A STUDY OF THE COMBINED SOCKET AND BUTT WELDING
OF PLASTIC PIPES USING
THROUGH TRANSMISSION INFRARED WELDING

DISSERTATION

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ABSTRACT

Welding of polyethylene (PE) pipes of different diameters is critical for the infrastructure of natural gas transmission as well as for numerous industrial applications. A relatively new method of combined socket and butt through transmission infrared (TTIr) welding for polyethylene pipe was developed. It involves radiant heating of an absorbing element that is placed at the weld interface with air cooling of the exterior of the socket. The absorber element is a 0.1 mm thick PE film with a small amount of carbon black (0.5% by weight).

A prototype infrared welding system using tungsten halogen lamps was constructed and it was used to evaluate the effects of welding parameters on the combined socket and butt welding of 60-mm outer diameter medium density PE gas pipes. In addition, the effects of coupling thickness on power transmission of the infrared radiation and the effects of coupling thickness and width on weld strength were evaluated. For some welding conditions it was possible to create very strong welds without deformation of the coupling, no discontinuities in the butt joint, and with minimum inner bead. The size and shape of the inner bead was also found to be a good indicator of weld quality and it may be useful for inspection of completed welds.

For successful welds it is important to minimize deformation of the socket while providing sufficient heat input to form the butt weld in addition to the socket weld. To
better understand the heat flow that occurs, finite element and analytical models for the heat transfer were developed. The model predictions were found to be in good agreement with experimental measurements of the temperature history in selected locations in the pipe. These models can be used to analyze and optimize the heating dynamics in the weld zone under different welding conditions.

The combined TTIr socket and butt welding method was also applied to polyvinylidene fluoride (PVDF) pipes for high purity water applications where the inner bead must be eliminated to avoid contamination. Using this method, it was possible to make strong joints without inner weld bead by inflating a silicon balloon with air pressure of 0.1724MPa (25psi) on the inside of the pipe at the weld area.

A feasibility study using a Nd:YAG laser source instead of lamps showed that it was possible to produce a spot weld between the PE coupling and pipes as well as a partial butt weld. It was proposed that by increasing the laser power and the spot size along with getting a more uniform power density distribution, laser sources could also be used to produce high quality welds.
DEDICATIONS

Dedicated to God and My Parents and Wife and Children
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CHAPTER 1

INTRODUCTION

1.1 Welding of Plastic Pipes

Following the introduction of plastic pipes in the 1960’s, their use has rapidly increased in a wide range of industries [1, 2, 3] and specially for distribution of gas and water because of their ability to resist corrosion, low weight, flexibility, and low cost as compared to steel pipes. In addition, thermoplastic pipes can be easily joined with simple welding machines without any specialized operator skills. Presently, most of the plastic pipes are joined by either hot-plate welding or electro-fusion welding.

Hot plate welding is one of the most popular methods for joining plastic pipes because it is a reliable and economical way of producing strong welds. The joining surfaces are heated and melted, then brought together into contact under pressure to form a joint. Figure 1.1 shows process and temperature histories during hot plate welding [4]. Hot plate welding can be divided into four phases: heating under pressure, heating without pressure, change-over, and welding and cooling [5, 6, 7].

Hot plate welds can have 100% of the parent material strength if the correct joining parameters are applied but the inner and outer bead that form during welding can cause stress concentrations during service. But hot plate welding as it is presently used has some disadvantages including high equipment cost, complicated operating process of
four phases, potential for contamination of hot plate due to contact heating, and possible sticking of molten polymer to the hot plate due to variations and wear of stick coating of the hot plate, which causes weakening of welds.

Figure 1.1: Hot Plate Welding Process [4]
For electro-fusion (EF) welding, the socket or interior of the fitting incorporates an electrical heating coil. The coil is heated by passing electric current through it; it causes the plastic material close to it to melt and create a fusion weld between the pipe and socket. However, electro-fusion welding has some disadvantages such as high cost for electro-fusion fittings, the need to thoroughly scrape and clean the surface of the pipe, and difficulty to assemble pipes and EF coupling before welding. Figure 1.2 shows a schematic of the cross section as well as a photo of and actual fitting for electro-fusion welding.

