machine a mechatronics system.

To successfully design the mechatronics system, key butt-fusion parameters, and equipment such as the heating tool, welding temperature, welding time, joining, and drag pressure need to be carefully tested, enhanced, optimized and analyzed to achieve a butt-fused joint with nearly 100 % parent pipe mechanical strength and characteristics. Thanks to modern research and breakthroughs in this field of pipe installation, a variety of fusion parameters, predictable experimental approaches of creating the acceptable range of welding conditions for all HDPE pipe geometries with an extensive range of environmental possibilities is possible. Scientifically changing the butt-fusion welding parameters and investigating the resulting joints can be expensive and time-consuming. Yet by clearly stating the pipe ranges and wall thicknesses to be joined by the butt fusion welding method, we can obtain the best results for optimizing the welding parameters to obtain the best weld joint.

Therefore, this research involved the designing and building of a semi-automatic butt fusion machine for welding HDPE pipes and fittings ranging between 90 to 315 mm which uses an algorithm that applies a gradual welding pressure at T4 ensuring that the melted surfaces of the pipes to be joined are evenly distributed by completely eliminating cold welds, bead misalignment, and non-uniform penetration of polyethylene chains since welding pressure is applied in intervals. The designed mechatronics system ensured that during the pipe joining stage, the microstructural chains at residual heated zones diffuse the polymer chains across the weld interface, where abundant HDPE chain networks can endure subjected stress levels related to base pipe material during testing and pipe use.

The designed mechatronics system guaranteed that no exposure of the partially cooled melted PE chains before fusion occurred during welding at T4, because a carefully optimized uniform force in this case welding pressure was applied to facilitate the homogenous thermal movement of the melted material which was strategically adjusted to eliminate exposure of the cold zones during the fusion stage. When a carefully optimized unvarying welding pressure is applied in the presence of heat during fusion at T4, such favorable conditions enhance the dispersion of

polyethylene chains throughout the material's matrix resulting in adequate meshing within the PE micro-structure chains. At the weld zone, polymer deformation occurs due to the series of changes taking place in the PE micro-structure chains during fusion. In the literature, it has been confirmed that polymer deformation contributes to a greater strength of PE material due to the resulting entangled chains in the PE microstructure. The entangled polymer chains are in the crystalline state of the material. The intermolecular bonds of PE in the crystalline stage are stronger than the intermolecular bonds in the amorphous state. In the literature, it was concluded that higher degrees of crystallinity due to welding can benefit the mechanical properties of welds.

Additionally, it may not be easy to create the environmental conditions encountered on project sites in the Middle East Desert or Northern Russia Tundra in the laboratory. The availability of a butt welding machine in this research increased the range of conditions in which experiments were conducted.

The designed mechatronics system was used to eliminate the major challenges currently being faced by engineers and technicians during pipe installation and servicing. The method used to design the machine, and the applied computer algorithm implemented to completely remove cold welds, bead misalignment, and non-uniform penetration of polyethylene chains were shown in the chapters to follow.

3. METHODOLOGY

The objective of this study is to build a mechatronic system that improves the resulting butt-fused joints by applying the joining pressure gradually during fusion at T4 and not linearly as described in the literature. In this research, the gradual application of joining pressure at T4 was achieved by developing a new welding algorithm that was integrated into the existing butt welding machine manufactured by Turan Makina Borfit.

Details can be seen on the welding chart adapted for this paper at T4 when welding pressure is 0 N/mm^2 , build-up welding pressure should be applied as follows,

$$(0 - P2) \text{ N/mm}^2,$$

$$[P2 - (P3 = \frac{P1}{2})] \text{ N/mm}^2,$$

$$\text{then finally } [(P3 = \frac{P1}{2}) - P1] \text{ N/mm}^2,$$

within 10 seconds, the resulting joint exerts similar properties to the parent pipe.

The details of the developed welding algorithm can be seen on the welding chart shown in Figure 3.21. Figure 3.2 shows the gradual application of joining pressure at T4 to improve butt fused joints.

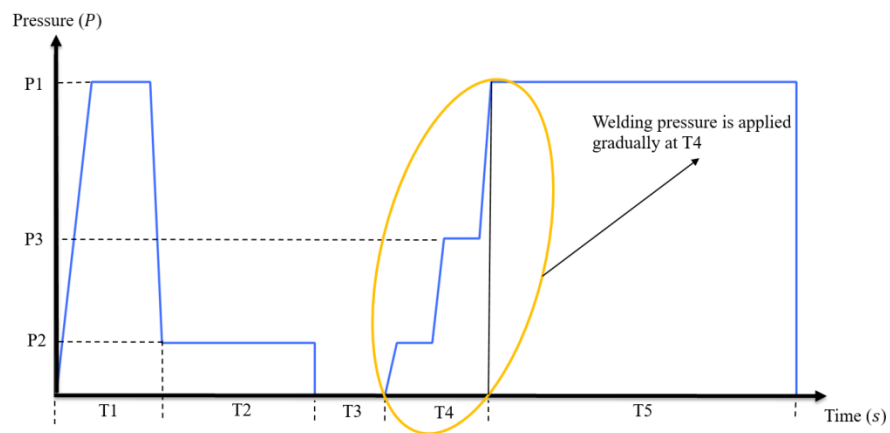


Figure 3.1: The gradual application of joining pressure at T4 to improve butt fused joints

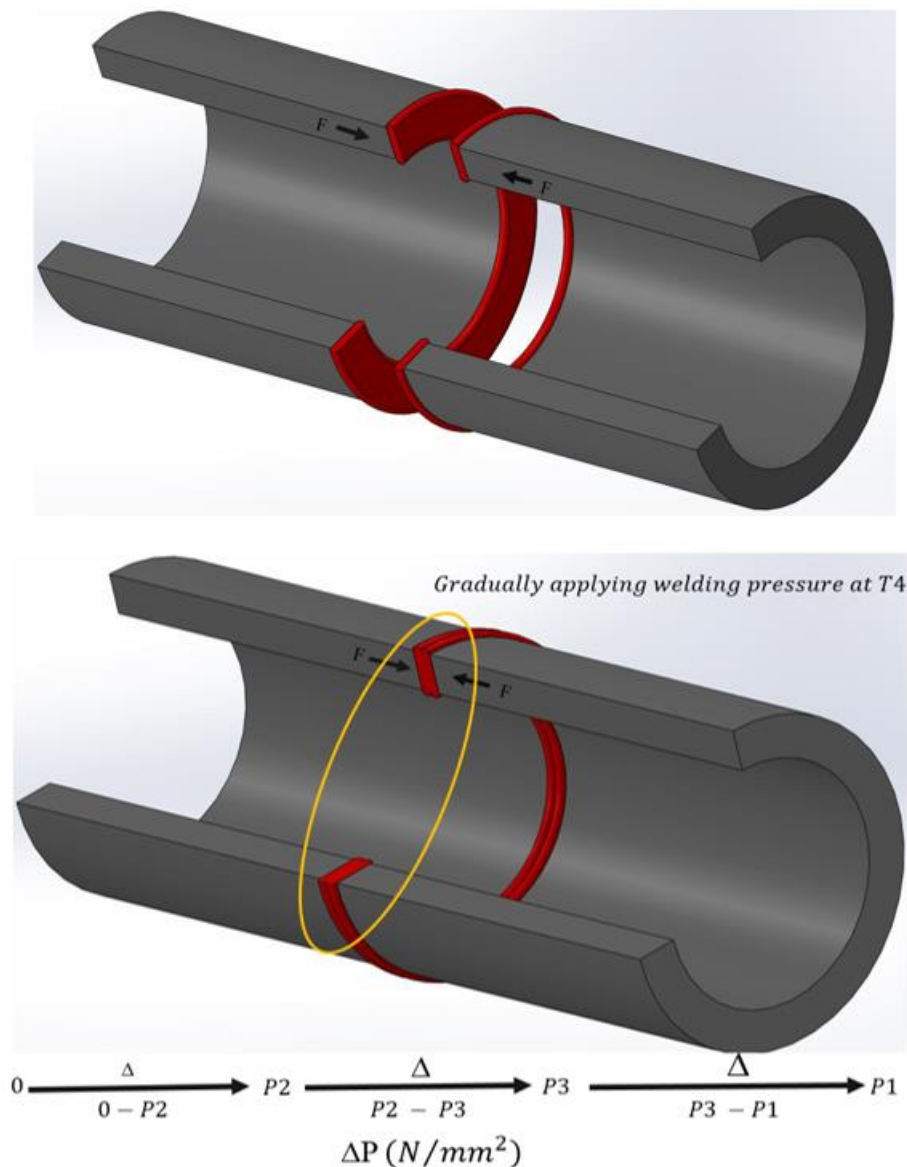


Figure 3.2: The gradual application of joining pressure at T4 to improve butt fused joints

With the new welding algorithm integrated into the PLC program, the semi-automatic welding machine ensured that;

- i. The less heated surfaces of the joints to be welded were not exposed or suddenly ejected when applying the joining pressure at T4.
- ii. The homogenous distribution of CB in the PE microstructure was successful.

Successfully implementing the above solutions in the mechatronic system produced joints that provided better mechanical and chemical performance properties. The

mechanical performance and chemical properties of the fused joints were tested using the test method described in HDPE pipe technical standards then the obtained results were compared to the literature.

The design stages of this system and overall thesis outline have been summarised in Figures 3.3 and 3.4.

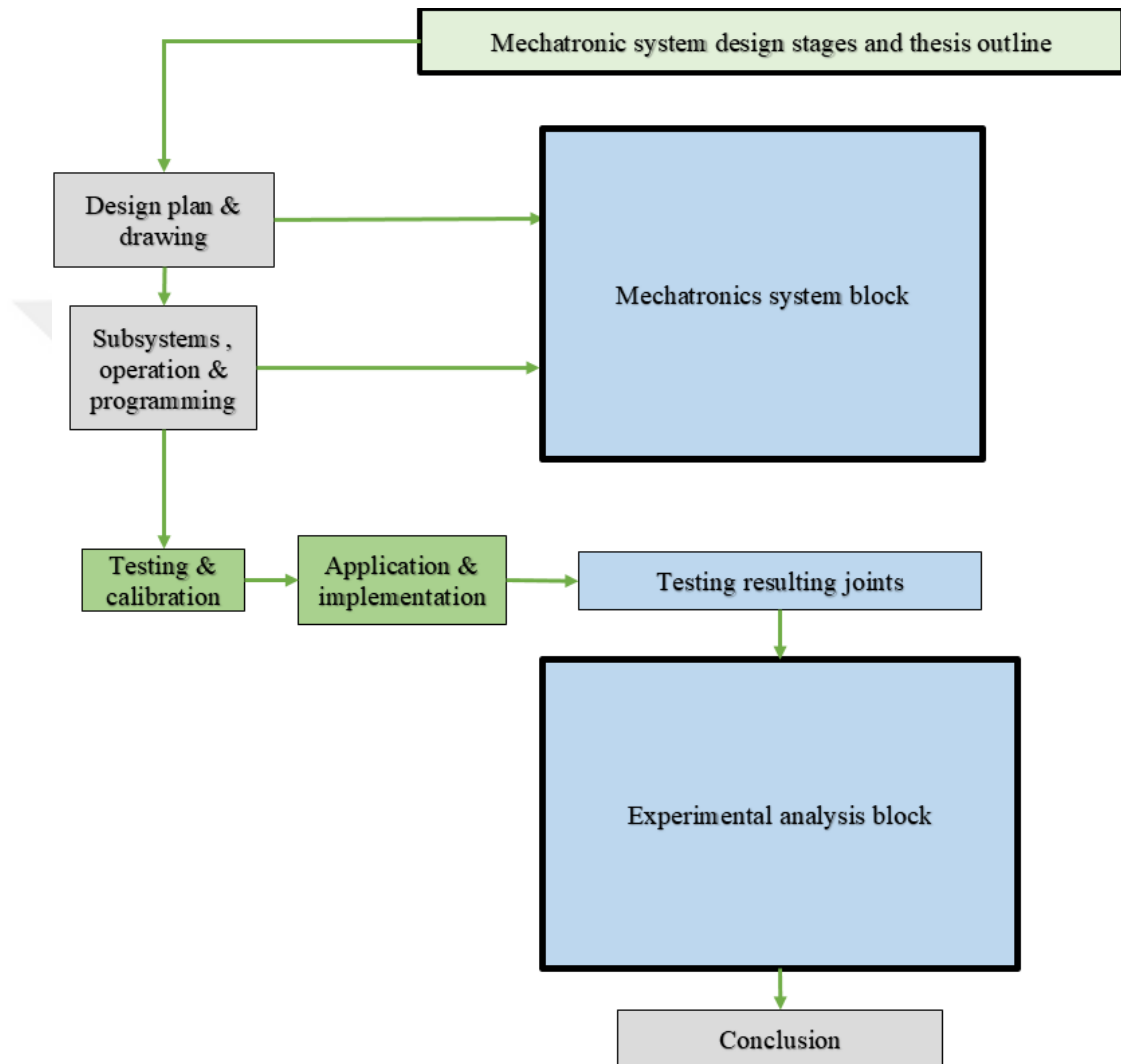


Figure 3.3: Summarised mechatronic system design stages and thesis outline

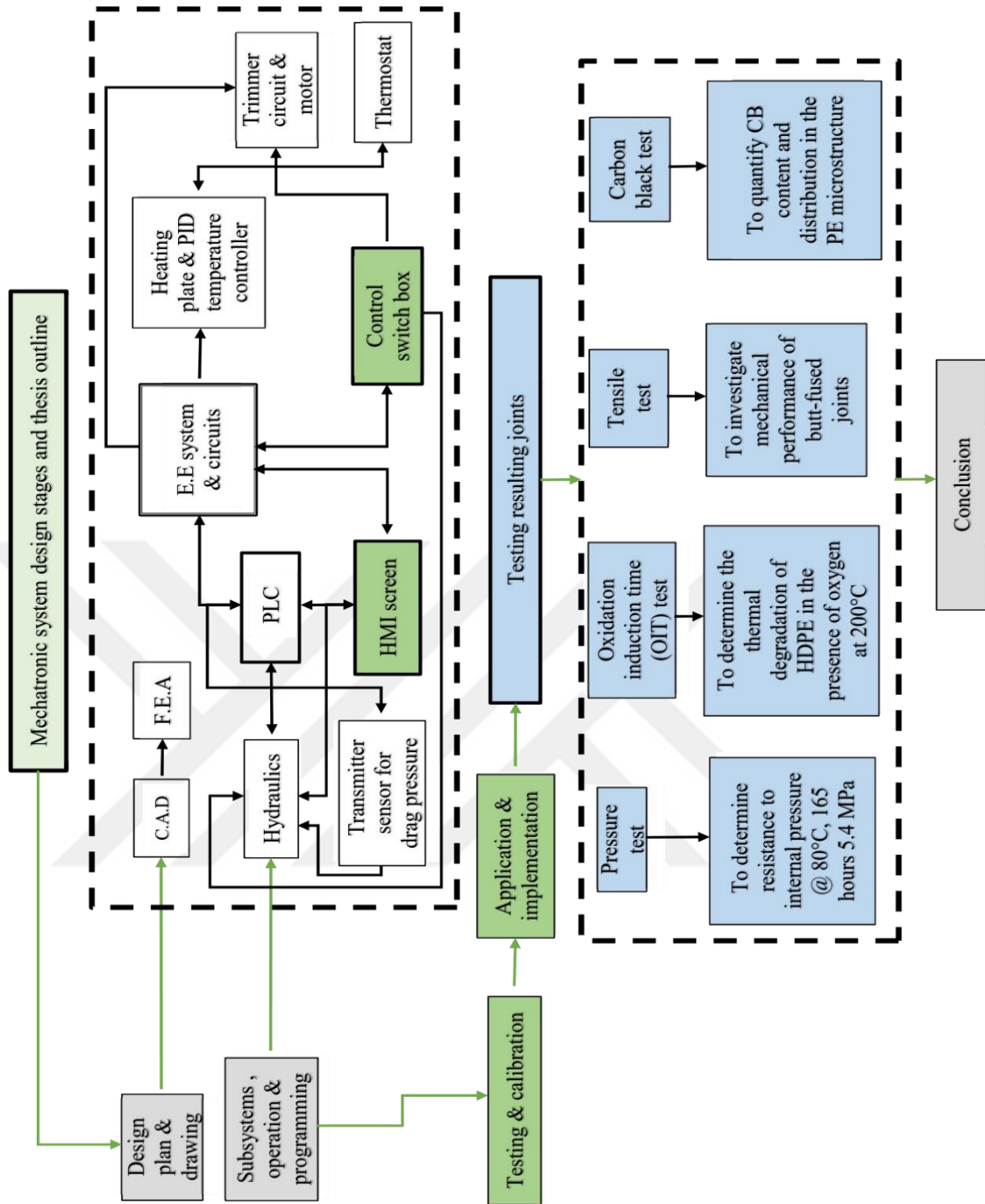


Figure 3.4: Detailed mechatronic system design stages and thesis outline

To successfully design the mechatronics system, key butt-fusion parameters, and equipment such as the heating tool, welding temperature, welding time, joining, and drag pressure need to be carefully tested, enhanced, optimized and analyzed to achieve a butt-fused joint with nearly 100 % parent pipe mechanical strength and characteristics. By clearly stating the pipe ranges and wall thicknesses to be joined by the butt fusion welding method, we were able to obtain the best results for optimizing the welding parameters to achieve the best weld joint.

The designed mechatronics system guaranteed that no exposure of the partially cooled melted PE chains before fusion occurred during welding at T4, because a carefully optimized uniform force in this case welding pressure was applied to facilitate the homogenous thermal movement of the melted material which was strategically adjusted to eliminate exposure of the cold zones during the fusion stage.

3.1 Common Defects in the Butt Fusion Process

When the welding pressure at build-up time T4 is suddenly applied linearly at once as shown in **Figure 3.5 butt fusion welding (Arbeiter et al. 2013)**, the melted surfaces to be joined on either end of the pipe can be easily displaced and in most instances spill out, hence exposing the unheated hard surfaces of the joints. This will result in any or all of the three defects: cold welds, bead misalignment, and non-uniform penetration of polyethylene chains. This is because the hard unheated surfaces cannot enhance the penetration of polyethylene chains, they lack an even and homogenized distribution of melted PE material during the joining period, and finally have poor intermolecular diffusion taking place from one pipe to the other which also affects the homogenous distribution of carbon black (CB) within the butt fused joint microstructure.

These identified series of defects result in the inadequate entanglement of HDPE molecular chains at the joint causing poor mechanical performance of the derived butt fused weld. These flaws can be avoided by either automating the system as proposed in this research, or by employing professional skilled personnel when welding HDPE pipes using the manual machine.

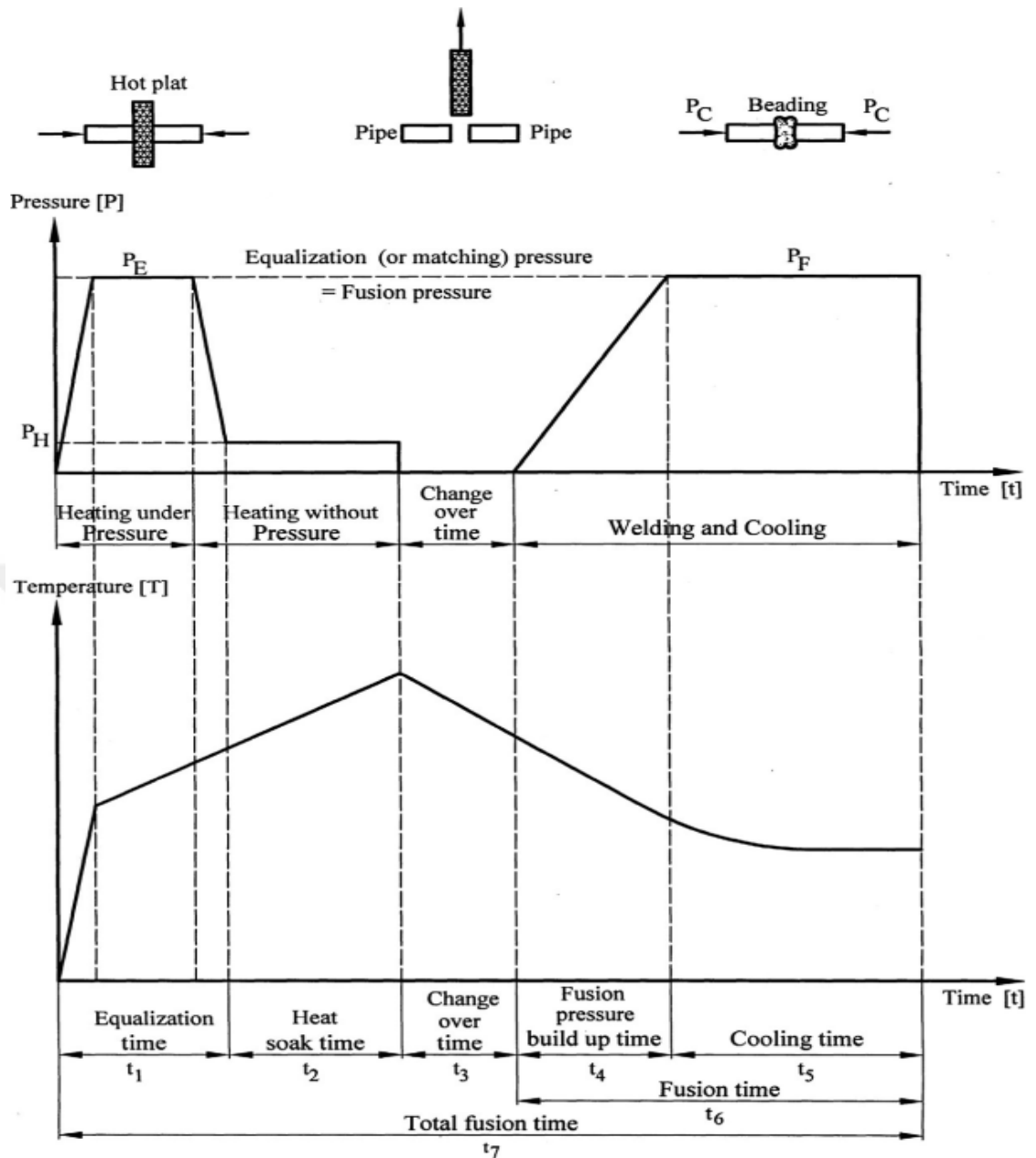


Figure 3.5: Butt fusion welding

Source: Arbeiter et al. (2013)

To achieve a successful butt-welded joint, the third step at T4 in the welding reference chart shown in Figure 3.5 should be applied gradually, and not linearly.