During the process of electro-fusion welding a number of flaws may also develop due to improper joint preparation or poor process procedure. For example, Figure 1.3 shows x-ray images of the fitting and pipes after electro-fusion welding. Figure 1.3(a) shows a normal welded part where the wires did not move significantly. On the other hand, Figure 1.3(b) shows the deviation in the electric wires after electro-fusion because of the excessive force being applied when inserting the pipes into coupling. Figure 1.4 shows a failure in the fusion region where region 1 has a large void and region 2 indicates that the pipe was not fully inserted. Figure 1.5 shows a failure in the bond area due to misalignment. Figure 1.6 shows the weld defect produced due to not fully inserting the pipe into the coupling.
(a) Schematic of Cross Section

(b) Actual Fitting for 75A

Figure 1.2: Cross Section for Electro-fusion Fitting
(a) X-ray photo of normal weld (Good welding)  
(b) X-ray photo showing deviation of wires (Bad welding)

Figure 1.3: X-ray Photo of Welded Part after EF Welding [Taken from Ref 8]

Figure 1.4: Failure in Fusion Bond Area due to Large Void [Taken from Ref 9]
Figure 1.5: Failure in Bond Area due to Misalignment Between Pipe and Fitting [Taken from Ref 9]

Figure 1.6: Weld Defect Resulting from Pipe not Being Pushed Fully into Coupling [Taken from Ref 10]
Electro-fusion joints can be particularly weak if the surface is not prepared properly and it is used mostly for small outside diameter pipes (below 75mm) because the electro-fusion coupling is very expensive for large diameter pipes. Both butt fusion and electro-fusion welding can produce high quality welds. However, butt fusion welding is a slow and complicated process and electro-fusion welding has an expensive consumable cost of the coupling and potential flaws like incomplete insertion of the pipe into the socket and deviation of the wire. Therefore, it would be beneficial for the gas and water industry if a convenient, safe and faster joining method could be developed. Infrared energy has been used for welding plastics and composites since late the 1980’s, but only a few technical papers about infrared welding of plastic pipes have been published. However, no study has yet been conducted on new welding methods to replace the electro-fusion and butt fusion welding methods. Therefore, in this study, the new combined socket and butt welding method using the basic concept based on through transmission infrared welding is applied to welding plastic pipes.

1.2 Through Transmission Infrared (TTIr) Welding

TTIr welding is where the radiation of suitable wavelength is transmitted through a transparent polymer to an absorbing interface that is in contact with the transparent polymer. Heat generation at the interface melts the transparent and absorbing polymers, [11] with the source being outside the weld zone. Thermal expansion during heating pressurizes the melt resulting in a weld. The process is shown schematically in Figure 1.7. Nearly all polymers are transparent to infrared energy in portions of the near and middle infrared part of spectrum which is from 750 to 3000nm. Sources of infrared (IR)
radiation include xenon and quartz halogen lamps (from 300 to 4000nm) and diodes lasers (808nm), and Nd: YAG lasers (1064nm). Even polymers that are opaque to visible light such as Teflon are highly transparent and can be welded using appropriate absorbing layers.

Figure 1.7: Concept of Through-Transmission Infrared Welding

1.3 Description of Combined Socket and Butt Infrared Welding of Plastic Pipes

The electromagnetic spectrum is divided into spectral ranges based on their wavelength. The infrared portion of the spectral range can also be divided. The near
infrared wavelength ranges from 0.78 to 1.5 µm, middle infrared ranges from 1.5-5.6 µm, far infrared ranges 5.6 to 8µm, and extreme infrared ranges 8 to 1000 µm (see Figure 1.8). Figure 1.9 shows the picture of double ended halogen infrared lamp and Figure 1.10 shows the actual output distribution of a typical quartz lamp compared to several other infrared emitters [12]. Lamp energy with the tungsten halogen lamp filament temperature of 2250°C is concentrated in the near infrared spectrum with the peak power at 1.15 µm as determined by Wien’s law [13]:

$$\lambda_{\text{max}} = \frac{2898 \mu mK}{T}$$  \hspace{1cm} (1-1)

where $\lambda_{\text{max}}$ is the peak wavelength, $T$ is the maximum absolute temperature of tungsten halogen filament. With the tungsten quartz-halogen lamp, some of the radiation is emitted at wavelengths below 0.3 µm, which is ultraviolet rays, and above 5.6 µm, which is far infrared rays.