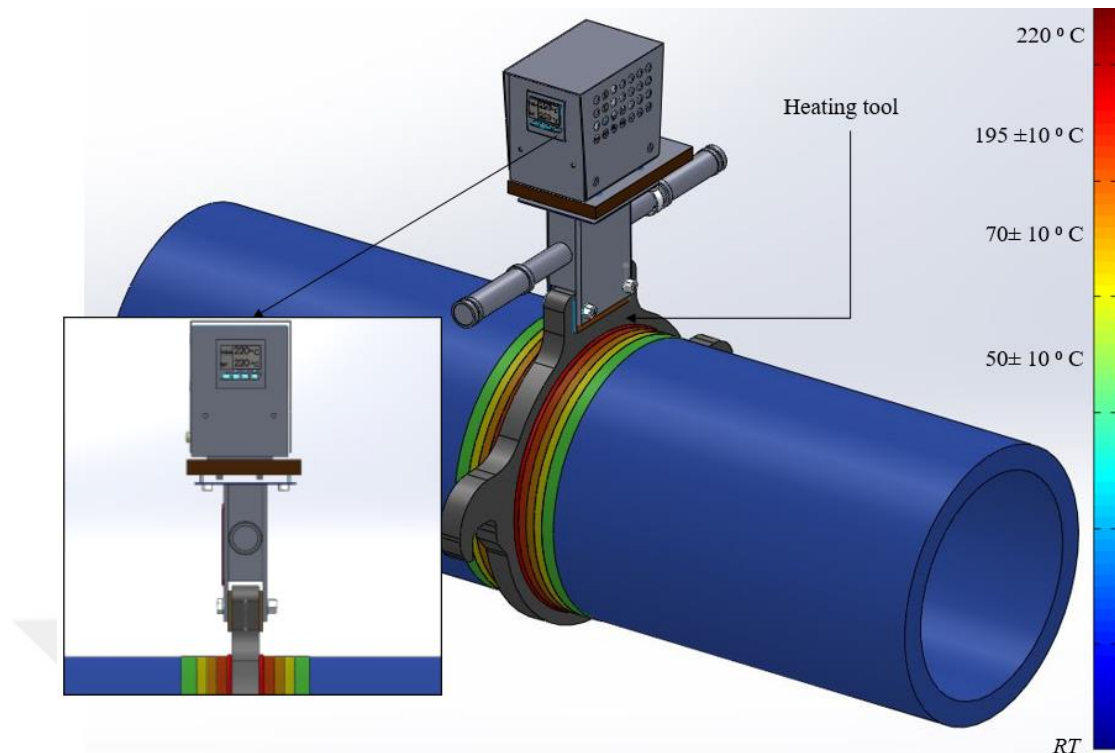


Figure 3.6: The observed temperature changes at T1 and T2 during the heating stage. The molecular structure of the butt-fused zone and temperature-affected sections are significant parameters that affect the final quality and mechanical characteristics of the butt-fusion process. Our research warrants that the heat-affected zone is carefully addressed to achieve an ultimate butt-fused joint with qualities and mechanical properties identical or similar to the HDPE parent pipe.

Gradually applying the welding pressure at T4 provides the melted surfaces of the pipes to be joined are evenly distributed because welding pressure is applied in intervals ensuring that the microstructural chains at residual molten zones positively affect the homogenous thermal movement of the material.

Figure 3.6 provides a summary of the events taking place during the initial heating of the joints before the heating tool is withdrawn; similar heat changes were observed in **Figure 3.7 heated zones during butt welding (Cai et al., 2018)**.

- i. Zone 1: The surface where the heater directly contacts the pipe 220°C .
- ii. Zone 2: The area where the temperature is $195 \pm 10^{\circ}\text{C}$.
- iii. Zone 3: The coldest zone that is the farthest from the heater and the least heated $170 \pm 10^{\circ}\text{C}$.

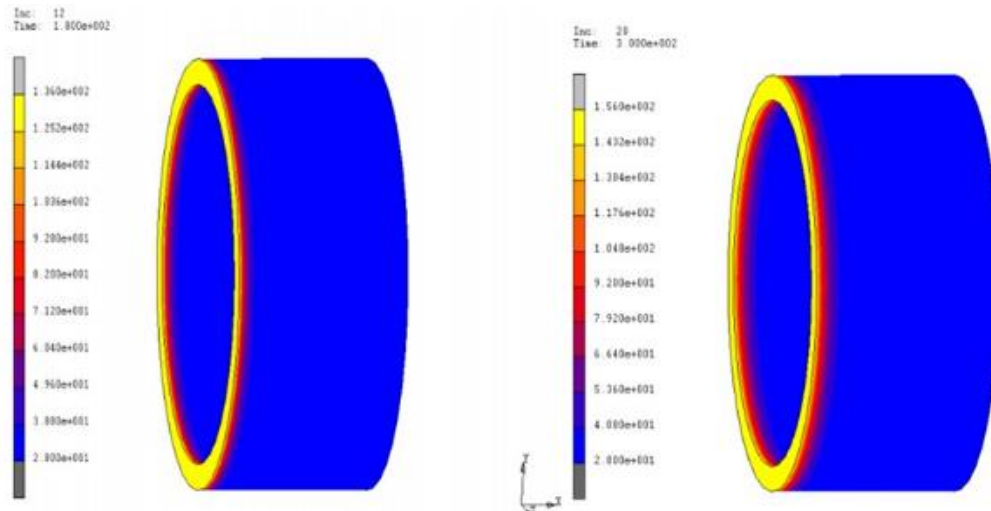


Figure 3.7: Heated zones during butt welding

Source: Cai et al. (2018)

The result of linearly applying the welding pressure as described in the literature in most cases pours out the melting surfaces in Zone 1 and Zone 2 causing them to protrude and flow onto the outer side of the pipe during the joining stage at T4. After the heating element is withdrawn, Zone 3 described in Figure 3.6 is then exposed and comes into contact on either side of the pipe to form a cold weld joint with poor mechanical performance.

For this research, the designed machine not only eliminates cold welds, bead misalignment, and non-uniform penetration of polyethylene chains during joining at T4 but also ensures that the ratio of the drag pressure + welding pressure to the heat applied during heating under the pressure stage is just sufficient enough to not expose Zone 3 before the heating tool is removed.

During the pressure build-up process at T4 intermolecular diffusion takes place from one pipe to the other. This stage is critical to ensure that the resulting welded joint is successful, in this research gradually applying the joining pressure at T4 for 10s in 3 stages, while pausing for 2s at least at each stage guaranteed a successful intermolecular diffusion for the welded joint because a PLC algorithm and program automatically executed this process.

Since welding pressure is applied in intervals, the designed mechatronics system guarantees that during the pipe joining stage, the microstructural chains on the melted zones effectively disperse the polymer chains across the weld interface, making it possible for enough microstructure PE chain webbing to occur, resulting in

a strong joint capable of bearing stress levels similar to those borne by the parent pipe material. It is a fact that the mechanical characteristics of PE are influenced by microstructure crystallinity, PE chain webbing, and microstructural density.

From the literature, it was shown that if any of the listed errors occur on a butt fused joint in a piping system, the resulting joint will exhibit poor mechanical performance hence increasing the chances of pipe failure on the welded sections in piping systems. With the research and experiments conducted so far in this paper, the build-up time and applying of pressure at T4 should be addressed and carefully investigated.

3.2 The Approach for the Butt Fusion Welding Machine Design

The designed mechatronics system was dedicated to resolving the common flaws experienced during the butt fusion process to improve the system and resulting welded joints by making use of CQI and QFD. To improve the design of the existing manual butt-fusion machine in this research, a feedback questionnaire was used to obtain information from the customers in this field of welding using the welding machines.

Table 3.1: Feedback form- the consumer complaints compiled using the surveys for manual butt welding machine is shown below

No	Questionnaires	1	2	3	4	5
1	Human labour and operational efficiency			X		
2	Operating condition of the machine				X	
3	Total power consumption of the system			X		
4	Quality of product					X
5	Life of casing, paintwork, and overall coating					X
6	Formation of rust on the machine panel and hydraulic pistons			X		
7	General design and color of the system			X		
8	Overall noise and vibration of the trimmer			X		
9	Portability and ease of use			X		
10	Hydraulic unit system response and performance				X	
11	Easy repair and electronic or electric component replacement			X		
12	Heating tool- ENDA 4402 digital PID temperature controller performance				X	
13	Welding performance of the machine			X		

Table 3.1: (Cont.) Feedback form- the consumer complaints compiled using the surveys for manual butt welding machine is shown below

No	Questionnaires	1	2	3	4	5
14	Recording and storage of performed welds	X				
15	Trimming tool motor and reduction drive performance				X	
16	Misalignment of pipes due to pistons and clamps		X			
17	Cold welds due to insufficient temperature				X	
18	Cold welds due to excess welding pressure				X	
19	Insufficient welding pressure				X	
21	Welding pressure drop during joining at T4					X
22	The overall life span of the machine				X	
23	The overall price of the system			X		
Customers Feedback	1-30%	31-50%	51%-70%	71%-80%	81%-100%	
Scale factor	1-Very Poor	2- Poor	3-Average	4-Good	5-Very Good	

Table 3.2 above shows the feedback form for the consumer complaints compiled using the surveys for manual butt welding machine.

All tests and machine component assembly were conducted at Turan Makina Borfit, Istanbul Turkey. During this research, we were granted access and permission to use all production facilities and laboratories when performing all tests including surveys which were conducted by collecting data from end-users using the Turan Makina manual butt welding machine. Some of the machine end-users include Danco Capital Kenya, Mirjana U.A.E, AtlasPlast Iraq, Tako Poland, Dematek Romania, Amu SHPK Albania, Crankstar International Trading Srilanka, Plast Middle East Sahara Emirates UAE, and Muna Noor Manufacturing & Trading L.L.C. Oman.

We used the data obtained from the feedback questionnaire to highlight the focus points, strategy, and resources to solve the challenges strictly associated with consumer requirements, to ultimately meet every client's demand and guarantee the success of each manufactured product to win more market share. The literature emphasizes that QFD can be adapted and applied to either develop the quality of products already in the market or produce new goods.

Table 3.3: Technical descriptions based on major customer complaints about manual butt welding machine

N.	Major-customer complaints	Technical descriptions and Design Solutions
1	Lack of track record and storage of performed welds	<ul style="list-style-type: none"> a. Add a memory card or storage device to store and record performed welds b. Create a system that supports USB flash records and storage c. Integrate PLC microcontroller and USB storage device
2	Faults resulting from cold welds due to insufficient temperature caused by equipment failure or mishandling	<ul style="list-style-type: none"> a. Automate the welding procedure by using a PLC microcontroller, valves, sensors, and hydraulic pistons b. Check the heating plate and ensure that the PID temperature controller is operating. If not sure reset the PID controller c. Check the contact of the resistors to the heating plate to ensure that there is a proper contact and the flow of current is stable
3	Welding pressure drop during joining at T4	<ul style="list-style-type: none"> a. Check the quick couplings on the hydraulic unit make sure they are firmly tightened and screwed b. Check the pressure accumulator device c. Automate and stabilize the application of pressure at T4 using a PLC microcontroller to automatically stabilize and regulate the pressure in case it drops
4	Insufficient welding pressure	<ul style="list-style-type: none"> a. Check the quick couplings on the hydraulic unit make sure they are firmly tightened and screwed b. Check the pressure accumulator device c. Automate the application of pressure in the system using a PLC microcontroller to ensure successful intermolecular diffusion for the welded joint

QFD was used to identify the common challenges customers were facing with the existing manual welding machine. To satisfy the customer requirements and detect the defects of the existing machine, the data collected from the survey above was used to improve the design structures, and performance of the manual butt welding machine. After analyzing the results of the survey, a competitive examination of the product and overall cost estimation was done, to meet the demands of the clients, a mechatronics system had to be designed for this paper. To effectively design the proposed system, results obtained from QFD and HOQ were applied, implemented, and integrated into the design. Table 3.2 clearly describes the technical descriptions based on major customer complaints about manual butt welding machine.

3.2.1 Implementation of QFD

The manual and automated butt welding machines have been used and designed by many industries in this field. To come up with a unique design that tackles most of the challenges faced by consumers as described in Table 3.2 can be challenging. Nevertheless, with research, technical experience, and reference to the literature, this paper came up with a solution to the challenges listed in Table 3.2 which were then implemented in the designed automatic butt fusion machine. As a result, the better design features integrated customer requirements and product developments which lead to a successful mechatronics system and design.

The automatic butt welding machine's design characteristics were generated from the findings of the following technical demands. Table 3.3 lists the technical requirements based on major customer complaints about manual butt welding machine

Table 3.4: Technical requirements based on major customer complaints about manual butt welding machine

Technical Requirements	Code	Scale factor (Importance)
Integrate PLC microcontroller and USB storage device to store and record welds	a	5
For temperature control use ENDA 4402 Digital PID Temperature Controller. To identify the surface temperature of the heating tool a thermocouple is implemented. The surface temperature is then recorded, regulated, and kept constant on a Digital PID Temperature Controller. The temperature of the heating plate is kept between 210-230' C because according to the study conducted by Zhiqiang et al. 2018) the best weld is obtained when welding temperature is between 210 °C to 230.	b	5
Automate the welding procedure by using a PLC microcontroller, valves, sensors, and hydraulic pistons to overcome cold welds resulting from human error	c	5
Automate the application of pressure at T4 using a PLC microcontroller to overcome welding pressure drop during joining at T4. An algorithm is used to maintain a fixed welding pressure in case there is any pressure drop the program integrated into the PLC will automatically apply a welding pressure until it is stable	d	5

Table 3.3: (Cont.) Technical requirements based on major customer complaints about manual butt welding machine

Technical Requirements				Code	Scale factor (Importance)
Automate the application of pressure in the system using a PLC microcontroller to overcome insufficient welding pressure challenges				e	5
<p>Automate by integrating the drag pressure and welding pressure for each pipe diameter in the PLC program to perform welds automatically for pipes with diameters 90-315 mm. Apply the formula which is similar to the one described by Krishna Mohan et al to calculate welding pressure</p> $P = \frac{(Outer\ Diameter\ D1\ area - Inner\ Diameter\ D2\ area) \times Material\ Thrust\ Coefficient}{CS\ area\ of\ machine\ hydraulic\ cylinder}$ <p>The drag pressure is automatically added to the welding pressure when initializing the machine.</p> <p>Drag pressure corresponds to the force required to overcome the internal friction of the equipment while moving the pipes. To find the drag pressure, the designed machine will use a pressure transmitter which will receive signals from a transducer connected to the hydraulic unit. The received signals will be sent to the PLC in the form of voltages between 1-5 volts. With this information, a drag pressure will be calculated for any pipe between 90-315 mm and added to the welding pressure(P1)</p>				f	5
<p>Integrate HMI -Touch Screen GMTCNT TSG-7 to control the hydraulic pistons and machine.</p> <p>-Use an HMI screen to input pipe wall thickness before welding</p> <p>- Use HMI screen to input pipe outer diameter before welding</p> <p>The above information is sent to the PLC to implement the operations described in f</p>				g	5
<p>Integrate and automate the application of welding pressure at T4 with a new algorithm that applies pressure in 3 gradual intervals at the build-up or joining stage ensuring that cold welds, bead misalignment, and non-uniform penetration of polyethylene chains are eliminated</p>				h	5
Scale factor(Importance)	1-Very low	2-low	3-Average	4-High	5-Very high

The designed mechatronics system was dedicated to resolving the common flaws experienced during the butt fusion process to improve the system and resulting welded joints by making use of CQI and QFD. The designed polyethylene pipe butt welding machine sections are shown in Figure 3.8 below.

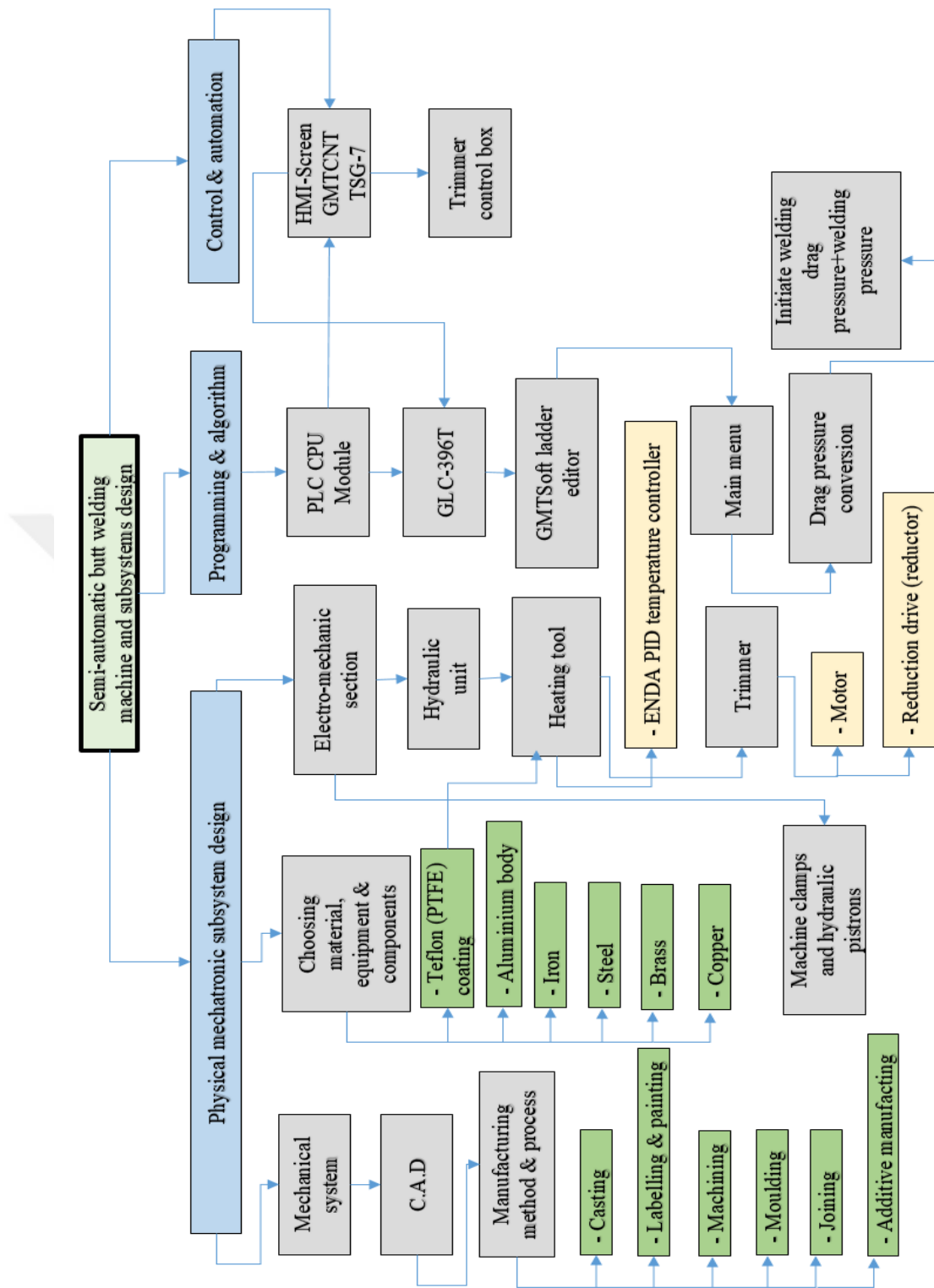


Figure 3.8: The semi-automatic butt fusion welding machine design and subsystems

4. BUTT WELDING MACHINE DESIGN FOR HDPE PIPES

Figure 4.1 briefly describes the summary of the machine's operation and the functions it performs. All the described functions below are inserted onto the HMI screen to achieve the demanded output response.

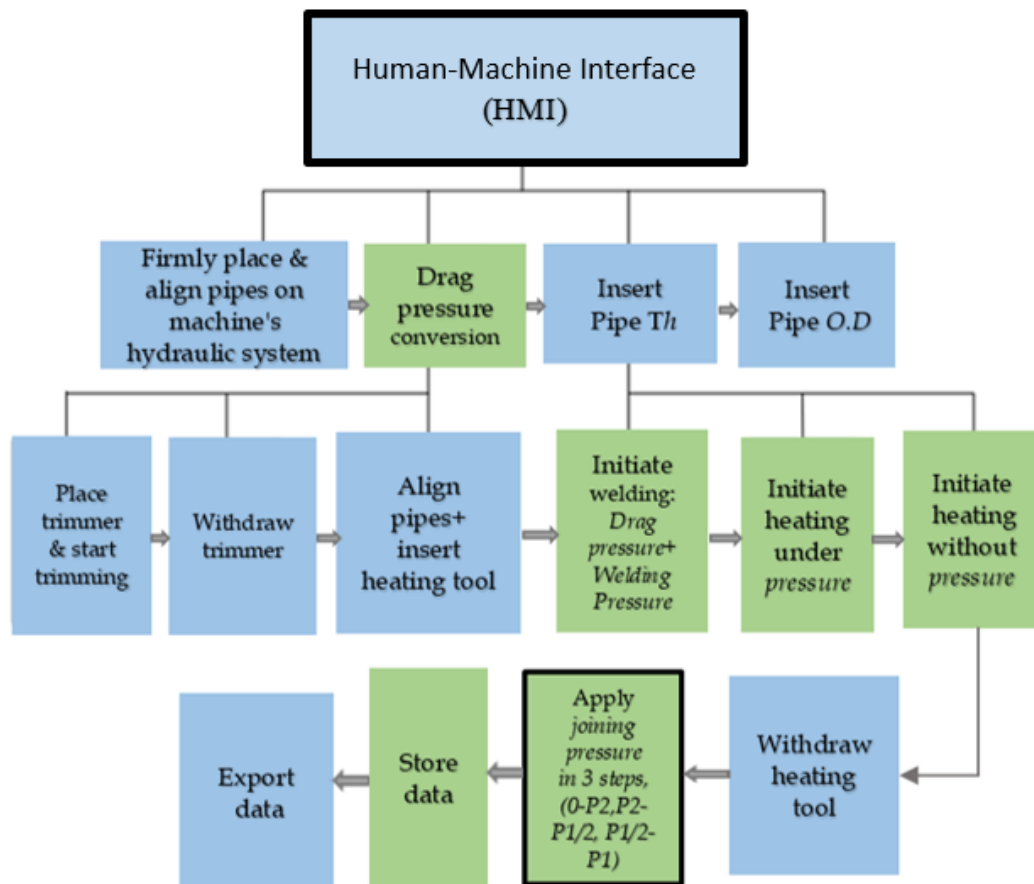


Figure 4.1: The summarised operation algorithm for the designed welding machine

The HMI touch screen model is GMTCNT TSG-070 / TSG-070E human machine interface operator panel and is manufactured by GMT Industrial Electronics Company.

4.1 PLC Program and Machine Working Principle Designed For This Paper

The programming language used for this design was ladder logic (ladder diagram LD) which is sometimes stated as PLC ladder logic programming. This programming

language was used and implemented to program a PLC. Coding was easy because ladder logic is much more visual and graphical compared to other programming languages. Instead of text code, coding is done by linking elements known as symbols which are represented by electrical symbols and logic circuits as we will see below. Having a background in electrical and electronics made this programming language easier to design and implement in the automatic butt welding machine.

The PLC CPU module used for this machine is GLC-396T manufactured by GMT Endüstriyel Elektronik San. ve Tic. Ltd. Şti. located in Istanbul, Turkey.

GLC-396T PLC CPU Module is operated by a 24VDC power and has an analog input, analog output 9 digital inputs 50 kHz counter, 6 transistor outputs (3 channels 100 kHz), WMI, RTC, Modbus, and TCP details can be accessed in the TDS Figure 7.3.

For this mechatronics system, the PLC CPU was programmed using GMTSoft ladder editor which can be accessed on GMT Endüstriyel Elektronik San. ve Tic. Ltd. Şti. company website. To successfully establish a connection between the PLC and upload the code GMTSoft program, the following connection methods were used USB Mini-B cable type, and standard CAT5 ethernet cable. A detailed data sheet including electrical diagrams and schematics of the PLC CPU module can be accessed in the appendix of this paper.

For copyright and patent purposes not all sections of the detailed ladder program code are shown in this paper. All software and coding shown in this section were used with permission from Turan Makina Borfit, Istanbul, Turkey.

4.2 Detailed PLC program

For this system, the drag pressure was automatically initiated using a pressure transmitter that receives signals from a transducer connected to the hydraulic unit. The received signals were sent to the PLC in the form of voltages between 1-5 volts. With this information, a drag pressure was calculated for any pipe between 90-315 mm.

Sections of this operation can be seen in the ladder code shown in Figure 4.2.

Drag pressure (P_d) corresponds to the force required to overcome the internal friction of the equipment while moving the pipes.

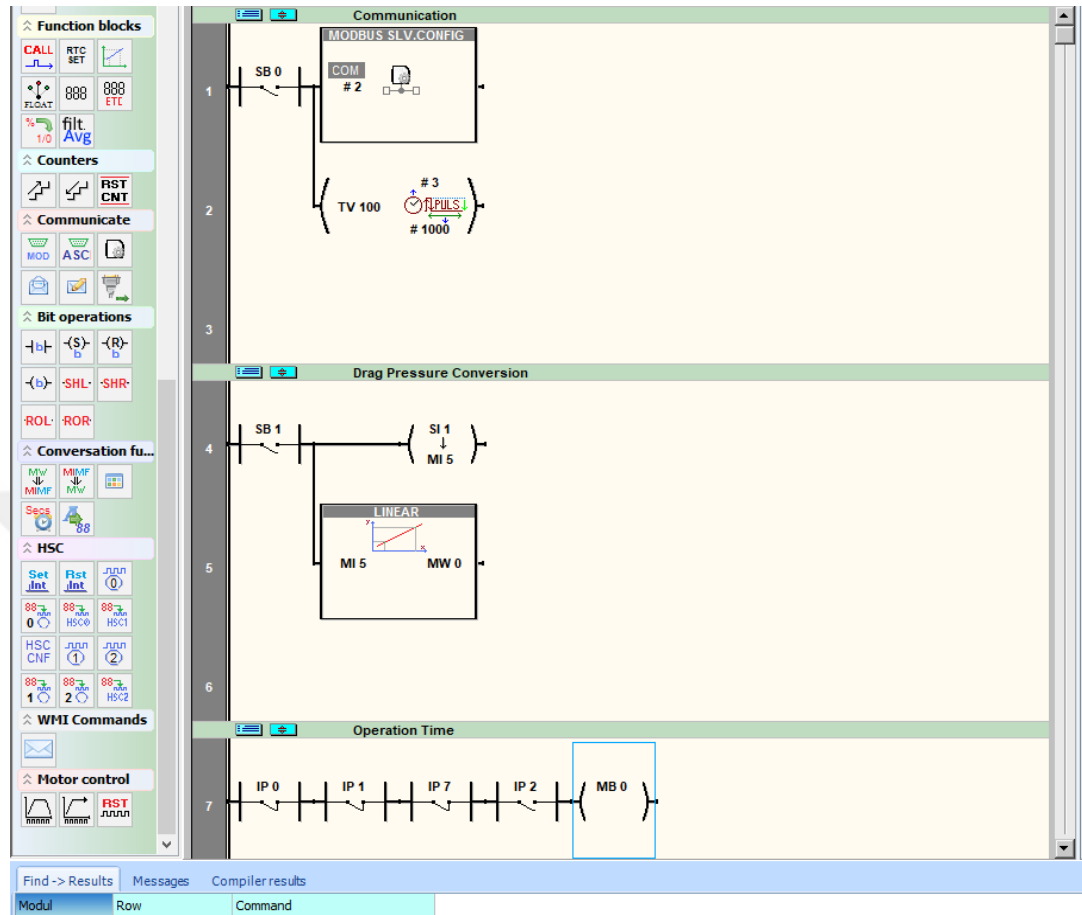


Figure 4.2: The PLC ladder code for machine processing and pressure conversion

The equation shown below was implemented in this section of the code (Figure 4.3). (Equation 4.1) (Mohan, 2016)

$$P = \frac{\text{Pipe Cross Sectional Area}(A_P) \cdot \text{Material Thrust Coefficient}(C_T)}{\text{Cross Sectional Area of Machine Hydraulic Cylinder}(A_{HC})} \quad (4.1)$$

$$P = \frac{(A_P) \cdot (C_T)}{(A_{HC})}$$

$$A_{RC} = 2\pi \frac{d}{2} h + 2\pi \left(\frac{d}{2}\right)^2 \quad (4.2)$$

The cylindrical area for the manufacturer's hydraulic cylinder (A_{HC}) is 14.13 cm².

According to the literature, the material thrust coefficient (C_T) for HDPE is 1.5 kg/cm².

The area of a cylinder A_{RC} was calculated using (Equation 4.2) (URL – 1)

In this machine design, the only varying parameters were the pipes' wall thicknesses and outer diameters which were inserted into the HMI screen to calculate the pipe's cross-sectional area (A_p). In formula 4.1 the rest of the parameters were held constant.

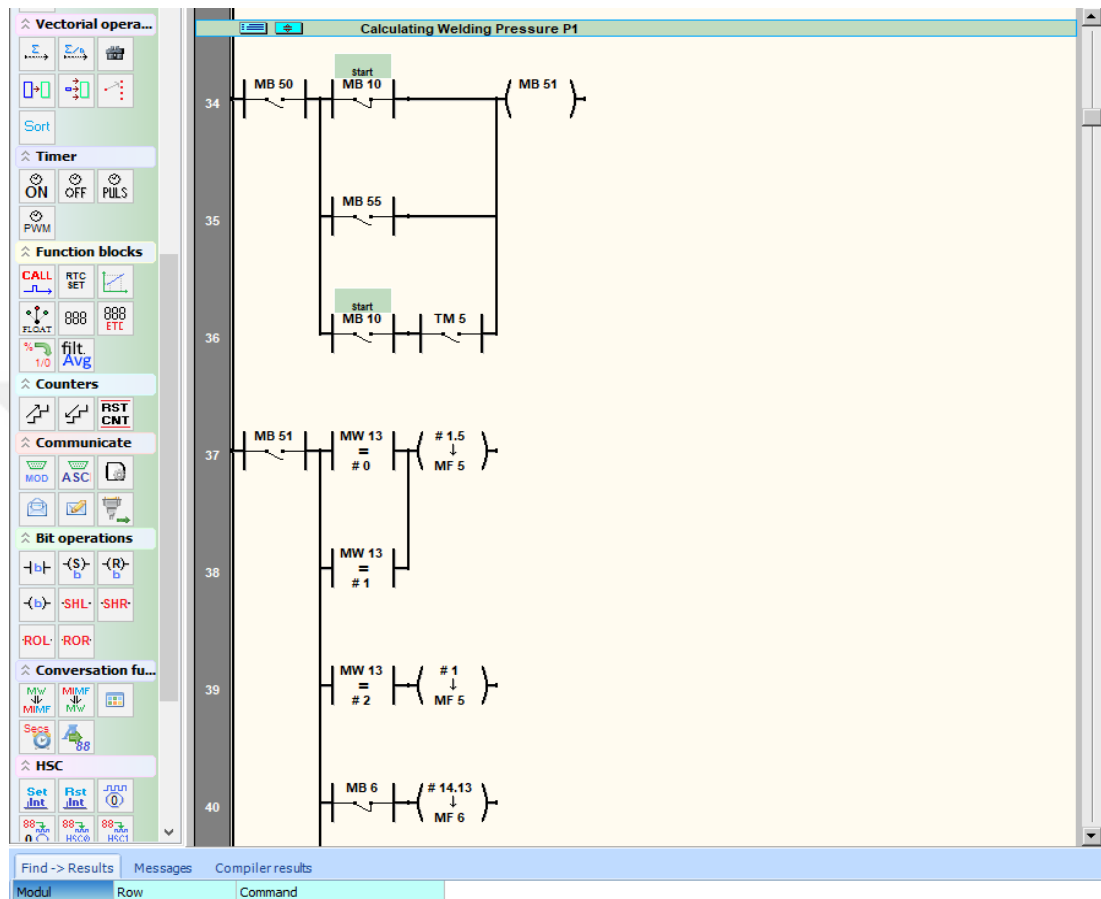


Figure 4.3: The ladder diagram program when implementing P1

Dimension details for the pipes to be welded ranging from 90-315 mm were inserted into the HMI screen, the following steps then followed;

- a. To initiate and perform the welds for pipes ranging between 90-315 mm, the pipe wall thickness, and outer diameter had to be inserted.
- b. Using the pipe O.D and wall thickness information entered on the HMI screen, the pipe welding pressure was automatically calculated and added to the drag pressure.

The section of the code shown in Figure 4.4 shows the implementation of drag pressure and welding pressure.

$$P1 = \text{drag pressure } (P_d) + \text{applied pressure } (P) \quad (4.3)$$

$$P1 = (Pd) + (P)$$

When welding pressure is 0 N/mm^2 , build-up joining pressure should be applied as follows,

$(0 \text{ to } P2) \text{ N/mm}^2$,

$[P2 \text{ to } (P3 = \frac{P1}{2})] \text{ N/mm}^2$, then finally

$[(P3 = \frac{P1}{2}) \text{ to } P1] \text{ N/mm}^2$, within 10 seconds, the resulting joint exerts similar properties to the parent pipe.

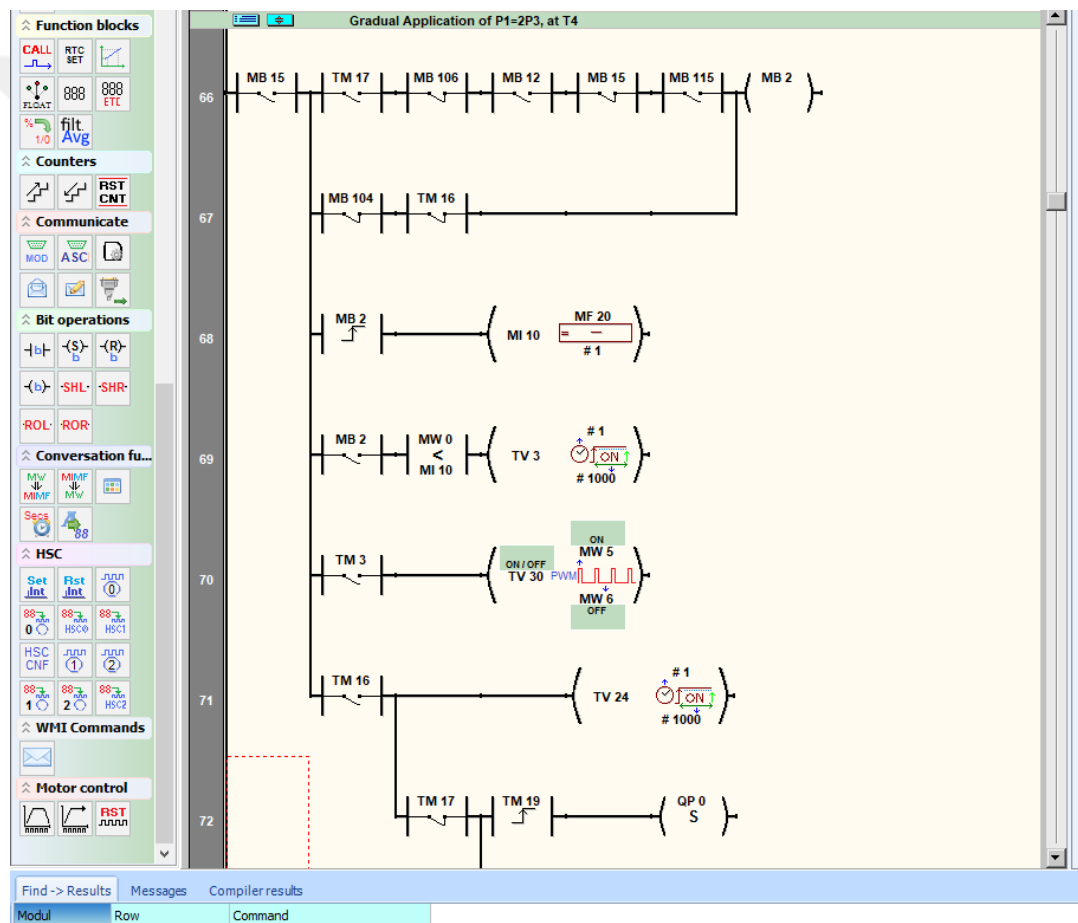


Figure 4.4: The ladder diagram program shows the gradual application of joining pressure $P1 = 2.P3$ at T4

The applied formula and details can be seen on the welding chart adapted for this paper at T4. The area of a cylinder ARC was calculated using (Equation 4.4) (URL – 1)

$$A_{RC} = 2\pi \frac{d}{2} h + 2\pi \left(\frac{d}{2}\right)^2 \quad (4.4)$$

Where;

d: Diameter (mm)

h: Height (mm)

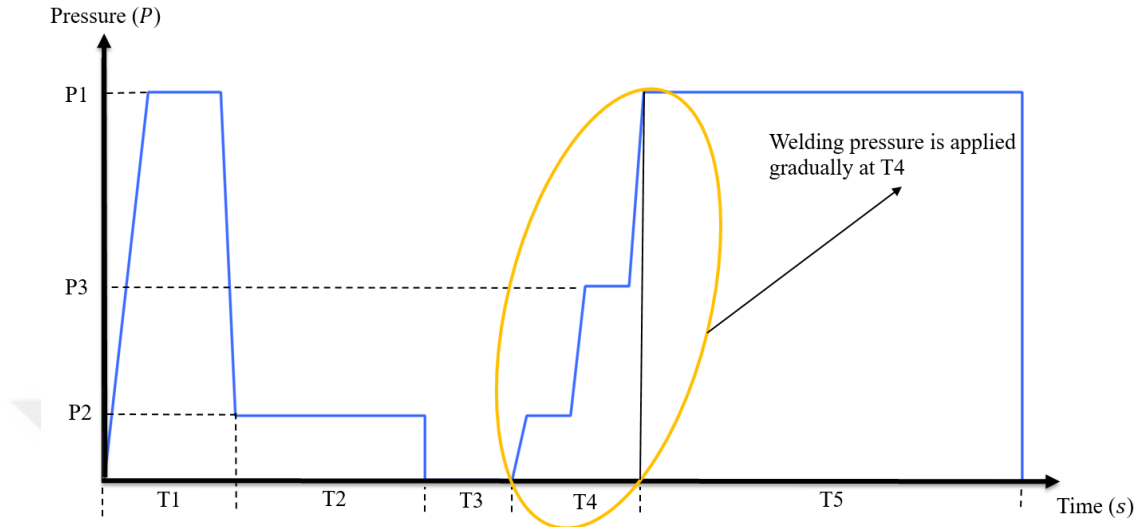


Figure 4.5: The applied welding algorithm to join the pipes at T4

Some of the sections of the coded ladder program fully implementing the proposed welding algorithm for joints with better mechanical performance were summarised above in this section. Using this logic and program, the semi-automatic machine ensured that all series of butt welding performed on this system resulted in successful intermolecular diffusion from one pipe to the other during the pressure build-up process at T4. Figure 4.5 shows the applied welding algorithm to join the pipes at T4.

4.3 Mechatronics Subsystems

Using CQI, the designed automatic butt welding machine improved the existing machine prototype manufactured by Turan Makina Borfit which welds HDPE pipes and fittings between 90-315 mm.

In the already existing machine manufactured by Turan Makina A.Ş. the machine sections are shown in Figure 4.6 the hydraulic unit design and the heating tool design, Figure 4.7 the trimmer design, and Figure 4.8 the machine body, clamps, and hydraulic pistons design (Turan Makina, Technical Catalogue, 2017). We applied the technical requirements described in Table 3.2 which ensured that the resulting welded joints eliminated cold welds, bead misalignment, and non-uniform penetration of polyethylene chains. This was achieved by the application of welding

pressure at T4 with the new algorithm which applies pressure in 3 gradual intervals at build-up or joining stage ensuring that the welded joints have similar or exact characteristics to the mother pipe or fitting.

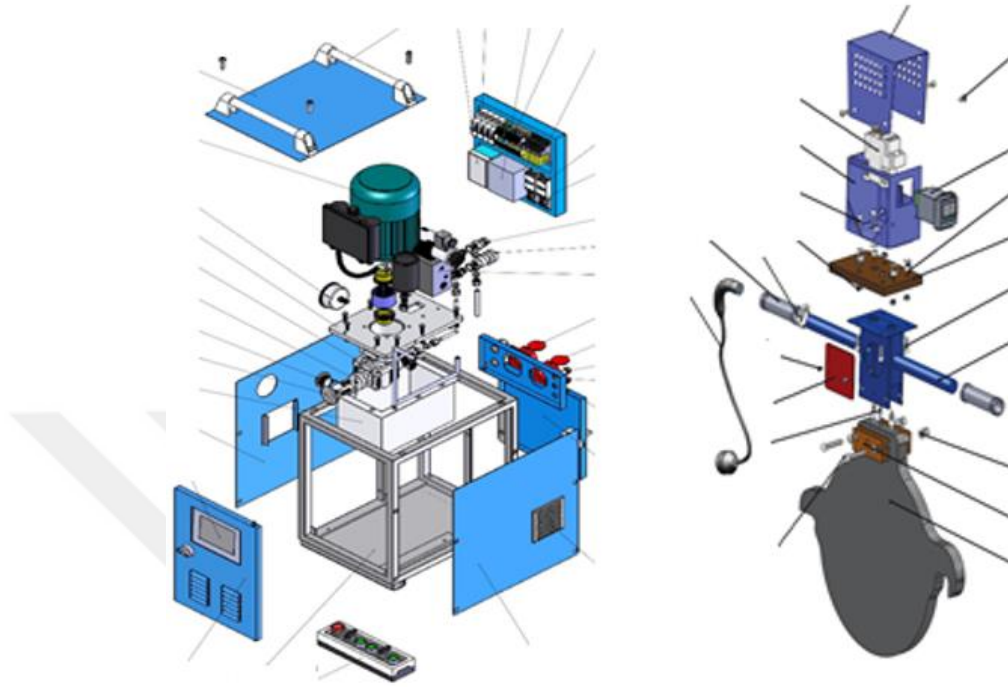


Figure 4.6: The hydraulic unit design and the heating tool design

Source: Turan Makina, Technical Catalogue. (2017).

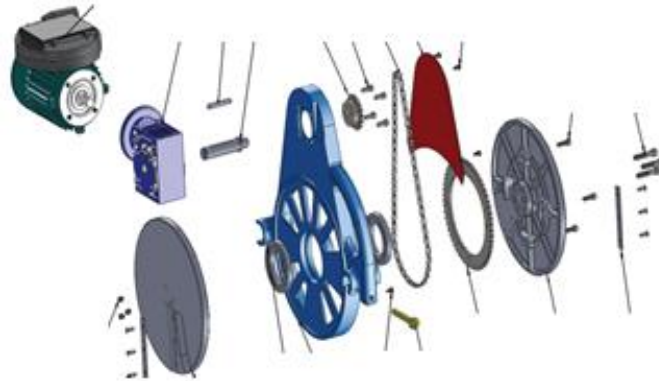


Figure 4.7: The trimmer design

Source: Turan Makina, Technical Catalogue. (2017).

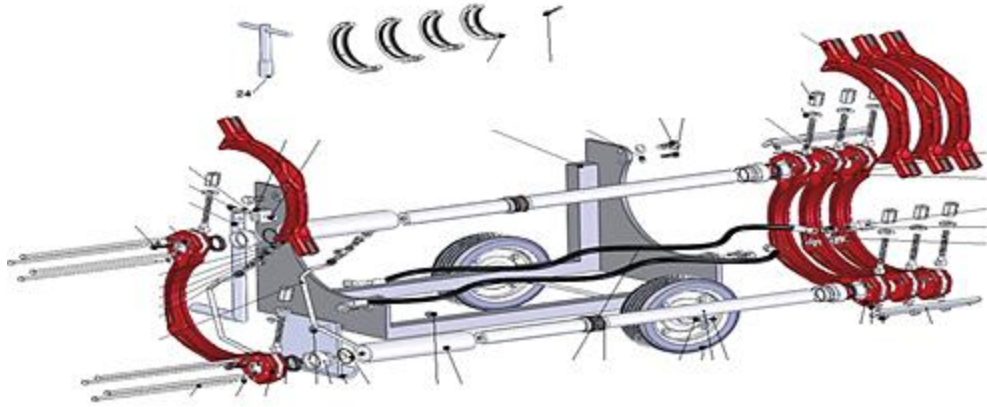


Figure 4.8: The machine body, clamps, and hydraulic pistons design

Source: Turan Makina, Technical Catalogue. (2017).

Figures 4.6-8 show Turan Makina Borfit 90-315 mm butt welding machine sections and design (The above technical drawings were used with permission from Turan Makina Borfit, Turkey).

The new welding algorithm was integrated into the butt fusion welding machine design shown above.

5. AUTOMATIC BUTT FUSION VS MANUAL BUTT FUSION

To test the integrity of the welded joints a series of tests needed to be conducted as per international welding standards and literature.

As mentioned in this paper, an automatic welding machine was designed to be used for our research. Utilizing the collected information from the literature, data from end-users and international standards as references, an algorithm, and PLC program was designed to successfully run the automatic butt welding machine. The designed machine successfully performed welds for pipes and joints between 90-315 mm outer diameters (O.D).

For this research, a series of welds using the semi-automatic butt welding machine had to be performed for comparing and contrasting the performance of the machine in terms of the resulting welded joints, another series of welds on a manually operated butt welding machine was performed.

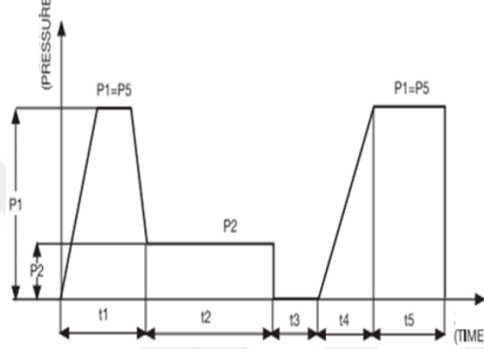
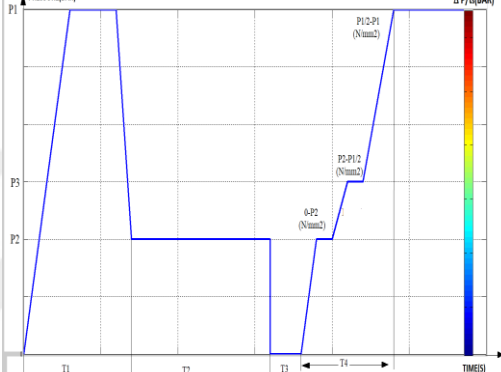
With this approach, we were able to compare the resulting joints from a manually operated welding machine (usually bound to cause defective welds due to human error) to the automatically operated butt welding machine (faulty welded joints are significantly reduced because the machine is operated automatically hence reducing human error). The other major advantage of the automatically operated butt welding machine is the capability to record all the welds performed on the machine.

5.1 Detailed Butt Fusion Welding Procedure

Table 5.1: Welding using manual butt fusion and automatic butt fusion of HDPE pipes and fittings

General Criteria and Welding Parameters	Manual Butt Fusion	Automatic Butt Fusion
Initialization and preparation of Heated Tool Butt Fusion	The heating tool was heated to 220°C. During the entire process, heating was maintained through a temperature control device.	The heating tool is heated to 220°C. During the entire process, heating was maintained through a temperature control device.
	Pipes to be welded (90-315 mm O.D) were carefully and steadily placed between the clamps of the machine. Then the drag pressure of the pipes was manually initiated by gradually applying pressure to the hydraulic pistons. From the manometer reading, the <i>pressure bar</i> at which the pipes move should be recorded and saved as the <i>drag pressure</i> for that type of pipe or joint size. The trimmer was then placed between the two pipes.	Pipes to be welded (90-315 mm O.D) were carefully and steadily placed between the clamps of the machine. On the HMI screen, insert the pipe wall thickness, and outer diameter. The drag pressure was automatically initiated using a <i>pressure transmitter</i> which received signals from a transducer connected to the hydraulic unit. The received signals were sent to the PLC in the form of voltages between 1-5 volts. With this information, a drag pressure was calculated for any pipe between 90-315 mm. The trimmer was then placed between the two pipes.
	Tips of the pipes to be welded were trimmed until 100% contact was achieved. The trimmer was then removed and the heated plate at 210 ±5°C was placed between the pipes.	Tips of the pipes to be welded were trimmed until 100% contact was achieved. The trimmer was then removed and the heated plate at 210 ±5°C was placed between the pipes.
T1: Joining period under required pressure to form lips	Using the welding parameter table (<i>see table 6</i>), the pipe <i>welding pressure</i> was manually added to the <i>drag pressure</i> . E.g. for a pipe with 90 mm O.D, the welding pressure was 3 BAR . The joints were pressed against the heated tool with a welding pressure of $P_1=P_2$ (The sum of drag pressure and welding pressure) until all areas were coplanar. The formation of beads was an indication that all areas were coplanar, the alignment was completed when the bead displacements had extended to the stated figure in table 6.	Using the pipe O.D and wall thickness information entered on the <i>HMI screen</i> , the pipe <i>welding pressure</i> was automatically calculated and added to the <i>drag pressure</i> . The joints were pressed against the heated tool with a welding pressure of P_1 (The sum of drag pressure and welding pressure) until all areas are coplanar. The formation of beads was an indication that all areas were coplanar, the alignment was completed when the bead displacements had extended to the stated figure in table 6.
T2: Heating time without pressure	Once T1 was finished, pipe tips were continuously heated while the heater was still between with a manually reduced near zero pressure of $0.01/mm^2$.	Once T1 was completed, the system automatically reduced the pressure with a near-zero value of $0.01/mm^2$, while the heater was still between the pipes.
T3: Time required to remove the heating plate	Once T2 was completed, the heating plate was removed. This stage was done manually and quickly to avoid the cooling of heated molten welded zones HDPE.	Once T2 was completed, the heating plate was removed. This stage was done manually and quickly to avoid the cooling of heated molten welded zones HDPE.
T4: Time required to increase the pressure(The welding pressure of the specified pipe)	The pipes were joined manually by linearly applying the welding pressure P1 as described in the literature.	The pipes were joined automatically by applying P1=2P3 for 10s in 3 stages, by pausing for at least 2s at each stage guaranteeing a successful intermolecular diffusion for the welded joint At T4, since welding pressure was $0 N/mm^2$, build-up welding pressure should be applied as follows, $(0-P_2) N/mm^2$, $(P_2-P_1/2)$, then finally $(P_1/2-P_1)$ within 10 seconds.