![Figure 1.8: Electromagnetic Spectrum](image)

Figure 1.8: Electromagnetic Spectrum
Polymer has absorption bands due to stretching, vibration, and scissoring, and similar types of molecular motions. If a polymer contains alcohol, carboxylic acid, or amide groups, it has absorption bands around 2 to 3 µm. As seen in Figure 1.11, most un-filled plastics are relatively transparent from 0.4 µm to 1.1 µm. Thus, wavelengths below 1.1 µm are preferred when welding plastics with TTIr. In addition, the IR radiation can be easily generated with laser diodes, Nd: YAG laser, and quartz halogen lamps.

Polyethylene (PE) has low absorption of the near infrared radiation (0.78 to 1.5 µm). However, middle infrared radiation with wavelengths in the range of 3.2 to 3.6 µm would be mostly absorbed in natural PE because PE contains carbon-hydrogen bonds.
Figure 1.10: Spectral Distribution of Several Infrared Radiant Sources [13]
In this work, a study to apply this transmitted infrared radiation for joining high density polyethylene pipes (HDPE) was accomplished and the welding process and equipment for combined socket and butt joining for plastic pipes was developed. This technique uses an IR energy source placed outside the joint area. IR radiation that passes through the coupling is absorbed by a black PE film that is placed at the interface and thus makes a socket joint between the inner surface of the PE coupling and outer surface of the pipe. The heat generated in the black PE gasket imbedded in the PE coupling also produces a butt joint between the pipes through conduction heat transfer. In other words, a socket and butt joints are made at the same time, resulting in a stronger weld. The process is shown schematically in Figure 1.12. This combined socket and butt welding
process also has benefits such as reduction of process time, cheaper equipment and coupling compared to conventional pipe welding methods, and a simple welding process.

Figure 1.12: The Schematic Diagram of the Infrared Welding Machine

1.4 Literature Review

Several projects have been conducted to join thermoplastic materials using through transmission infrared welding technique. The amount of transmitted energy relative to air for different unfilled polymers of thickness 0.25mm and 0.5mm was
measured and it was found that the variation between the polymers was small[15]. This study shows that natural polymers transmit IR radiation at the wavelength produced from quartz halogen lamps and some variation in transmission between 0.2mm and 0.5mm thickness occurred. Some polymers such as Polystyrene (PS), Poly methyl methacrylate (PMMA), and Polycarbonate (PC) transmitted most of the incident radiation. On the other hand, opaque polymers such as Polypropylene (PP), High density polyethylene (HDPE), Polyphenylene sulfide (PPS), and High impact polystyrene (HIPS) transmitted slightly less than natural PS, PMMA. It was also observed that pigments, fillers, coatings and other components of polymer formulations affect the amounts of reflection and absorption for incident radiation. Gimm [15] evaluated the effects of color on absorption and observed that absorption was strongest for the red samples, weakest for the blue, and decreased as the colors changed from yellow to green.

TTIr welding was conducted in a continuous manner using quartz-halogen lamps attached to the end of a robot arm [16]. In this study, it was demonstrated that this manner offered the advantage of welding shapes with complex curvatures and using dual lamps attached to the end of a robot arm gave an increased weld speed over a single lamp. TTIr butt welding technique was applied by placing a black PE film, that had carbon black added, between the ends of the coupons [17]. The polyethylene coupons were welded in 10 seconds when a 1.6 mm polypropylene filter was used.

Savitski [18] conducted a feasibility study for simultaneous butt and lap joint for Polyvinylidene fluoride (PVDF) pipe using TTIr. In this study, a strip heater was used as an IR radiation source. The assembly with pipes, coupling and black absorbing films was rotated in a way that the joint surface remained at the same distance from the radiant
source. Two absorbing film were positioned in the joint; one between the two pipes and the other between the outside surface of the pipe and the inner surface of the coupling. However, in this study, no cooling system was not set up to cool the exterior of the coupling and thus heating was not maintained for long enough, due to overheating of coupling, so that a butt joint was not completely created.

1.5 Objectives

The primary objectives of this work are to experimentally study the applicability of the combined socket and butt joining process for HDPE gas pipes and to evaluate the welding components and parameters and joint strength for joining 60-mm outer diameter (OD) PE gas pipes using the prototype IR welding system. This includes experimental and theoretical evaluation for the process components affecting the joint quality. Theoretically analyzing the mechanical performance and heat flow of coupling evaluate the effect of coupling thickness and width on weld quality. Experimentally study IR absorption of the black film as a function of thickness and carbon black content. Study theoretically and experimentally the heat flow during welding. Experimentally evaluate the joint strength using destructive mechanical tests. Evaluate the feasibility of creating beadless combined socket and butt welds in PVDF pipes. Study the use of Nd: YAG laser as an alternative IR source.