Table 5.1: (Cont.) Welding using manual butt fusion and automatic butt fusion of HDPE pipes and fittings

General Criteria and Welding Parameters	Manual Butt Fusion	Automatic Butt Fusion
T5: Cooling time with pressure.	After applying the pressure at T4. Depending on the pipe diameter and size, the joints were not dismantled immediately but were left to cool as described in Table 6. At times a pressure drop of 2-10 BAR occurred during the cooling time.	After applying the pressure at T4. Depending on the pipe diameter and size, the joints were not dismantled immediately but were left to cool as described in Table 6. No pressure drop occurred because the designed system was installed with a pressure regulator which automatically stabilized any occurring pressure changes
 <p data-bbox="300 996 774 1052">Manual butt fusion operation principle graph according to literature</p>		 <p data-bbox="885 1030 1396 1086">Automatic butt fusion operation principle graph for this research</p>
Pressure changes and definitions on the butt fusion welding parameter graph		
P1: Welding pressure.	P2: Applied pressure near-zero during the heat soak period	P1: Welding pressure. This is the sum of the configured drag pressure and welding pressure.

As it can be easily seen in the manual butt-fusion section, all procedures are done manually, human error is bound to happen at certain points especially during the welding process. It might be hard to remember each step and parameter shown in Table 5.1, the need for highly skilled operators is inevitable.

For the designed automatic butt fusion section, the steps involved in welding are done automatically. Another added advantage of the automatic machine is that all the welds performed were recorded on a screen for observation and reference. It might be hard to remember each step and parameter especially when a series of welds are being performed at once. Except for the placement and withdrawal of the heating tool and trimmer, all the steps shown in Table 5.1 automatic butt fusion section are done automatically.

Each step and every parameter described in butt-fusion is critical in obtaining a perfect weld. Since HDPE pipes have a lifespan of over 30 years or more, they are suitable to be executed in various pipe installation projects. Therefore, the welded

joints need to meet the required standards to decrease the possibility of failure in a pipe network system which may result from a faulty weld and mishandling of the welding equipment.

Table 5.2: Butt fusion welding parameters used for this research

Material PE 100 SDR 11 PN 16 cylindrical area for the hydraulic piston is 14. 13 CM ²								
Outer diameter (OD) mm	Wall thickness mm	The applied pressure (P) (N/mm ²)	Lip thickness mm	T2 (min)	T3 (s)	T4 (s)	T5 (min)	Total (min)
75	6,8	0.2	1,2	1,25 min	5-6	10	10	12
90	8,2	0.3	1,3	1,5 min	6-8	10	12	14
110	10	0.4	1,5	2 min	6-8	10	15	17
125	11,4	0.5	1,6	2,2 min	6-8	10	17	20
140	12,7	0.6	1,8	2,35 min	8-10	10	19	22
160	14,6	0.7	2	3 min	8-10	10	22	25
180	16,4	0.9	2,1	3,15 min	8-10	10	25	28
200	18,2	1.1	2,3	3,4 min	8-10	10	27	31
225	20,5	1.5	2,6	4 min	10-12	10	31	35
250	22,7	1.8	2,8	4,35 min	10-12	10	34	39
280	25,4	2.2	3	5 min	10-12	10	38	44
315	28,6	2.8	3,4	5,45 min	12-16	10	43	49
355	32,2	3.5	3,7	6,25 min	12-16	10	48	55
400	36,3	4.5	4,1	7,15 min	12-16	10	54	62
450	40,9	5.5	4,6	8,15 min	16-20	10	61	70
500	45,4	7.0	5	9 min	16-20	10	68	78

1 kg/cm² = 0.981 bar ; 1 bar= 0.1 MPa; 1 bar = 0.1 N/mm²

By inserting the parameters described in Table 5.2, the designed mechatronics system performed the welds of pipes between 9-315 mm successfully.

Table 5.3: Welding parameters (DVS 2207-2007)

1 Nominal wall thickness mm	2 Alignment Heated tool temperature Bead displacement on heated tool after alignment time (alignment P = 0,15 N/mm ²) mm	3 Heating-up Heating-up time =10 x wall thickness p= ≤ 0,01 (N/mm ²) s	4 Changeover Changeover time Maximum time s	5 Fusion Fusion pressure time s	5 Joining Chilling period with fusion pressure (minimum values) P = 0,15 N/mm ² ± 0,01 min
up to 4,5	0,5	up to 45	5	5	6
4,5... 7	1	45... 70	5... 6	5... 6	6... 10
7... 12	1,5	70... 120	6... 8	6... 8	10... 16
12... 19	2,0	120... 190	8... 10	8... 11	16... 24
19... 26	2,5	190... 260	10... 12	11... 14	24... 32
26... 37	3,0	260... 370	12... 16	14... 19	32... 45
37... 50	3,5	370... 500	16... 20	19... 25	45... 60
50... 70	4,0	500... 700	20... 25	25... 35	60... 80

Source: (DVS 2207, 2007)

$$A_{RC} = 2\pi \frac{d}{2} h + 2\pi \left(\frac{d}{2}\right)^2 \quad (5.1)$$

Where;

d: Diameter of the pipe (mm)

h: Height of the pipe (mm)

A_{RC} : Area of a right cylinder. Which is defined when the axis (one of the sides of the rectangle) is perpendicular to the radius (r), then the cylinder, so formed, is called a right circular cylinder. The area of a cylinder A_{RC} was calculated using (Equation 5.1) (URL – 1).

For reference the welding parameters described in the literature were observed from Table 5.4 (DVS 2207, 2007).

6. EXPERIMENTAL ANALYSIS AND RESULTS FOR BUTT FUSION

As already discussed, the objective of this paper was to design a semi-automatic butt-welding machine using corrective quality improvement. The designed system ensured that the resulting butt-fused joints are per (DVS-2207-1, 2007) international standard while eliminating welding errors that may result from mishandling of the welding equipment. These errors usually occur due to the linear application of welding pressure at T4 as shown in the literature butt fusion graphs, or poor workmanship as addressed in the literature. For butt fusion, obtaining high-quality welding is not possible all the time due to the necessity of very high skill, and the use of complicated welding machines for the welding process.

Automating the welding process in the semi-automatic butt welding machine by integrating the proposed welding algorithm eliminated the faults. The algorithm safeguards that welding pressure at T4 is applied gradually in 3 intervals guaranteeing that during the pressure build-up process at T4, successful intermolecular diffusion takes place from one pipe to the other. The mechanical properties, chemical properties, and performance of the fused joints were tested using the test method classified in (International Organization for Standardization, 13953-tensile strength for butt fusion, 2001), (International Organization for Standardization, 11357- Plastics - Differential scanning calorimetry (DSC) - Part 1: General principles, 2009) & (International Organization for Standardization, Determination of Carbon Black Content by Calcination and Pyrolysis -Test Method and Basic Specification , 1986), and (International Organization for Standardization, 1167-3 Thermoplastics pipes, fittings, and assemblies for the conveyance of fluids - Determination of the resistance to internal pressure - Part 3: Preparation of components , 2007). The obtained results were then compared with the results in literature.

In this research, test samples were obtained from HDPE pipes extruded from Borouge HE3490-LS Table 6.1 (Borouge Borstar HE3490-LS Black HDPE TDS, 2006) . This type of HDPE raw material is classified as having a well-dispersed

carbon black content and is recommended for use in HDPE pressure pipe systems for applications in potable water, and natural gas pipeline systems.

Table 6.1: The physical properties of Borouge HE3490-LS HDPE raw material

Property	Unit	Value
Density (compound)	kg/m^3	959
Melt flow rate (190°C/5.0 kg)	g/10 min	0.24
Melt flow rate (190°C/5.0 kg)	g/10 min	6.5
Tensile stress at yield (50 mm/min)	MPa	25
Elongation at break	%	≥600
Carbon black content	%	2.41
Carbon black dispersion		1.0
Oxidation induction time (OIT) 210 °C	min	(210°C)

Source: Borouge Borstar HE3490-LS Black HDPE TDS, (2006)

6.1 Testing the Physical and Mechanical Properties of the Resulting Joints

The mechanical properties of the fused and unfused joints were subjected to the tensile strength test method described in the literature and international standards. The obtained results were then compared to the literature, and MATLAB simulation.

6.1.1 Testing method for tensile strength and failure mode of un-welded HDPE pipe samples

For better comparison, unfused pipe sample specimens were extracted and subjected to the tensile strength test. Using the series of methods specified by ISO 6259, determining the tensile properties of HDPE pipes with 90 mm was done.

Before performing the test, the following properties had to be defined.

- Stress at yield (σ_y)

For each sample, the tensile stress at the yield on the base of the primary cross-sectional area of the test specimen, using Equation (6.1) (EN ISO 6259, 2015).

$$\sigma_Y = \frac{F}{A} \quad (6.1)$$

Where;

σ_y : Tensile stress at yield, expressed in mega Pascal (MPa) $1 \text{ MPa} = 1 \text{ N/mm}^2$;

F: The force at yield expressed in Newton (N);

A: The primary cross-sectional area of the test piece, expressed in square millimeters (mm^2).

Stress measured at the yield strain it is expressed in mega Pascal (MPa)

Note: In fact, the yield stress must be evaluated from the cross-sectional area of the samples at yield, however for convenience, the primary and initial cross-sectional area is applied.

- Elongation at break (ϵ_b)

For each sample, the elongation at break was calculated with; Equation (6.2) (EN ISO 6259, 2015).

$$\epsilon_b = \frac{L-L_0}{L_0} \cdot 100 \quad (6.2)$$

Where;

ϵ_b : elongation at break (%);

L: gauge length at break, (mm);

L₀: primary & initial gauge length of the sample, (mm) calculated from the gauge length at the break it is expressed as a percentage (%)

- Force at yield (F)

Force measured at yield it is expressed in Newton (N)

- Yield

Conversion from elastic to plastic deformation is usually characterized by a reduction or shoulder in the stress-strain curve.

Through investigating the stress yield and elongation at break criteria for the unwelded pipe samples, we were able to compare the butt-fused sample's stress at yield

and elongation at break graphs to see which of the two machines produced welded joints with mechanical characteristics similar to the parent pipe.

By machining a pipe sample of 90 mm with wall thickness 8.2 mm and PN 16 as shown in Figure 6.2, in the longitudinal direction, samples were derived to perform the tests. The mechanical properties were then investigated and measured by performing tests using the Devotrans machine. Figure 6.1 shows the Devotrans tensile compression testing machine setup

Table 6.2: Description of samples for tensile test

Type	Material	Sample name	Description
Set 1	HE3490-LS HDPE	S1, S2, S3	Unfused HDPE parent pipe samples
Set 2	HE3490-LS HDPE	W1, W2, W3	Butt fused HDPE samples with new welding algorithm
Set 3	HE3490-LS HDPE	Y1, Y2, Y3	Butt fused HDPE samples with the welding procedure from the literature

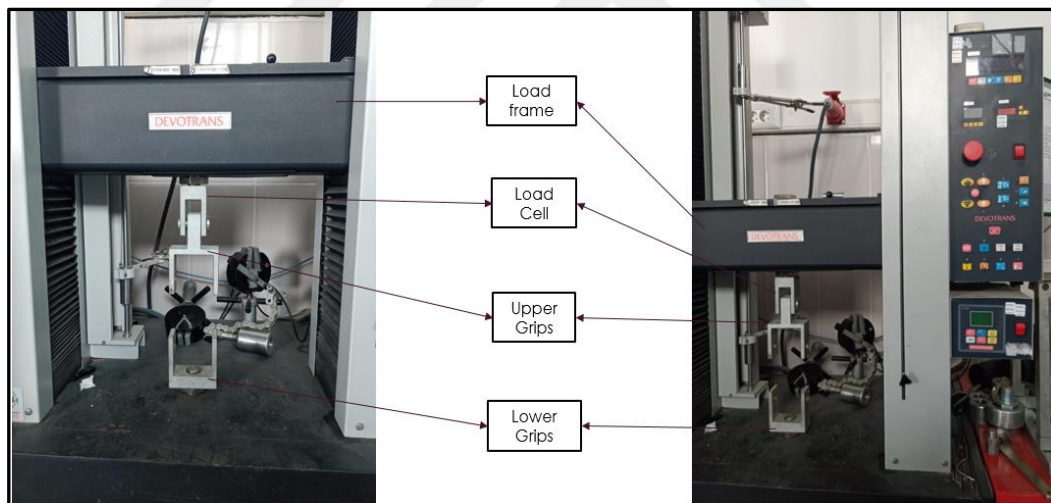


Figure 6.1: Devotrans tensile compression testing machine setup

Figure 6.2 shows the Type 1, 2 & 3 test sample options for determining the tensile properties (ISO 6259, Thermoplastics pipes -Determination of tensile properties, 2015).

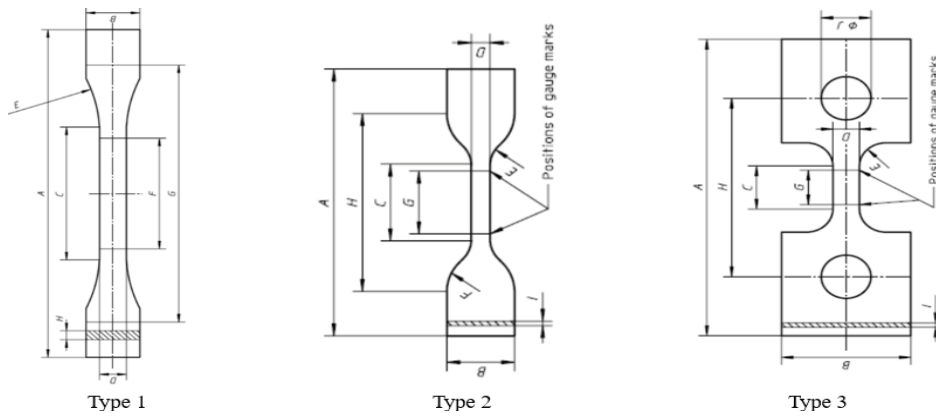


Figure 6.2: Type 1, 2 & 3 test sample options for determining the tensile properties of HDPE pipes

Source: ISO 6259, Thermoplastics pipes -Determination of tensile properties, (2015).

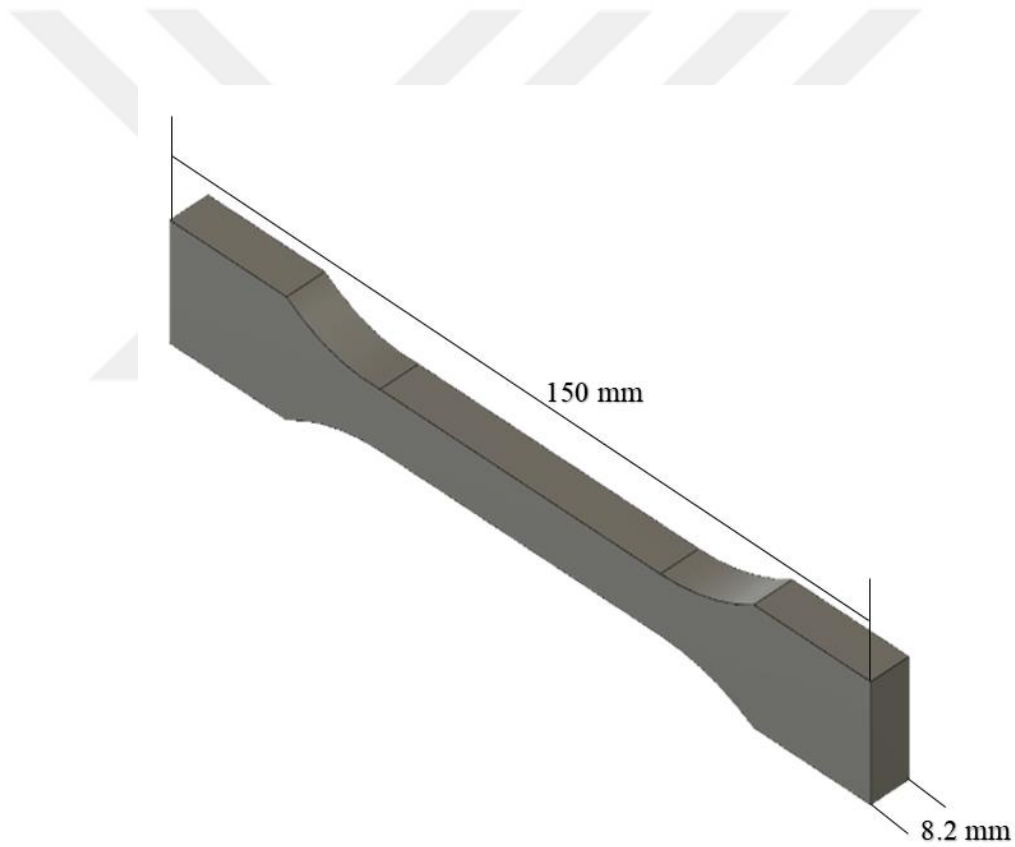


Figure 6.3: Type 1 test sample extracted for this research



Figure 6.4: Preparation of type 1 test pieces from a 90 mm HDPE Pipe with 8.2 mm wall thickness

Figure 6.3 shows the Type 1 test sample extracted for this research. Similar test pieces described in Figure 6.4 were used in the literature when investigating the resulting quality of pipe samples and fused joints, their mechanical characteristics, and mechanical performance in installed water supply systems.

For our experiment, the test speed depended on the sample selected (Type 1, 2, or 3 as shown in Figure 6.2) and the thickness of the pipe. To obtain correct estimates the preparation of test pieces and test speeds were applied following ISO 6259 for this research.

The test speed for our experiment was 50mm/min and test sample type 1 can be seen from Table 6.3 (ISO 6259, 2015) and Figure 6.5 respectively. Figure 6.5 shows the tensile test machine setup with samples.

Table 6.3: Type of test piece and test speeds to be used as specified by ISO 6259

The nominal wall thickness of the pipe (e_n) (mm)	Type of test piece	Test speed (mm/min)
$e_n \leq 5$	2	100
$5 < e_n \leq 12$	1	50
$12 < e_n \leq 25$	1	25
	3	10
$e_n > 25$	3	10

Source: (ISO 6259, 2015)

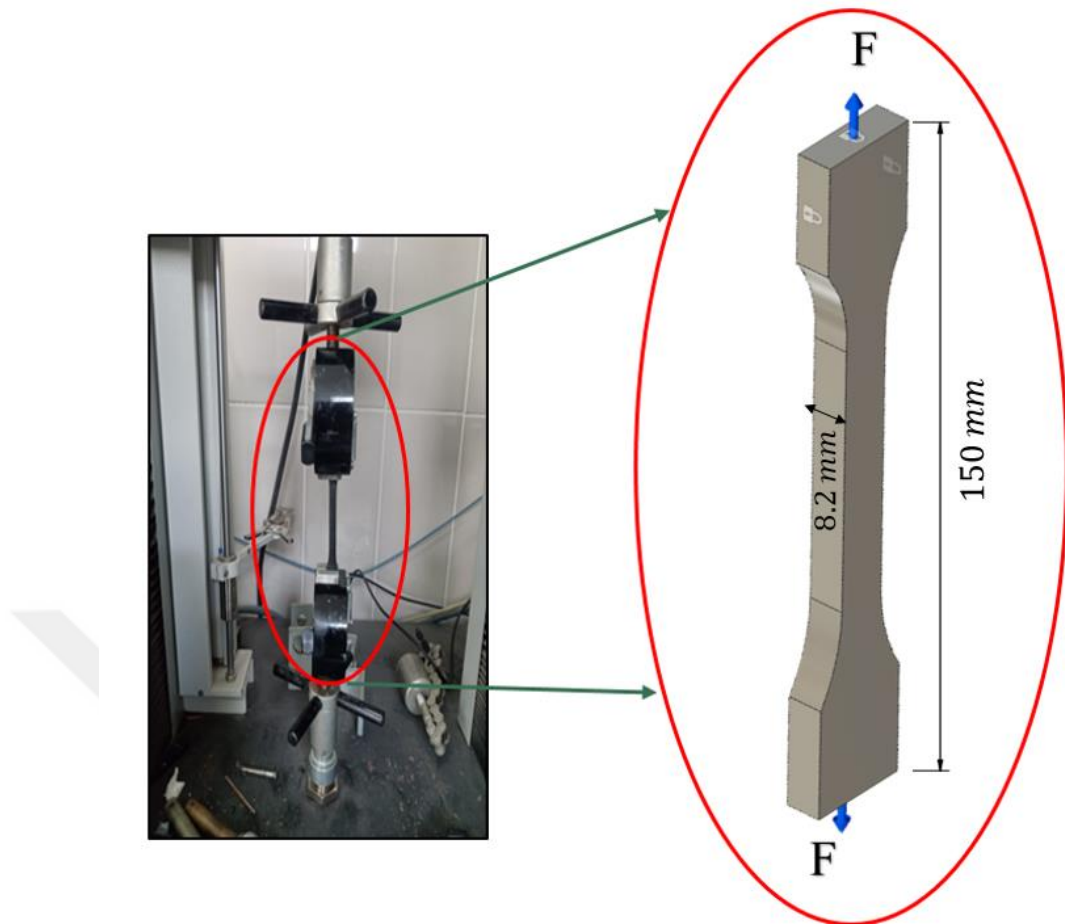


Figure 6.5: The tensile test machine setup with samples

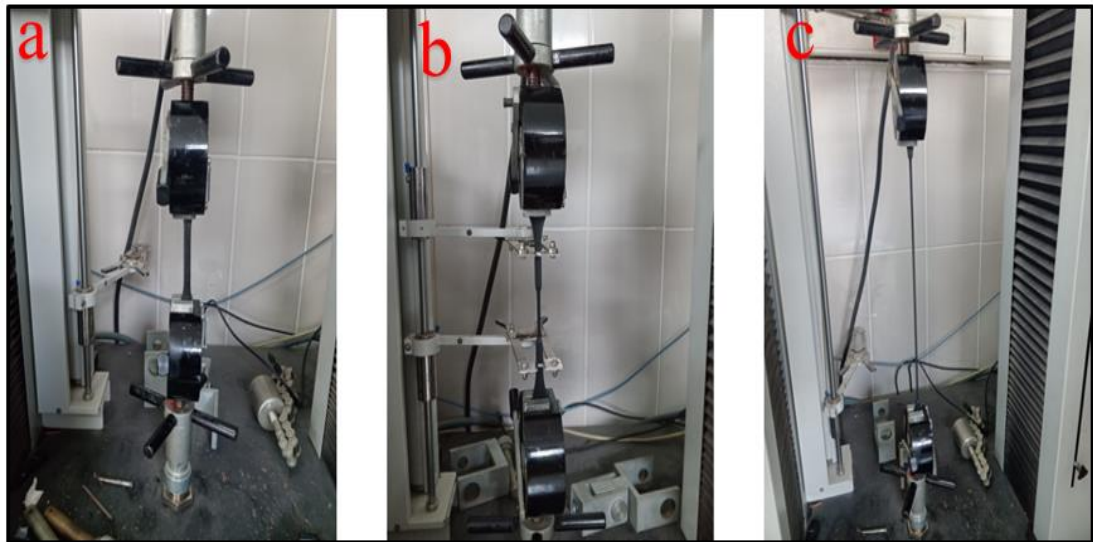


Figure 6.6: The observed elongation on test samples from unwelded pipe specimens
 Figure 6.6 shows the observed elongation on test samples from unwelded pipe specimens. A series of 4 tests were performed on the machine. The resulting curves for 3 test samples can be seen in Figure 6.7.

The general appearance of load–elongation curves was characterized by four (4) main zones:

- I. Zone 1 is the linear response that enlightens the elastic behavior of the material
- II. Zone 2 is the appearance of the plastic deformation
- III. Zone 3 represents the beginning of the micro-structural hardening stage due to the realignment of the PE chains in the direction of the applied stress.
- IV. Zone 4 begins before the final rupture and is marked by a hardening characteristic.

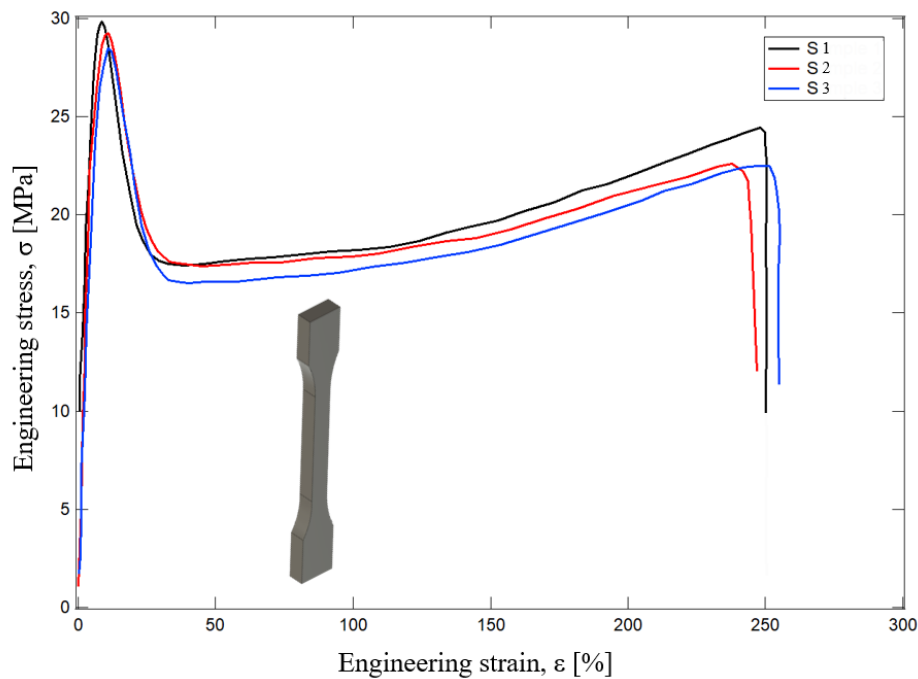


Figure 6.7: The engineering stress-strain curves for unfused pipe samples

Similar results and graphs were obtained from the tests performed in the literature for test speeds 50 mm/min. Figure 6.7 shows the engineering stress-strain curves for unfused pipe samples. Similar results can be seen in **Figure 6.8** where the engineering stress & strain curves for HDPE pipe were investigated (**Bagory, Sallam & Younan, 2014**).

However, it was observed that the difference in the tensile test sample and specimen configuration affect the resulting stress, strain, and elongation at break graph.

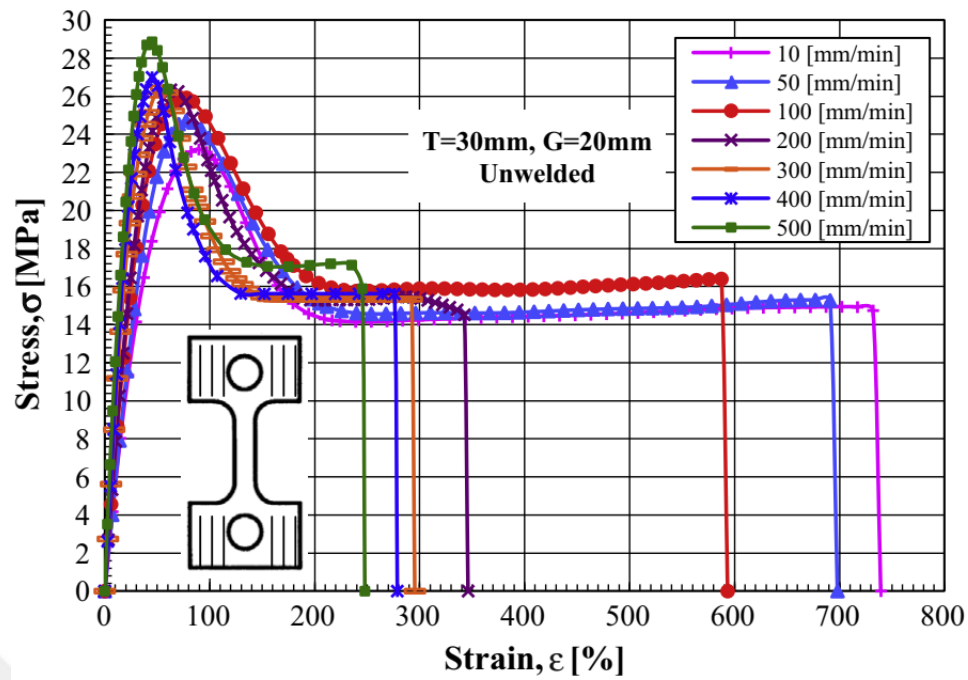


Figure 6.8: Engineering stress & strain curves for HDPE pipe

Source: Bagory, Sallam & Younan. (2014)

6.1.2 Testing method for tensile strength and failure mode of butt-fused joints

This section describes the test method used to investigate the mechanical performance of butt-fused joints. The method used here was applied with reference to ISO 6259 and ISO 13953, determination of tensile properties for HDPE pipes.

Significance: Determines the tensile strength and failure mode of samples obtained from a butt-welded joint of not less than 90 mm. The failure mode and tensile strength are used as criteria for the evaluation of the butt-fused joint. Failure types. (a. Ductile Failure), (b. Brittle failure). From previous research, we know that tensile strength is the indicator of the strength of the material in the longitudinal direction while elongation reflects the limit the test specimen cut from a pipe or joint can be extended to before breaking.

Using butt fused samples obtained from the designed machine, the integrity and mechanical performance of the resulting welded joints were tested by applying the testing method described in this section. The results obtained from our experiment were then compared to the results obtained by the literature.

6.1.3 Procedure

A dumb-bell shape specimen is cut out from the butt-fused sample as specified by the standard. The shape of the test piece amount, and dimensions shall depend on the outer diameter dn of the butt fused pipe. Samples are then carefully placed in the jaws of the tensile tester. The initial distance between the jaws is kept as specified in the standard. Figure 6.9 shows the pipe samples (a) and trimming (b).



Figure 6.9: The pipe samples (a) and trimming (b)

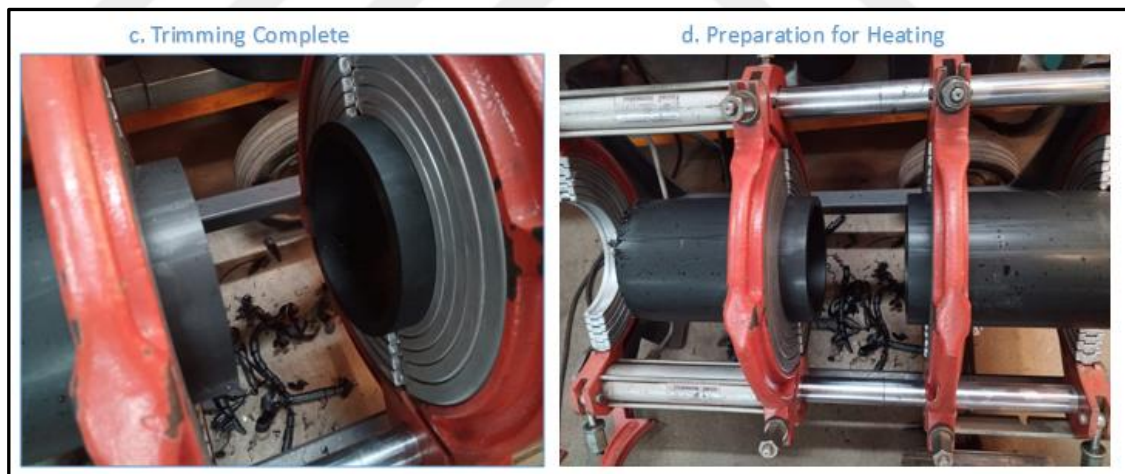


Figure 6.10: The pipe edges after trimming (c) and completion (d) right before heating commences



Figure 6.11: Heating (e) and butt fusion (f) of pipe samples



Figure 6.12: The welded samples (g) and machining for tensile test sample extraction (h)

Figure 6.10 shows the pipe edges after trimming (c) and completion (d) right before heating commences. Figure 6.11 shows heating (e) and butt fusion (f) of pipe samples, finally Figure 6.12 shows the welded samples (g) and machining for tensile test sample extraction (h). Sample preparation for tensile strength test, sections are shown in Figures **a** to **h** above. During the tensile test, the extracted specimens are pulled apart at a steady rate of 5 mm/min which is dependent on the wall thickness. The inbuilt software of the computer which operates the tensile tester records percentage of elongation and tensile stress.

a). For this experiment, the test speed for butt-fused joints was 5mm/min.

b). The pipes welded for this experiment were 90 mm and 110 mm O.D with thicknesses 8.2 mm and 10.0 mm respectively.

c). The pipes described in 'b' can be welded and used in piping systems with pressure nominal (PN) 16 SDR 11.

6.1.4 Samples for butt-fused joint specimens extracted from the designed semi-automatic welding machine

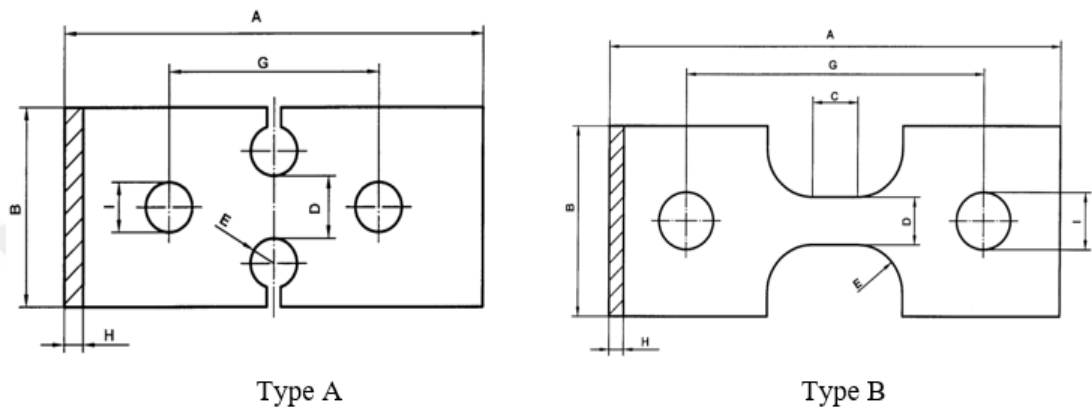


Figure 6.13: Type A-sample specimen for butt fused pipes with thickness $e < 25$ mm, Type B-sample specimen for butt fused pipes with thickness $e \geq 25$ mm (ISO 13953, 2001)

Source: ISO 13953, Polyethylene (PE) Pipes and Fittings-Determination of the Tensile Strength and Failure Mode of Test Pieces from a Butt-Fused Joint. (2001).

Similar samples for Type B specimens were used by the literature. To investigate the mechanical characteristics of the butt-fused and unfused samples, their experiment had tensile test samples which were cut longitudinally from pipes with thickness= 30 mm. **Figure 6.13** shows type A-sample specimen for butt fused pipes with thickness $e < 25$ mm, Type B-sample specimen for butt fused pipes with thickness $e \geq 25$ mm (ISO 13953, 2001). Since experiments performed in this paper involved pipes between 90-110 mm outer diameters, Type A test samples had to be used as specified in **Table 6.4** (ISO 13953, 2001).

Table 6.4: A list of technical specifications for tensile strength test for butt-fused joints

Nominal outer diameter (d_n , mm)	Number of test pieces
$90 \leq d_n < 110$	2
$110 \leq d_n < 180$	4
$180 \leq d_n < 315$	6
$315 \leq d_n$	7

Source: (ISO 13953, 2001)

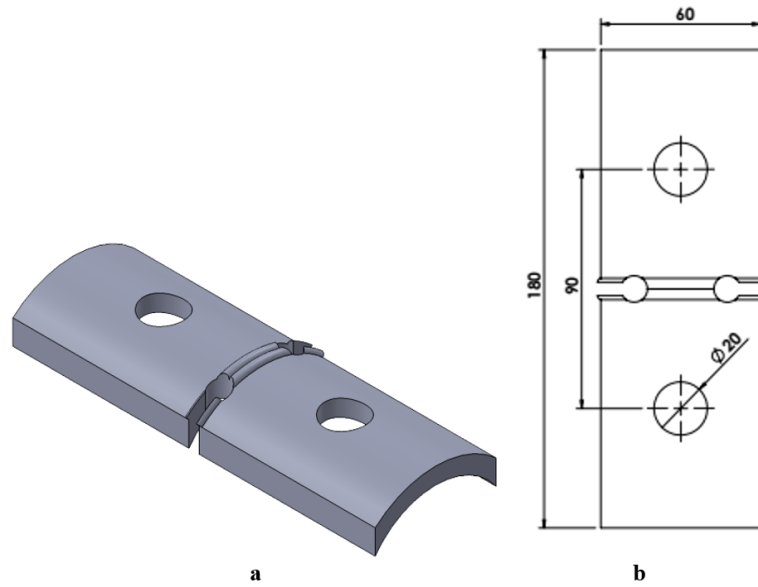


Figure 6.14: The machined type a tensile 2-D and 3-D samples (for <25 mm wall thickness) (a,b)

Figure 6.14 shows the 2D and 3D samples (for <25 mm wall thickness) (a,b) as described in the literature.



Figure 6.15: The extracted butt fused samples for tensile strength test

Figure 6.15 shows the extracted and machined butt fused samples for tensile strength test to be used in this experiment and Figure 6.16 shows the tensile test machine setup with samples.

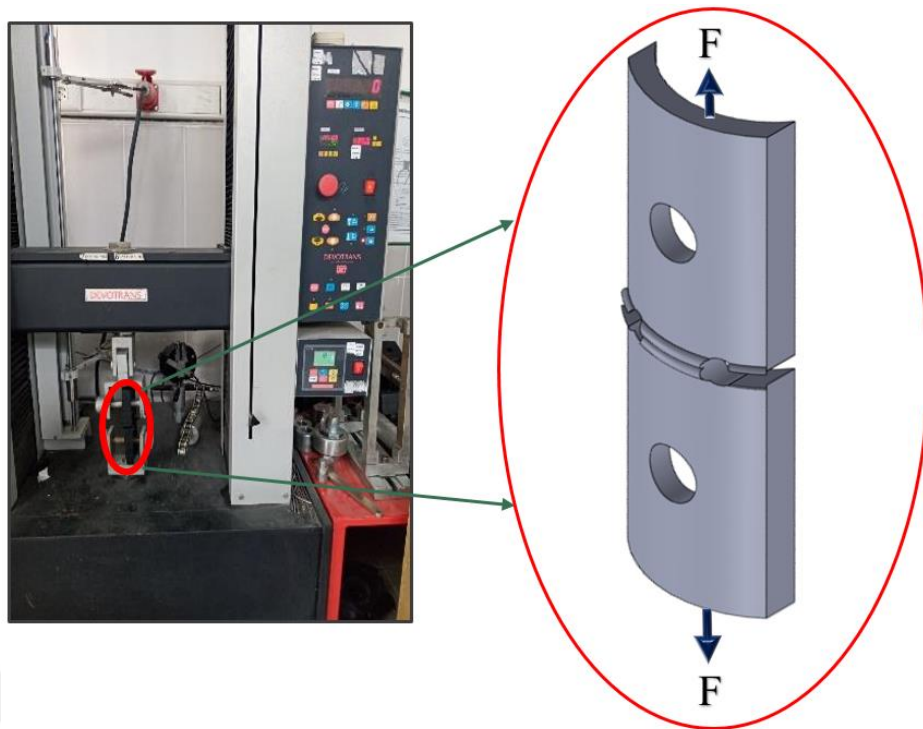


Figure 6.16: The tensile test machine setup with samples

The ductile failure mode for each sample obtained by welding using the automatic welding machine is recorded and shown in Figures 6.17. With the reference to the welding standard, this is the acceptance criteria for a butt-fused joint with high-performance mechanical characteristics.

For comparison, in Figure 6.18 an identical failure mode was recorded (Yu et al. 2020).

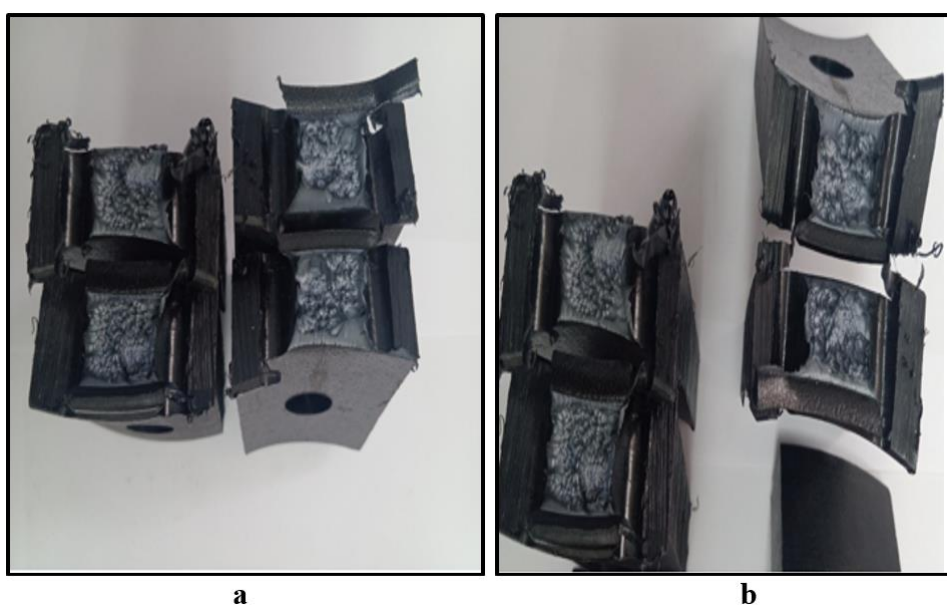


Figure 6.17: The resulting specimens and failure modes can be seen in Figures a and b above

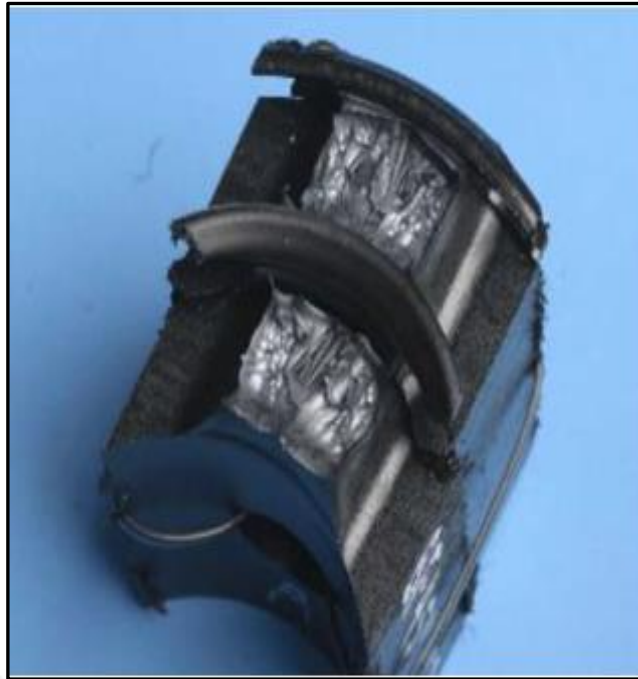


Figure 6.18: Ductile failure mode

Source: Yu et al. (2020)

Ductile failures are characterized by a series of plastic deformations which all result in shape and distortion changes on a macro scale (Lukas & Boge, 2011). A replica used to define what was occurring on a micro-structural level can be seen in Figure 6.19 (Lukas & Boge, 2011).

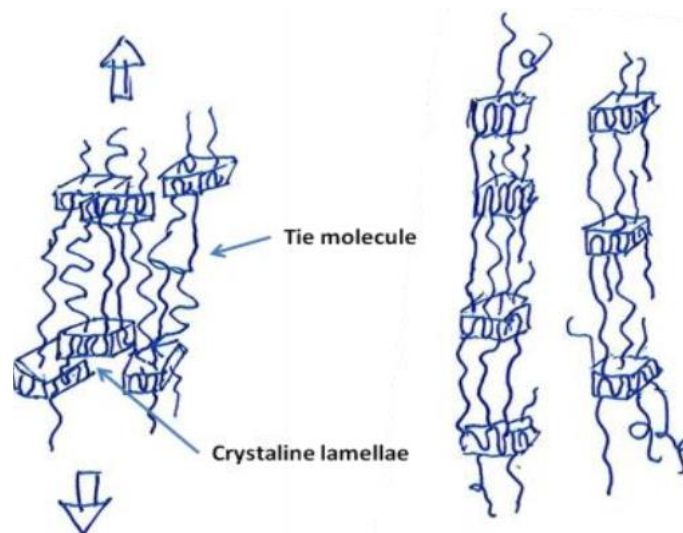


Figure 6.19: Micro-structural presentation of ductile deformation

Source: Lukas & Boge. (2011)

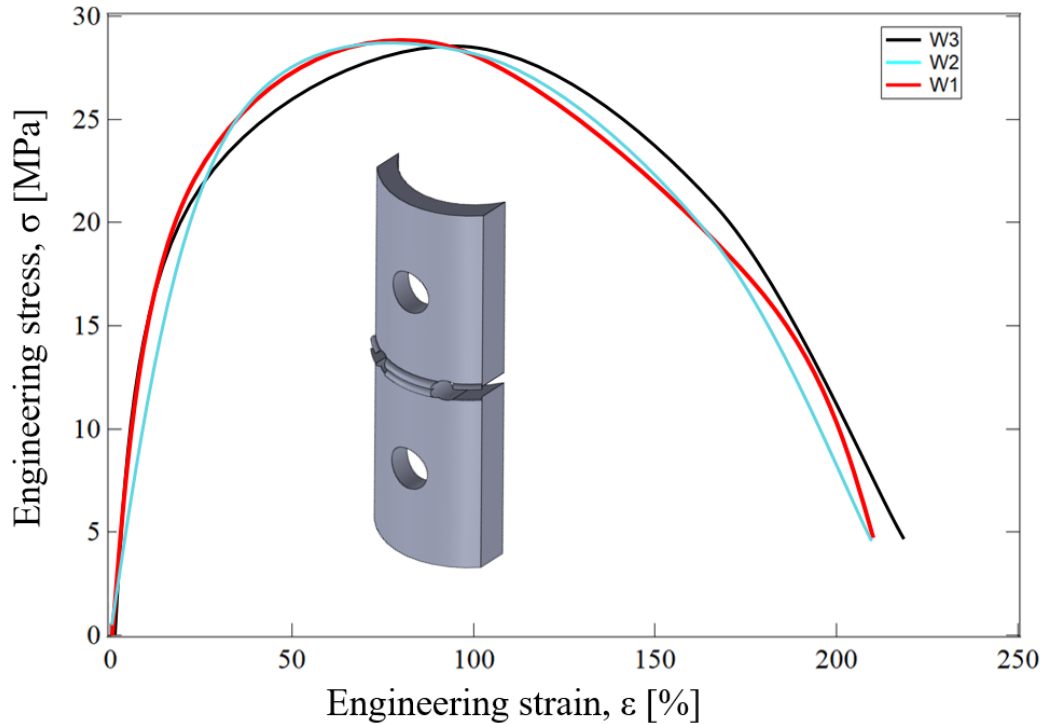


Figure 6.20: The engineering stress-strain curves for butt fused samples obtained from the automatic welding machine

Figure 6.20 shows the resulting strain-stress curves from butt-fused samples performed by the automated welding machine.