The dissertation is divided into the following sections: Chapter 2 describes the design and construction of the prototype TTIr welding unit for combined socket and butt welding. Chapter 3 shows the analysis and experimental evaluation of coupling thickness and width on IR transmission and mechanical performance of the joint. Chapter 4
evaluates the effect of IR absorption layer thickness and carbon black content in absorption layer on weld quality. Chapter 5 shows the theoretical and experimental analysis of heat flow during welding. Chapter 6 describes the combined socket and butt welding of PE gas pipes and the evaluation of joint strength using destructive mechanical tests. Chapter 7 evaluates the feasibility of creating beadless combined socket and butt welds in PVDF pipes. Chapter 8 evaluates the feasibility for PE gas pipe using Nd: YAG laser source. Chapter 9 shows the conclusions and recommendations.
CHAPTER 2

DESIGN AND CONSTRUCTION OF THE TTIr WELDING UNIT

2.1 Introduction

The infrared welding equipment used to weld the plastic pipes was designed and built for this work. As shown in Figure 2.1, it is composed of the IR heating chamber as an IR radiation source, a silicon-controlled rectifier (SCR) controller which controls the lamp power, a timer to control the heating time, temperature display to be connected via a thermocouple which is positioned in the IR welding unit to measure the temperature of any desired weld zone, and the start button to initiate the weld sequence. In addition, a compressed air hose is connected to the bottom portion of the IR heating chamber to provide cooling of the coupling surface. The joint area is centered in the middle of the IR welding unit and secured by the clamping device to prevent changes in the original alignment due to thermal expansion during the welding process. After the welded pipes are positioned, the welding process is manually conducted under the pre-set welding conditions. The welding process has two simple steps of heating time and joining and cooling. The TTIr welding conditions such as lamp power, heating time, and cooling pressure can be accurately set.
2.2 Heating Chamber with IR lamps

The heating chamber of the unit has a tubular shape and incorporates 16 IR halogen lamps (100W, 130V, 79.4mm) supported by ceramic holders. Figure 2.2 shows a diagram of IR heating chamber and Figure 2.3 shows a 3-D depiction of the chamber and Figure 2.4 shows a photo of inside of the chamber. The distance between the lamps is 10mm. The lamps are positioned at a distance of 13mm from the surface of 60mm outer diameter pipes and 7 mm from the surface of the coupling. The diameter of the inner circle of IR lamps is about 90 mm. Therefore, the unit provides uniform heating over the entire joint area.
Figure 2.2: Diagram of Heating Chamber of IR Welding Unit
Figure 2.3: The Entire Heating Chamber of IR Welding Unit

Figure 2.4: The Inner Picture of Heating Chamber of IR Welding Unit
2.3 SCR Lamp Power Controller

A silicon-controlled rectifier (SCR) lamp (Model Abco, 100W, 130V, and 79.4mm) controller operating at 110V, 60Hz was used to vary the voltage and current supplied to the lamps. The maximum current is 25amp.

2.4 Digital Time Controller

The digital timer that was used to control the heating time can be set from 1 second to 999 hours. The heating time starts when the IR lamps receive full voltage when the timer is activated by pressing the start timer button. At the end of preset heating time, the voltage to the lamp automatically is turned off.

2.5 Cooling System

A 7-mm ID cooling system hose is connected to the bottom portion of the IR heating chamber and the airflow is used to prevent over heating of the outer surface of the coupling during the welding sequence. The cooling air pressure can be increased up to a maximum of 0.6895MPa (100 psi) by an air pressure regulator as shown in Figure 2.5. In order to provide uniform cooling over the whole coupling, the air inlet T-valve was connected to the cooling system hose as. As shown in Figure 2.6 both sides of the T-valve were cut for better cooling for coupling and an additional air outlet was machined in the center of T-valve for better cooling of the bottom portion of the coupling. The cooling air is also discharged by a diffused air outlet at the top of the IR heating unit as can be seen in Figure 2.7.
Figure 2.5: The Cooling System to be Connected to Infrared Welding Unit

Figure 2.6: Air Inlet Valve for Cooling of Coupling during Heating Phase
2.6 Clamping Device