After performing the tests, the butt fused joints conducted by the automatic welding machine were all in ductile failure mode which simply meant that the applied welding algorithm guaranteed that successful polyethylene entanglement had occurred during the fusion process at T4.

Since we know that plastics are defined and categorized by the shape of their stress-strain curves; they can be hard & tough, hard & strong, soft & tough, hard & brittle, or soft & weak (Stress-strain graph-Polymer Classification viewed 15 September, 2021).

HDPE for use in pipe applications and installations should possess both hard and tough characteristics. With this in mind, it can be seen that the resulting curves shown in Figure 6.20 from samples obtained by performing the butt fusion process using the automatic welding machines have a high modulus (steep-slope) which associates with the hardness of the materials, and a high elongation before break, the large range below stress-strain curve which associates with the material's toughness.

Similar results and graphs were obtained from the tests performed in the literature as shown Figure 6.21 (Bagory, Sallam & Younan, 2014).

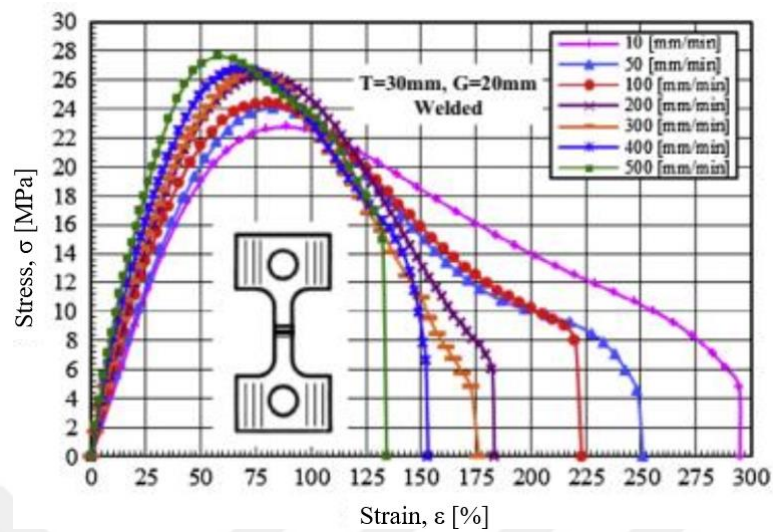


Figure 6.21: The stress & strain curves for 6 butt fused pipe samples

Source: Bagory, Sallam & Younan. (2014)

However, as it can be seen in the curves below the butt-fused joints conducted by the manual welding machine had some welded pipe samples resulting in brittle failure mode which meant that not all joints guaranteed a successful polyethylene entanglement during fusion at T4.

6.1.5 Samples for butt-fused joint specimens extracted from the manual welding machine

An identical procedure was used to prepare the specimens and perform the tests described in section 6.1.3. The resulting specimens and failure modes can be seen in Figure 6.22 below.

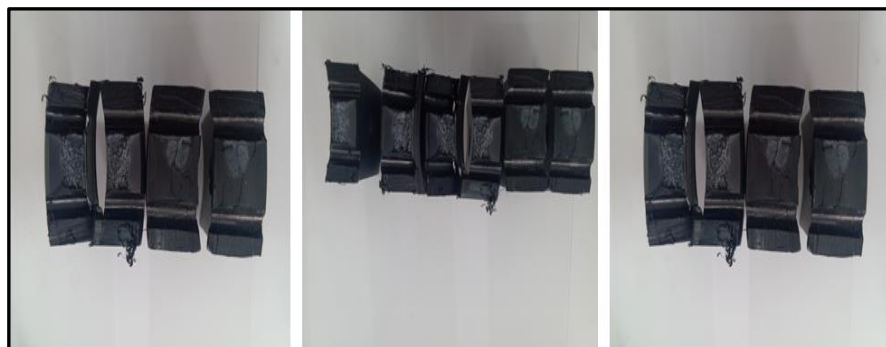


Figure 6.22: The brittle failure mode occurred from 3 tested samples out of 4 after performing butt welding on a manual welding machine

A brittle failure or deformation exhibits no plastic deformation characteristics and usually occurs below the yield stress of the HDPE material (Lukas Boge, 2011), see Figure 6.23 (Lukas Boge, 2011).

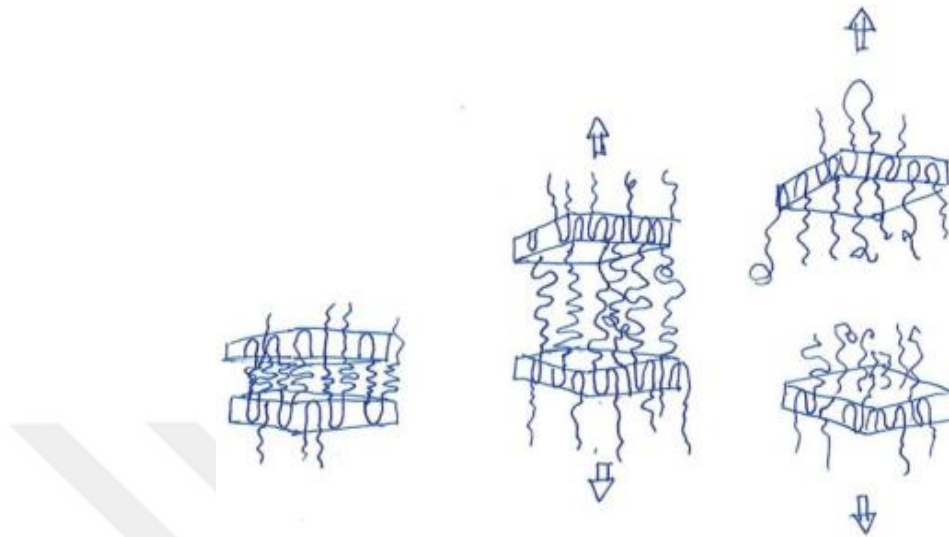


Figure 6.23: Micro-structural presentation of brittle failure deformation (Lukas & Boge, 2011)

Source: Lukas & Boge. (2011)

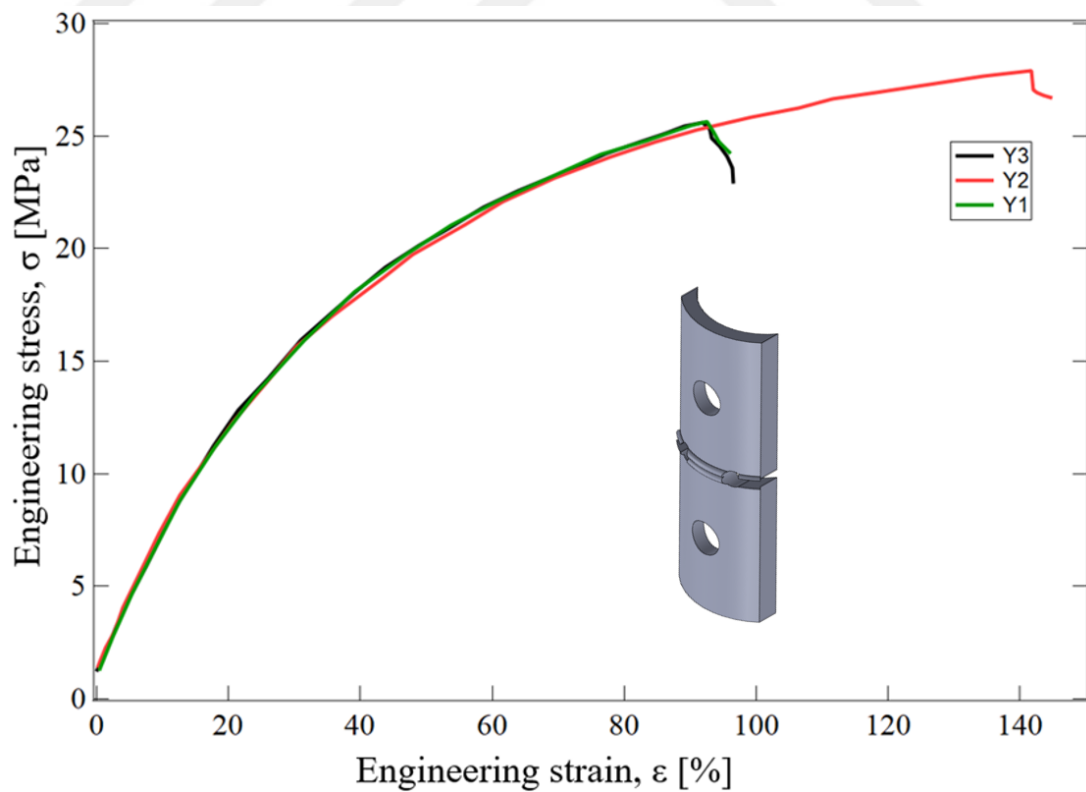


Figure 6.24: The engineering stress-strain curves for butt fused samples obtained from the manual butt welding machine

To reduce the chances of failure and improve the resulting joints on butt-fused joints in piping systems, it was observed that highly skilled technicians are required to perform butt fusion on the manually operated machine. Figure 6.24 shows the engineering stress-strain curves for butt fused samples obtained from the manual butt welding machine.

6.2 Testing the Long Term Performance Properties of the Resulting Joints Using the Hydrostatic Pressure Test

The significance of this test method is to determine the resistance to internal hydrostatic pressure at 80°C for 165 hours, under the pressure of 5.4 MPa for butt fused pipe samples. The test procedure was conducted following ISO 1167. In this test, generally, the butt fused sample is subjected to various pressure-induced hoop stresses at 20°C/80°C for a specific duration, in this case for 165 hours. The welded pipes and fittings should not balloon or rupture within the test duration. Table 6.5 lists down the equipment used when performing the hydrostatic pressure test.

6.2.1 Testing equipment

Table 6.5: Equipment used when performing the hydrostatic pressure test

Device description	Brand/ manufacturer	Model	Device (Serial) No	Device code
Pressure device	Polinar	-	L-1-01	L-1-01
Test tank 1	Turan	ETC 4420/Digital	L-2-01	L-2-01
Test tank 2	Turan	ETC 4420/Digital	L-2-02	L-2-02
Test tank 3	Turan	ETC 4420/Digital	L-2-03	L-2-03

6.2.2 Procedure

One test piece with the required length was cut and fitted with end caps. The sample is filled with water and conditioned for the minimum specified time, as per ISO 1167. The end cap or similar test equipment is connected to the pressurizing equipment and pressurized smoothly to the specified value, calculated using any of the formulae given below.

To evaluate a long-term internal pressure rating by investigating the material's enduring strength, functioning temperature, application settings, and pipe size, the equations are shown below are used.

a.) Operation pressure evaluation using the measured dimensions of the pipe sample. Equation (6.3) (EN ISO 1167-3, 2007).

$$P_{hs} = 10\sigma \frac{2e_{min}}{d_{em}-e_{min}} \quad (6.3)$$

b.) Operation pressure evaluation using the nominal dimensions of the pipe sample Equation (6.4) (EN ISO 1167-3, 2007).

$$P_{hs} = 10\sigma \frac{2e_n}{d_n-e_n} \quad (6.4)$$

σ : Induced stress in MPa: The ring stress in MPa that will be created by the applied pressure

d_n : Nominal outer diameter of test specimen in mm

e_n : The nominal wall thickness of the test piece in mm

c.) Pressure calculations based on SDR of test piece pipe or fitting. Equation (6.5) (EN ISO 1167-3, 2007).

$$P_{hs} = 10\sigma \frac{2(10\sigma)}{[SDR]-1} \quad (6.5)$$

σ : Induced stress in MPa: The ring stress in MPa that will be created by the applied pressure

SDR: Standard dimensional ratio (SDR). The ratio of the nominal outside diameter of a pipe to nominal wall thickness

For this experiment and research, the resistance to internal pressure at 80°C for 165 hours under the applied pressure of 5.4 MPa was performed on samples acquired from the butt-fused joints performed by the semi-automatic welding machine. Samples were obtained by welding two 250 mm end caps to a 250-90° elbow, the test pieces can be seen below.

Both samples had a wall thickness of 9.6 mm, 250 mm outer diameter, PN 6, and finally SDR 26. Figure 6.25 shows the 250-90° HDPE elbow and 250 end cap schematics and drawing before welding.

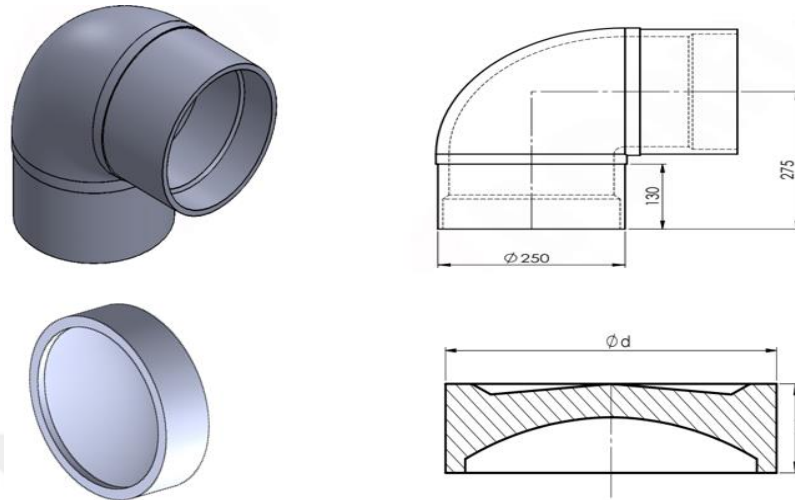


Figure 6.25: 250-90° HDPE elbow and 250 end cap schematics and drawing before welding

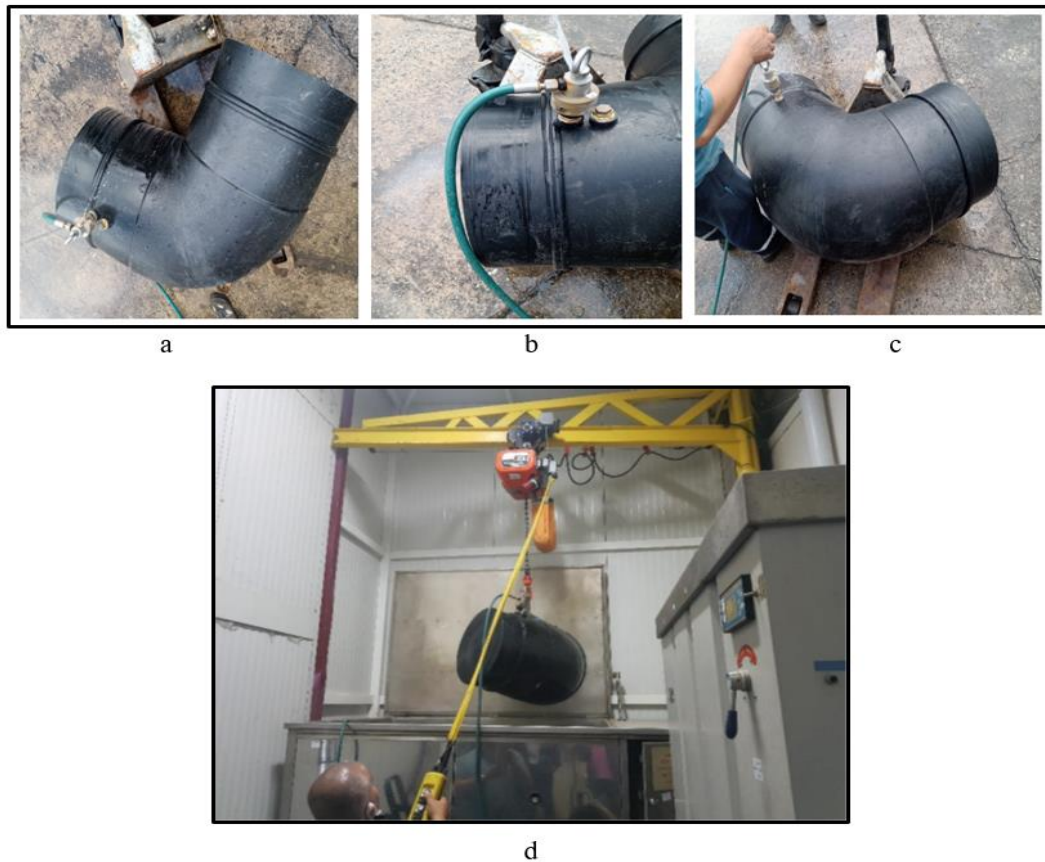


Figure 6.26: The hydrostatic pressure test preparation of 250 HDPE end cap welded with 250-90° elbow with induced hoop (circumferential) stress of 5.4 MPa for 165 hours at 8080°C

As shown in Figure 6.26, the samples are welded then filled with hot water which did not exceed the test temperature water (80°C). Then as shown in Table 6.6 (ISO 1167-3, 2007) samples are conditioned for the minimum specified time with corresponding wall thickness (e_{min}).

Table 6.6: Minimum conditioning period (hour)

e_{min} (mm)	Minimum conditioning period (hour)
$e_{min} < 3$	1
$3 \leq e_{min} < 8$	3
$8 \leq e_{min} < 16$	6
$16 \leq e_{min} < 32$	10
$32 \leq e_{min}$	16

Source: (ISO 1167-3, 2007)



Figure 6.27: The testing equipment for hydrostatic pressure

Figure 6.27 shows the testing equipment for hydrostatic pressure. After the conditioning process, the test pressure is gradually and continuously applied to the samples. The test pressure was calculated using the given Equation 6.3.

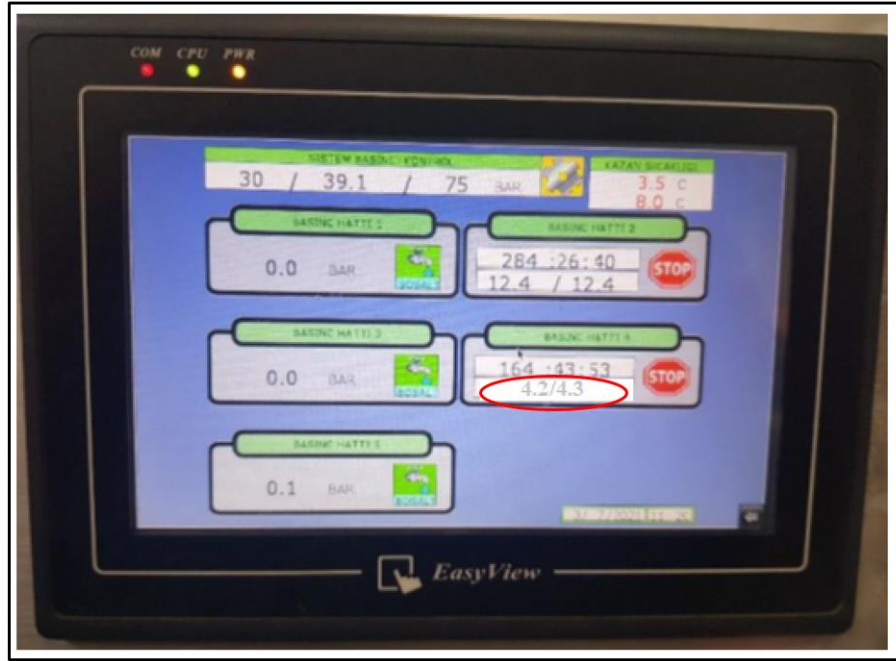


Figure 6.28: The testing equipment screen, time, and pressure initialization

$$P_{hs} = 10\sigma \frac{2e_{min}}{d_{em} - e_{min}}$$

σ = Induced Stress in MPa was defined as 5.4 MPa which is also known as the circumferential (hoop) stress for HDPE (PE 100). In ASTM D2837 and PPI TR-3, this is also known as the hydrostatic design stress. Figure 6.28 shows the testing equipment screen, time, and pressure initialization. Equation (6.3) (EN ISO 1167-3,2007).

Applied pressure;

$$P_{hs} = \frac{(10 * 5.4 * 2 * 9.6)}{(250 - 9.6)} = 4.3 \text{ bar} = 0.43 \text{ MPa}$$

Pressure P_{hs} is then applied and inserted on the machine shown in Figure 6.28. Afterward, the samples were submerged into a boiler which was preheated to 80°C. The clock was then set for 165 hours, and the tank was fully covered during the duration of the test.

After 165 hours, the samples were extracted from the tank and did not show any rupture or failure.

The acceptance criteria for this test is that fittings and test samples shall not balloon or rupture within the test duration. No damage should occur at ≥ 165 hours. The butt-fused samples welded using the designed mechatronics system conformed to the international standards acceptance criteria. Figure 6.29 shows that the Test 165 h / 80 °C / 5,4MPa was successfully completed, and safely removed from the boiler Figure 6.30.



Figure 6.29: Test 165 h / 80 °C / 5,4MPa was successfully completed



Figure 6.30: The tested samples were removed from the boiler, after visual inspection, no damage was observed

6.3 Testing the Chemical Performance Properties of the Resulting Joints Using the Oxidation Induction Time (OIT) Test

The significance of this test method is to determine the thermal degradation of HDPE. The test procedure was conducted as per (ISO 11357-6, 2009). Polyethylene is usually inert to most chemicals except very strong oxidizing agents. Polyethylene is susceptible to reacting with oxygen at higher temperatures, for this reason, stabilizers are added to stop such oxidation reactions. Resistance of the material to such oxidation reaction is very essential since the processing of the material by extrusion, injection molding and joining of pipes by butt-fusion takes place at higher temperature i.e., around 200°C, in the presence of oxygen.

For this paper, the resistance to oxidation for the butt-fused pipes in the presence of oxygen was investigated. Butt-fused samples will be obtained from the performed welds on the designed machine. Table 6.7 lists the equipment used for testing oxidation induction time (OIT).

6.3.1 Testing equipment

Table 6.7: Equipment used for testing oxidation induction time (OIT)

Device Description	Brand /Manufacturer	Model	Device (Serial) No	Device Code
Analytical scale	PRECISA	XB 220A	W55238	L-6-01
(OIT testing device)	IPV	DSC 500A	20130626089	L-11-01
Differential scanning calorimeter	-	-	-	-

6.3.2 Procedure

A nitrogen flow of 50±5 cm³/min was established, through the differential scanning calorimeter. 2 pans, the first one contained a sample of weight 15±0.5 mg (one test piece) and another blank/ reference was placed in the calorimeter cell. The instrument was set to run isothermally at 200°C±0.1°C, then the temperature rose at a rate of 20°C/min from the ambient temperature then stabilized at 200°C for 5 minutes. The thermo-gram values were then recorded (the plot of the heat flow against time). After switching over to oxygen, this point was marked on the thermo-gram. The thermo-gram was run until exothermic oxidation had occurred and had reached its maximum.

When interpreting the results, thermal stability was expressed as the time taken, in minutes from the introduction of oxygen to the capture of the stretched baseline and the line drawn to the exotherm at the point of the maximum gradient. Table 6.8 shows the significant parameters tested for oxidation induction time (OIT).

Table 6.8: Parameters tested for oxidation induction time (OIT)

Symbol	Definitions
ΔT	The temperature variance between the specimen & the reference vessel
ΔQ	Flowing energy variance between the specimen & reference vessel
OIT	The period in which the temperature difference or energy flow difference between the container in which the test sample is located and the reference container remains constant

The acceptance criteria for this test is that OIT shall be ≥ 20 minutes

Figure 6.31 shows the testing equipment for thermal stability. For all butt-fused samples obtained from the manual and automatic butt-fusion machine, the graph shown in Figure 6.32 was identical. This was because the pipe samples used during the butt fusion process for both machines were produced from the same batch of raw materials, also we kept the welding temperature constant in all the experiments conducted, in conclusion, we noticed that the oxidation induction time (OIT) for both sample groups obtained by either manual butt fusion or automatic butt fusion was more than 20 minutes.



Figure 6.31: The testing equipment for thermal stability

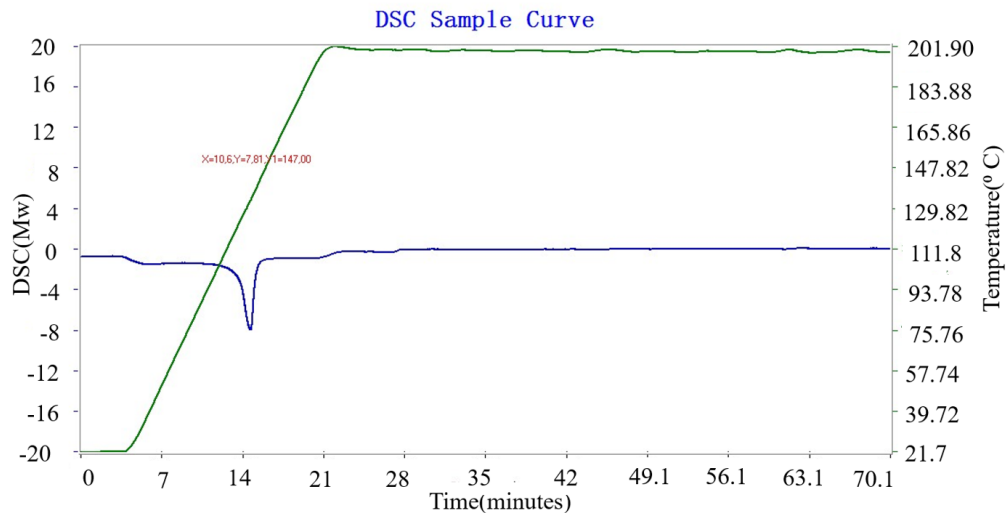


Figure 6.32: The OIT curve resulting from welded samples from both the manual and automatic welding machine

With the results from this research, it is safe to say the method of fusion used has a negligible effect on the time it takes for oxidation to occur on the welded pipe samples 20 minutes.

6.4 Investigating the mechanical performance properties of the resulting joints using the test method for determining carbon black (CB) content

The significance of this test method is to determine the resistance of HDPE pipes to UV radiation which leads to thermal and photo-degradation. Polyethylene being natural in color is susceptible to being attacked by UV radiation of the sun when exposed. As a result, polyethylene degrades and loses its properties. When a certain quantity of carbon black is compounded with polyethylene, carbon black absorbs UV radiation protecting the polymer from thermal and photodegradation.

In the literature, it was emphasized that to provide sufficient ultraviolet radiation protection, CB should be homogeneously displaced or diffused in the PE microstructural matrix (Yu et al. 2020). An even distribution of CB in the PE microstructural matrix is achieved by a homogenized diffusion of molten PE during joining at T4. Since the designed machine ensures that the pressure applied in intervals at T4 is just sufficient enough not to scatter the heated PE in zone 1 and zone 2 as shown in this study. In similar research, it was confirmed that pipes having a slight uneven diffusion or dispersion of CB in the PE microstructural matrix were characterized by a combination of ductile and brittle failures, while an even and

homogenized black and natural PE material not containing CB were characterized by ductile failures only (Deveci, Nisha & Eryigit, 2018).

This paper and research proved that in the HDPE matrix a homogenous distribution of CB improves the tensile properties of the HDPE material up to a certain CB loading provided that proper processing equipment is used. In this case for butt fused joints, a proper butt welding machine should be used which ensures the homogenous distribution and diffusion of molten heated HDPE during joining at T4 occurs successfully.

The other literature and research emphasized that a homogenized diffusion or distribution of CB in the PE microstructural matrix is vital to accomplish absolute UV radiation protection Yu et al. (2005); Niu et al. (2014). A great number of published studies concentrated on the effect of CB and its properties on preventing thermal oxidation and photodegradation of PE. Other research areas included the characteristics of CB content, its distribution, and the effect it has on the mechanical behavior of HDPE Liang & Yang, (2009); Chodák & Krupa, (1999); Accorsi & John, (2000) and Rwei, Zloczower & Feke (1992). From these previous researches and similar obtained data, it is safe to conclude that a homogenized distribution of CB in the PE matrix of HDPE pipes improves the mechanical and tensile characteristics of the material. Figure 6.33 below shows the Engineering stress-strain (a) and true stress-strain (b) (Shaofeng & Kang, 2014).

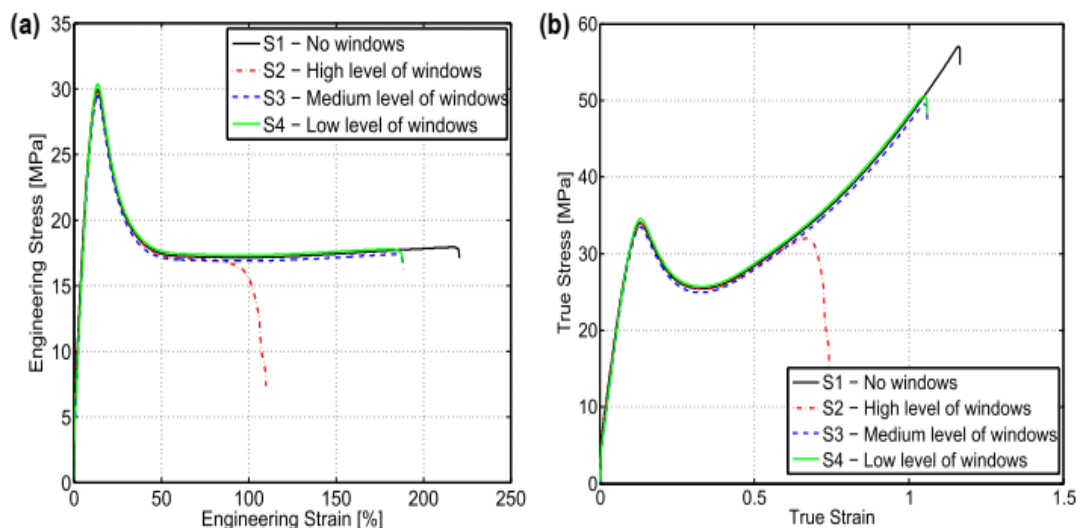


Figure 6.33: Engineering stress-strain (a) and true stress-strain (b) The effects of the CB content dispersion on the mechanical properties of HDPE

Source: Shaofeng & Kang. (2014)

Inadequate diffusion and spreading of CB in HDPE microstructure usually occurs due to the insufficient mixing of CB and natural PE. The two processes that involve the mixing of CB and natural PE are the extrusion process during manufacturing, and during the butt-fusion process when welding pipe joints and pieces.

Windows are zones characterized by poor CB volume. Windows mostly appear due to poor mixing of CB and natural polyethylene material during the extrusion process when manufacturing and in other cases during butt fusion when joining pipes and fittings.

In previous research, it was observed that the presence of windows in the PE matrix affects the welding and fusion interface. Lack of fusion may occur due to the presence of windows in the heated PE joints' microstructure at T4. Additionally, in previous research, a series of brittle failures in PE joints between pipes with inadequate CB diffusion was observed (Report No: 3002003089. Pennsylvania Edge Notched Tensile Test, 2016). In a similar research, the importance for design engineers to fully comprehend the impact of having a homogenized CB dispersion in PE pipes and the effect it has on the mechanical integrity of PE butt fused joints of HDPE pipes were highlighted (Deveci et al, 2018).

Our research used the method described below to investigate the importance of the homogenous distribution CB and the effect it has on the mechanical characteristics and integrity of polyethylene butt fusion joints. To observe the carbon black distribution, test samples were obtained from the butt fused joint sections with ductile failure characteristics that were performed by the automatic welding machine which were then compared to test samples obtained from the manual butt welding machine with brittle failure characteristics.

Since the designed automatic machine ensures that the pressure applied in intervals at T4 is just sufficient enough not to scatter the heated PE in zone 1 and zone 2. Table 6.9 and Figure 6.34 shows the testing equipment used to quantify carbon black content and density for HDPE butt fused joints.

6.4.1 Test equipment

Table 6.9: Equipment used for testing carbon black content

Device Description	Brand/Manufacturer	Model	Device (Serial) No	Device Code
Carbon black content test device	JINGMI	XGNB_N/SR93/SHIMADEN	L-26-01	L-26-01
Analytical balance scale	PRECISA	XB 220 A	W55248	L-6-01

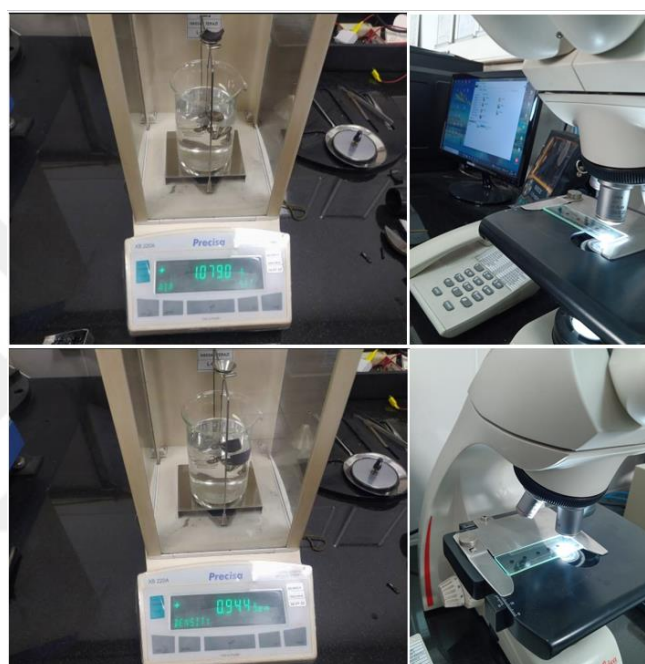


Figure 6.34: The testing equipment used to quantify carbon black content and density for HDPE butt fused joints

6.4.2 Procedure

The combustion boat was calcined (burning to powder) at 900°C to constant weight, cooled in desiccators and approximately, 1 g of sample was weighed nearest to 0.0001 g and placed in the boat. The boat with the sample was placed in the inlet of the combustion tube previously heated to 550±50°C. The system was purged with a flow of nitrogen at the rate of 200cm³/min for 5 minutes. Subsequently, the boat with the sample was placed in the center of the combustion tube and pyrolyzed (decomposed by temperature effect) for 45 minutes under a nitrogen flow of 100cm³/min. At the end of 45 minutes, the sample was cooled for 10 minutes still under the flow of nitrogen. The boat was cooled in a desiccator and weighed to a

constant mass nearest 0.0001 g. Finally, the sample in the boat was calcined at a temperature of 900±50°C to constant mass.

The boat was cooled and weighed to the nearest 0.0001g. The percentage of carbon black was calculated as follows.

$$\% \text{ Carbon Black Content} = [(m_2 - m_3) / m_1] \times 100$$

$$\% \text{ Ash Percentage} = [(m_3 - m) / m_1] \times 100$$

Where, m = Mass of empty boat g

m1 = Mass of the test piece

m2 = Sample mass and total mass of boat g after pyrolysis at 500°C g

m3 = Total mass of sample and boat after calcination at 900° C.

6.4.3 Acceptance criteria and results

For this research calcination and pyrolysis, methods were used to determine CB content- 550 °C (±50) - 900 °C (±50°C) - 1gr. CB content should be 2.0 – 2.5 % by mass. Table 6.10 describes a summary of quantifying carbon black content and the acceptance criteria.

Table 6.10: Quantifying carbon black content and acceptance criteria

Comments and Acceptance criteria	
CB dispersion	The average degree of CB dispersion at 180°C- 30min must be ≤ 3. [TS ISO 18553]
CB content %	Carbon black content shall be 2.0 – 2.5 % by mass. [ISO 6964]
MFR (g/10min)	Must be between 0.2 and 1.4 g/10 min. ± 20% of maximum deviation nominal value (Raw Material). ISO 1133-1
Density (g/cm³)	Must be ≥0.930. [EN ISO 1183-1]

Figure 6.35 shows the samples for carbon dispersion, **d1-d6** are samples from the automatic welding machine, **d7-d12** are samples from the manual welding machine. Figure 6.36 shows the photomicrographs observed for CB dispersion. Butt fused samples obtained from d1, d2, d3 magnified at X100, Figure 6.37, Figure 6.38, and Figure 6.39 shows the histograms for sample d1, d2, and d3. Figure 6.40 shows the photomicrographs observed for CB dispersion. Butt fused samples obtained from d7,

d8, d9 magnified at X100. Figure 6.41, Figure 6.42, and Figure 6.43 shows the histograms for sample d7, d8, and d9.

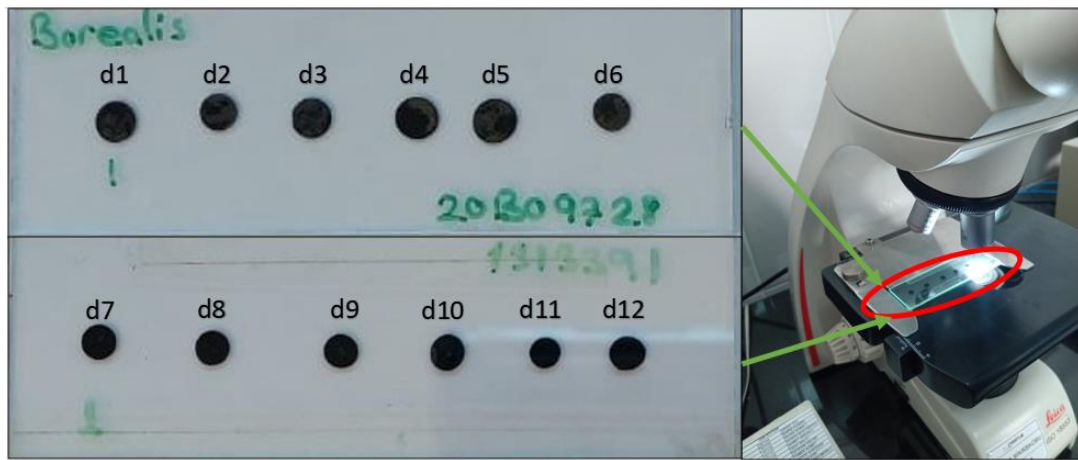


Figure 6.35: The figure above shows the testing setup used to determine the carbon black distribution for butt fused joints

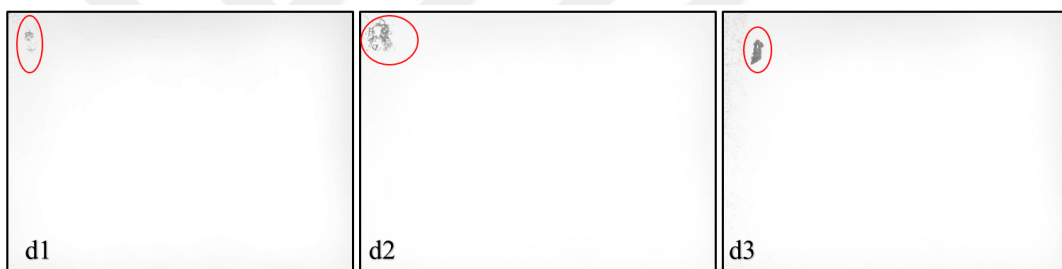


Figure 6.36: Photomicrographs observed for CB dispersion. Butt fused samples obtained from d1, d2, d3 magnified at X100

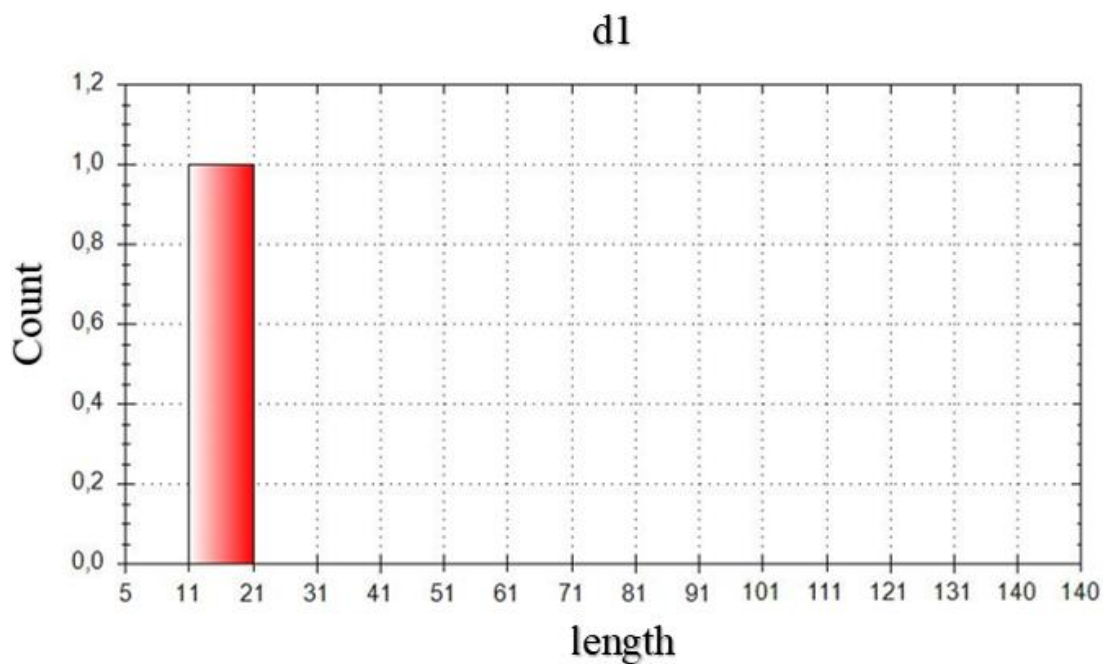


Figure 6.37: Histogram for sample d1

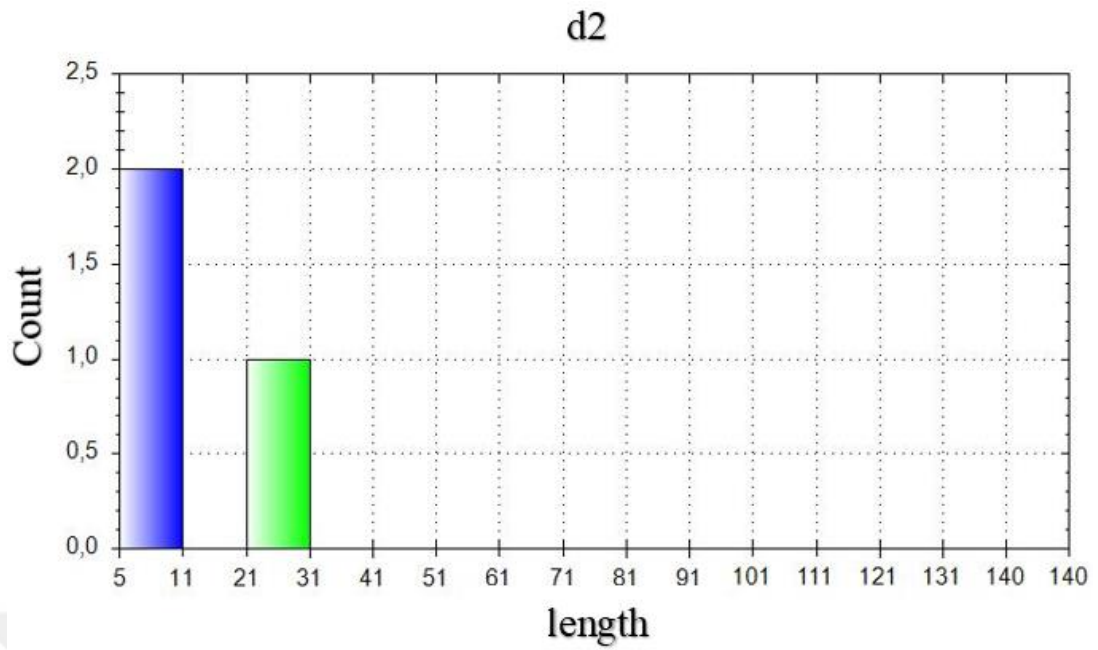


Figure 6.38 Histogram for sample d2

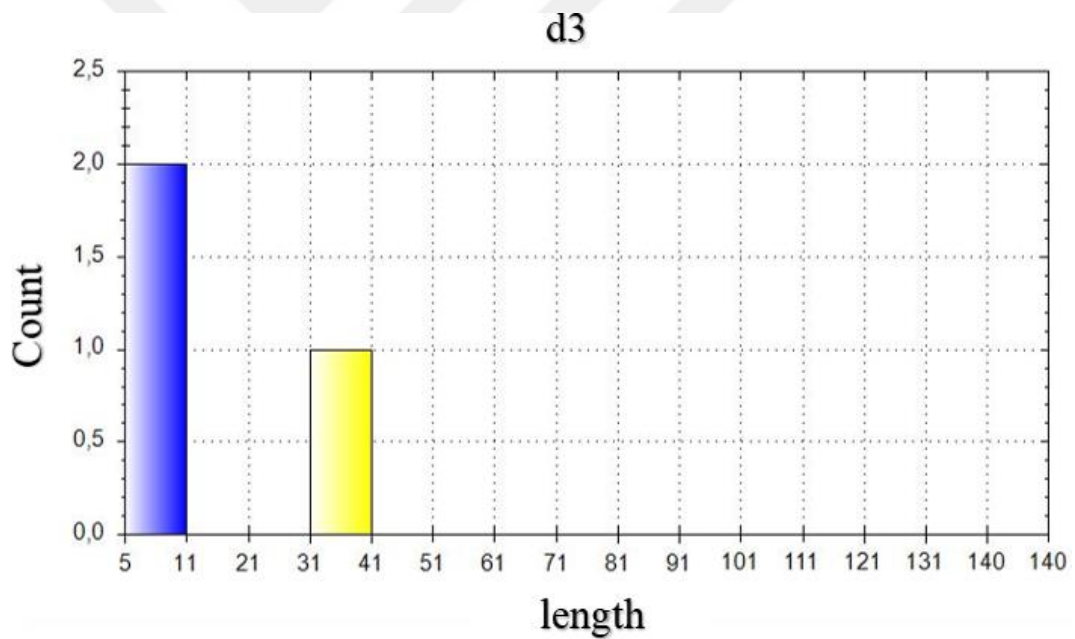


Figure 6.39 Histogram for sample d3

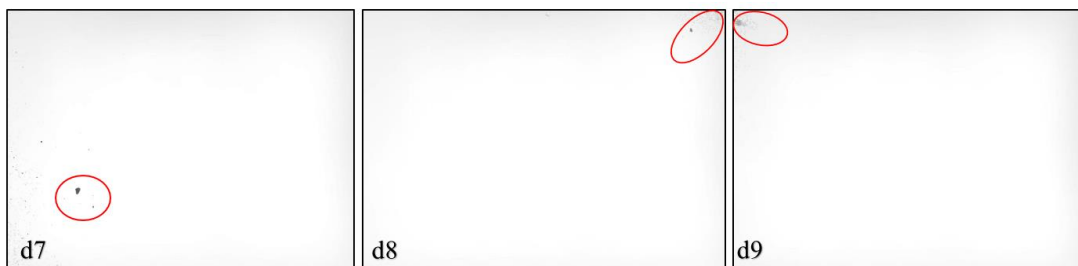


Figure 6.40: Photomicrographs observed for CB dispersion. Butt fused samples obtained from d7, d8, d9 magnified at X100

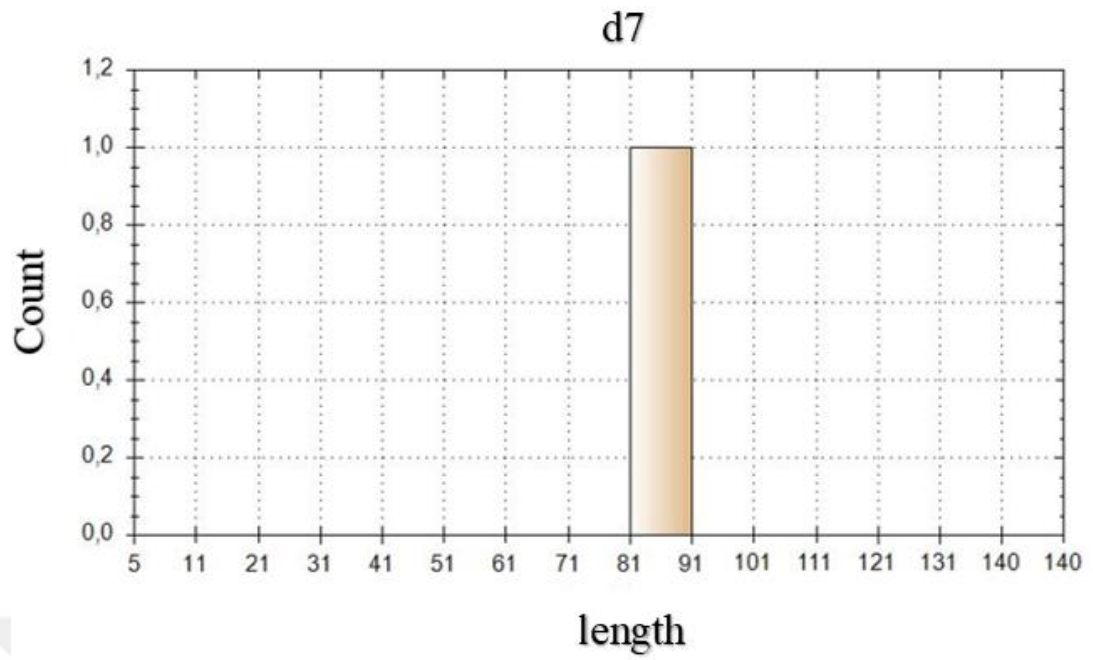


Figure 6.41 Histogram for sample d7

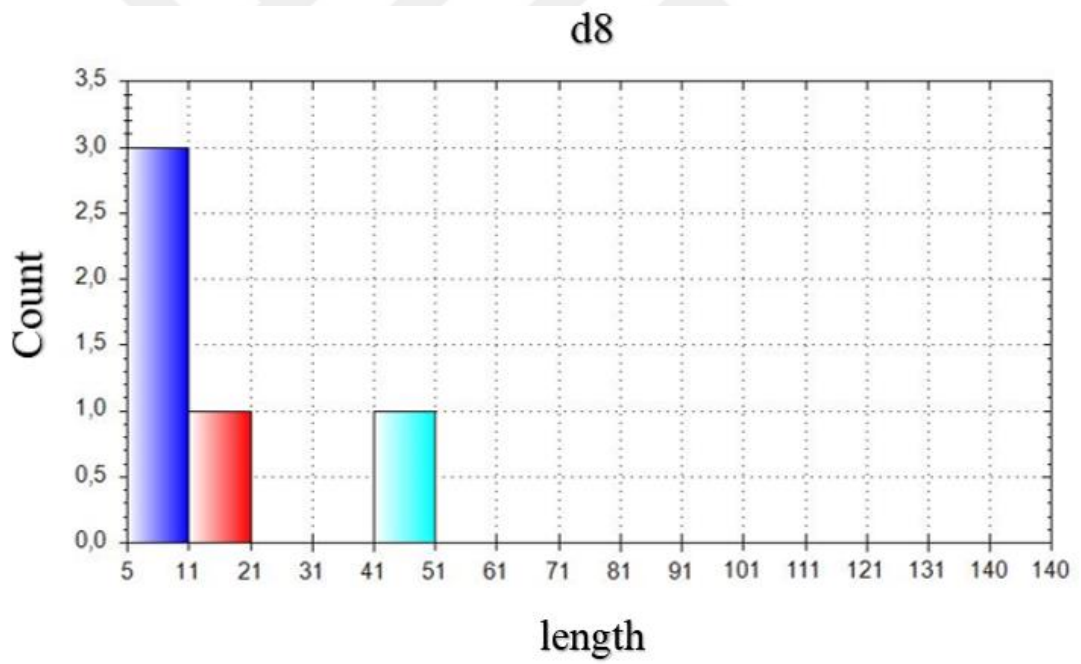


Figure 6.42 Histogram for sample d8

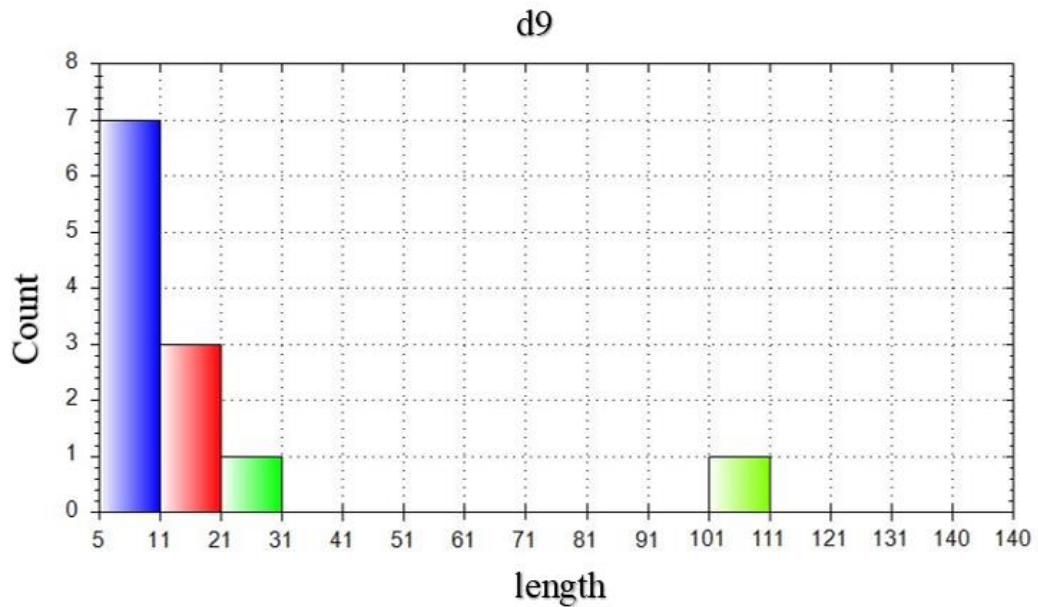


Figure 6.43 Histogram for sample d9

Table 6.11 shows the grades based on the largest dimensions of the particles and agglomerates (ISO 18553, 2013).

Table 6.11: Grades based on the largest dimensions of the particles and agglomerates

Grade	Dimensions μm														
	5 to 10	11 to 20	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	> 140
	Maximum number of particles and agglomerates														
0															
0,5	1														
1	3	1													
1,5	6	3	1												
2	12	6	3	1											
2,5		12	6	3	1										
3			12	6	3	1									
3,5				12	6	3	1								
4					12	6	3	1							
4,5						12	6	3	1						
5							12	6	3	1					
5,5								12	6	3	1				
6									12	6	3	1			
6,5										12	6	3	1		
7											12	6	3	1	

Source: (ISO 18553, 2013)

Since the standard specifies that the average carbon black dispersion at 180°C for 30 minutes must be ≤ 3 (ISO 18553, 2013), the obtained average results from samples d7, d8, and d9 were ≥ 3 as shown in the above histograms. This meant that samples obtained from the manual welding machine had poor carbon dispersion in the PE microstructure. Nevertheless, the samples d1, d2, and d3 all had a carbon black dispersion of ≤ 3 , this meant that the carbon black distribution in the samples obtained from the semi-automatic welding machine had homogenous and higher grades of CB distribution in the PE matrix.

Table 6.12: Results obtained for carbon black (CB) content, melt mass flow rate (MFR), and density

Carbon black (CB) content, melt mass flow rate (MFR), and density of welded samples and parent pipe samples									
Samples (Raw material used; BOROUGE HE3490LS)	Parent Pipe			Automated machine buff-fused samples obtained from joint			Manual machine buff-fused samples obtained from joint		
	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples
Average CB Dispersion Grade	0.5	0.5	0.6	1	2	1,0	3.2	2.5	4.5
Average CB Content %	2.12	2.20	2.15	2.25	2.4	2.38	1.8	2	1.7
Average MFR (g/10min)	0.2377	0.2401	0.2396	0.22	0.24	0.22	0.23	0.23	0.956
Average Density (g/cm^3)	0.959	0.958	0.959	0.950	0.965	0.960	0.956	0.958	0.956

The CB content, MFR, and density of all samples are given in Table 6.12. All test samples obtained from the automatic and manual machine's butt fused samples had shown very similar values and results to the parent pipe samples in physical and melt properties.

Nevertheless, CB content and the degree of CB dispersion slightly differed for the samples obtained from the manual butt welding machine. This was because welding pressure at T4 was not applied gradually but linearly as specified by the literature. Linearly applying the welding pressure at T4 does not guarantee the homogenous

distribution of heated molten PE, hence affecting the CB dispersion in the PE matrix during joining.

As it can be seen from Table 6.12, the results obtained by the automatic welding machine which applies welding pressure at T4 gradually guarantees the homogenous dispersion of CB in the heated molten PE matrix. The designed automatic welding machine overcomes the issue discussed in the literature, inadequate distribution and diffusion of CB in PE pipes are expected if CB and natural PE material are inefficiently combined, due to poor workmanship or machinery, which results in poor mechanical performance from the subsequent butt-fused joints.

The results in Table 6.12 also correlate to the results obtained when performing the tensile strength test for butt-fused samples. A homogenous dispersion of CB in the PE matrix improves the mechanical performance of HDPE. In the literature, brittle failures in PE butt-fused joints between pipes with inadequate CB dispersal were observed (Report No: 3002003089. Pennsylvania Edge Notched Tensile Test, 2016). These brittle failures were also observed in this paper from some of the samples obtained by welding and linearly applying pressure at T4 with the manual welding machine. For our research, all tensile test samples obtained from the designed automatic welding machine had better mechanical properties (ductile failure modes with a slightly higher modulus). From this section, we can see that the automatic welding machine also produced samples with a better CB dispersion.

7. CONCLUSION AND RECOMMENDATIONS

This paper explored the major attractive feature of HDPE pipe materials, which is the method in which they can be joined to a network of HDPE pipes in engineering projects using the butt fusion welding technique. In this research, the designed mechatronics system was used to eliminate the major challenges currently being faced by engineers and technicians during pipe installation and servicing. The method used to design the machine, and the applied implemented computer algorithm completely removed cold welds, bead misalignment, and non-uniform penetration of polyethylene chains.

The butt welding technique is a welding method used to join HDPE pipes by heating the pipe ends to be joined using a heated tool (heated mirror) with a temperature range of 200-220 °C. The major advantage of HDPE pipes compared to their steel, iron and other metal counterparts in pipework for engineering projects is that they can be used in a wide series of pipe systems and applications. Despite the material being plastic, it offers the same service or even better compared to pipes made from metal elements and alloys which are usually difficult to maintain. For example, metallic pipes corrode under seawater conditions, they are rigid, heavy, and expensive. Therefore, the use of plastic pipes has increased for applications like distribution of potable water, discharge of wastewater, transport of gas, and intake and discharge of seawater. Today in many nuclear power plants, cast iron tertiary cooling pipework is being replaced by HDPE as an alternative material for designing and erecting cooling pipework.

By utilizing the collected data from the literature, data from end-users, international standards, carefully studying the butt fusion welding procedure, and considering all the processes involved, the designed system successfully performed the butt welding procedure without any welding errors resulting from the mishandling of the welding equipment and poor workmanship, the mechatronics system had enhanced and optimized key butt-fusion parameters, namely the drag pressure which was automatically adapted by use of a transmitter sensor before commencing the welding

procedure, and the joining pressure at T4 which was applied automatically and gradually using a new algorithm guaranteeing a butt-fused joint with nearly 100 % parent pipe mechanical strength and characteristics.

The designed mechatronics system guaranteed that no exposure of the partially cooled melted PE chains before fusion occurred during welding at T4, because a carefully optimized uniform force in this case welding pressure was applied to facilitate the homogenous thermal movement of the melted material which was strategically adjusted to eliminate exposure of the cold zones during the fusion stage. Since a carefully optimized unvarying welding pressure was applied in the presence of heat during fusion at T4, such favorable conditions enhanced the dispersion of polyethylene chains throughout the material's matrix resulting in adequate meshing within the PE micro-structure chains.

7.1. Results

To test the integrity of the welded joints a series of tests were conducted following the international welding standards and literature. Using the automatic butt welding machine, and a manually operated butt welding machine a series of welds were performed on both machines to compare and contrast the performance of the machine in terms of the resulting welded joints. With this approach, we were able to compare the resulting joints from a manually operated welding machine to the automatically operated butt welding machine.

The butt fused samples from the semi-automatic welding machine were characterized by better mechanical strength, longer life span and excellent performance compared to the butt fused samples from the manually operated welding machine which was characterized by poor mechanical strength and performance in some joints because the fused joints obtained from the manual welding machine had some welded pipe samples resulting in brittle failure mode which meant that not all joints guaranteed a successful polyethylene entanglement during fusion at T4.

- The resistance to internal hydrostatic pressure at 80°C for 165 hours, under the pressure of 5.4 MPa for both machines' butt fused pipe samples was performed to evaluate a long-term internal pressure rating by investigating the material's enduring strength, functioning temperature, application

settings, and pipe size, tests had shown that both the manual welding machine and automatic welding machine samples did not rupture or break after 165 hours.

- Also, the oxidation induction time (OIT) for both sample groups obtained by either manual butt fusion or automatic butt fusion was more than 20 minutes because the samples used were produced from the same batch of raw materials. Therefore, it is safe to say the method of fusion used has a negligible effect on the time it takes for oxidation to occur on the welded pipe samples.
- However, it was observed that a nonhomogeneous distribution of CB in the PE matrix for samples performed by the manual welding machine had a significant effect on the resulting butt-fused joints' mechanical performance. This is why some of the resulting fused joints from the manual welding machine resulted in brittle failure mode during the tensile strength test as shown in Figure 7.1.

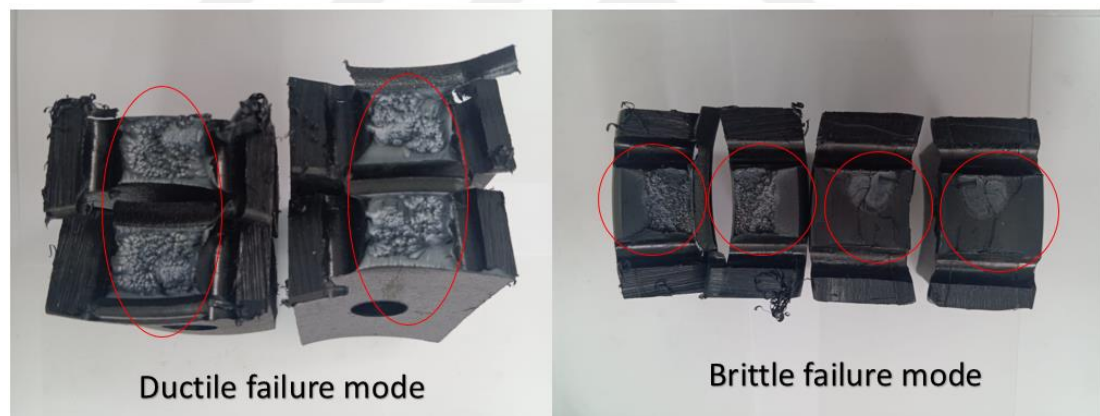


Figure 7.1: The ductile failure mode and brittle failure mode for butt fused HDPE samples

7.2. Recommendations

To improve the performance of the designed semi-automatic butt fusion welding machine, future studies should explore the possibility of integrating a data logger into the system. During this study, it was observed that it was going to be more convenient not to only store the performed welds onto the system but also to print out the performed welds on paper on-site. The current system only stored data that could be exported to a computer via an external drive. However, on-site it is not always possible to have a computer available.

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APPENDICES

Appendix-1: Circuitry and panel connections for mechatronics system

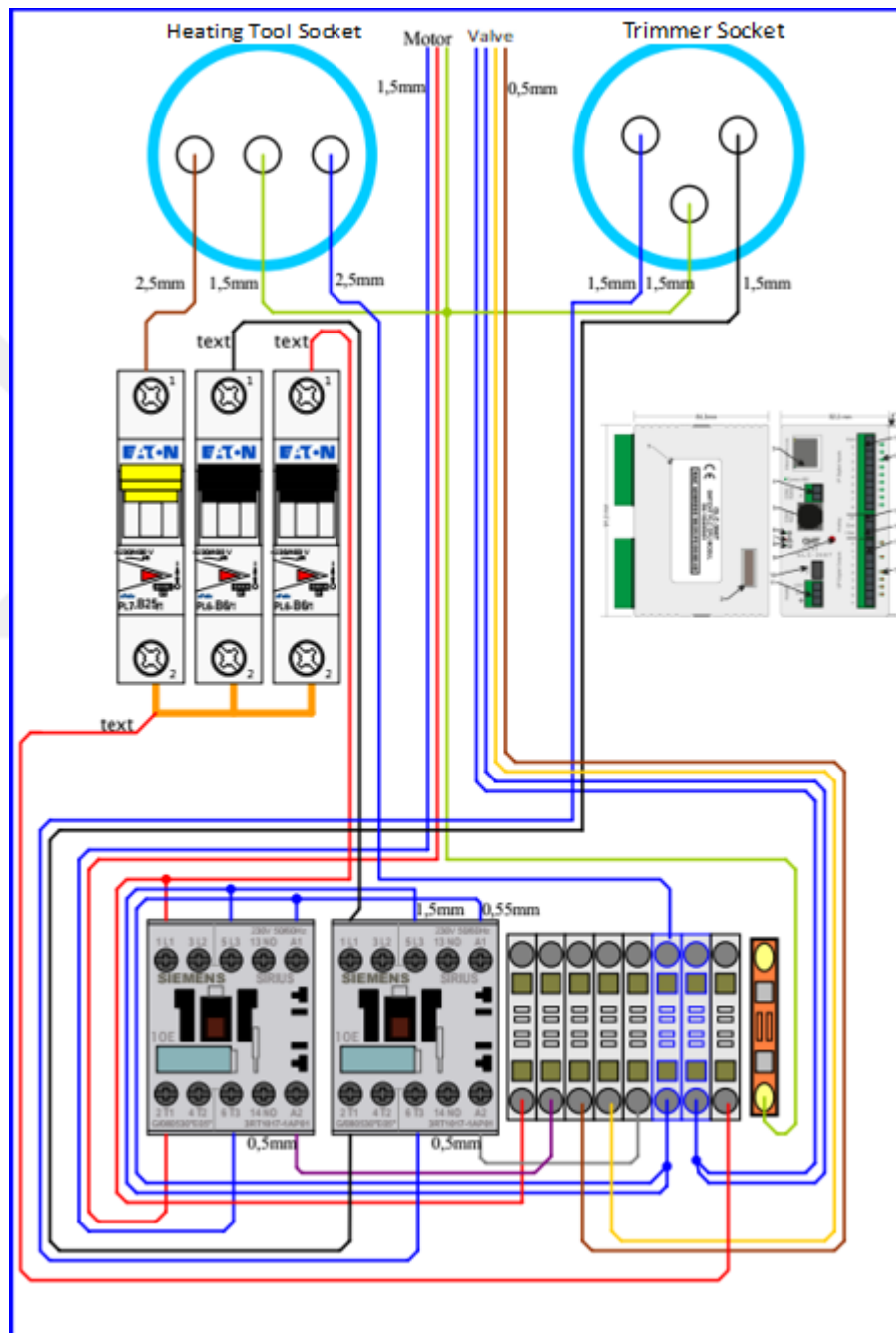
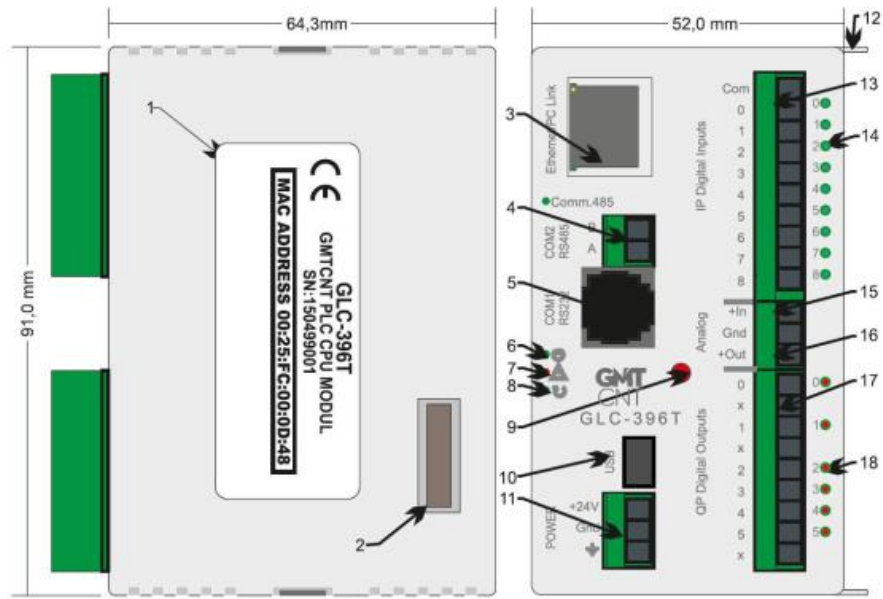


Figure 7.2: The semi-automatic butt welding machine connection diagram and panel

Appendix-2: PLC CPU Modules-Technical Specifications and Drawing



1	PLC label	10	USB port
2	Extention Module BUS connection port	11	Supply clip
3	100Mb ethernet port	12	Extention module mounting clip
4	Rs485	13	Digital input clip block
5	Rs232	14	Digital input status leds
6	PLC power led	15	Analog input clip
7	PLC fault led	16	Analog output clip
8	PLC run led	17	Digital output clip block
9	Reset button	18	Digital output status leds

Figure 7.3. GMT PLC Module www.gmtcontrol.com

RESUME

Sangwani Sinkala

An organized and skilled Mechatronics Engineer with 3 years of experience in Pre-sale Engineering Design, and Technical Support. Possessing a solid background in Mechanical, Electrical, and Electronics systems for designing Mechatronics structures and circuits on-site and in the manufacturing industry. Highly ambitious, successful, and career-focused candidate with the expectation of advancing knowledge in the field of Engineering.

Experience:

Mechatronics and technical support engineer –Turan Makina Borfit, Istanbul.

June 2020 – Present

Technical sales support engineer – Gedik and Partners, Istanbul.

September 2019 – June 2020

Technical sales engineer– Avrupa Temper, Malatya

April 2019 – September 2020

Site engineer intern– Yapı Merkezi Holding A.Ş, Y.E.S Project, Yozgat

June 2018 – August 2018

Projects:

Pneumatic system robot gripper design *June 2021*

Automatic irrigation system design *June 2020*

Simple radar system design *June 2020*

Technical Skills:

Fundamental electronic circuit design, SolidWorks, MATLAB Programming + Tool Box Tools, AutoDesk Fusion 360, Proteus, CISCO Packet Tracer, Kali Linux, C++ Programming, PLC Ladder Programming, Arduinio Micro Controllers to design driver circuits for mechatronic systems.