On either side of the IR heating chamber there is clamping device that is 50mm long and with inner diameter equal to the outer diameter of the pipe (see Figure 2.8). Therefore, it is tightly latched after closing the lid of the clamping device so that the welded pipe is tightly fixed by the clamping device and it maintains the original alignment.
Figure 2.8: Photo of Clamping Device
CHAPTER 3

ANALYSIS OF MECHANICAL PERFORMANCE AND HEAT FLOW OF COUPLING

3.1 Introduction

In order to optimize the joint quality of the combined socket and butt welding process for plastic gas pipe, three of factors such as thickness and width of coupling, thickness and carbon black content of black film, and cooling system need to be evaluated. In this chapter, the coupling thickness and width are evaluated using three criteria: mechanical failure for coupling itself, maximum stress in weld zone, and IR transmission through coupling (thickness only) and its effect on heat flow.

The mechanical performance of the joint will depend on both the coupling thickness and width. If we have incomplete or no butt joint, the coupling needs to be thick enough to support tensile loading of the pipe to the point where the pipe fails prior to coupling. The width of the coupling will affect load transfer in shear from the pipe to the coupling. Wider couplings will make it easier to distribute the load over a larger area and avoid premature failure of the coupling or weld.

The coupling thickness will also affect transmission of IR radiation through the coupling. Some of the IR radiation is reflected, absorbed, and transmitted through the coupling. As the coupling thickness increases so will the absorption resulting in less IR radiation reaching the black film at the interface. This will also affect the heat flow and
may hinder the formation of the butt joint. Therefore, at the end of this chapter experimental study of coupling absorption and heat flow is discussed.

3.2 Evaluation of Effects of Coupling Thickness on Joint Mechanical Performance

3.2.1 Analytical Results

Figure 3.1 shows a simplified analysis of tensile failure in the pipe and coupling. Neglecting stress concentrations, the tensile failure load for different thickness couplings can be calculated by multiplying the area of coupling with the maximum tensile strength of HDPE (17.64MPa). The tensile failure load for 5mm thick coupling was 1781kgf, which is just a little higher than the failure load of 1,762kgf for 6 mm thick pipe. The selection of the coupling thickness can be considered on the basis that the tensile strength of the coupling should at least be stronger than that of the pipe itself. Therefore, it can be concluded that the coupling thickness should be more than 5-mm thickness.

3.2.2 Finite Element Analysis Results

Another factor that was considered in evaluating the thickness of the coupling was the maximum tensile stress in the weld zone. The maximum stress in the joint was evaluated by using elastic finite element analysis (FEA) with ANSYS [19] for typical tensile loading of the pipe. Six models were analyzed for coupling thickness varying from 1 to 6mm in 1mm increments.
11. Tensile failure for 5-mm-thick coupling

\[ A = \pi (r_3^2 - r_2^2) = 3.14 \times (35^2 - 29^2) = 0.989 \times 10^{-3} \, m^2 \]

\[ F = \sigma_{\text{tension}} \times A = 17,640,000 \frac{N}{m^2} \times 0.989 \times 10^{-3} \, m^2 = 17,450N = 1,781kgf \]

2. Tensile failure for pipe itself

\[ A = \pi (r_2^2 - r_1^2) = 3.14 \times (29^2 - 23^2) = 9.79 \times 10^{-4} \, m^2 \]

\[ F = \sigma_{\text{tension}} \times A = 17,640,000 \frac{N}{m^2} \times 9.79 \times 10^{-4} \, m^2 = 17,270N = 1,762kgf \]

Figure 3.1: Calculation for Tensile Failure for Coupling Itself
Using the symmetric nature of the geometry, half of the welded pipe and coupling were modeled and a tensile loading of 0.678MPa (98 psi) was applied on the wall area of the pipe on the right and symmetric boundary condition (axial direction) was applied at the left end, as shown in Figure 3.2. The tensile loading of 0.678MPa (98 psi) was obtained by applying the joint loading condition for gas pipes. During installation and service, welded joints for gas pipes may be subjected to various loads such as internal pressure, soil pressure, and car weight, which can affect their behavior. For a maximum usage pressure of 4kgf/cm$^2$, the internal pressure is

$$W_i = 4 \frac{kgf}{cm^2} = 0.4MPa(58.015 psi) \quad (3-1)$$

The soil pressure can be determined using the following Equation [20]:

$$r = 0.002 \frac{kg}{cm^3} \quad g = 980 \frac{cm}{sec^2} = 9.8 \frac{m}{sec^2} \quad h = 120 cm$$

$$W_f = r \cdot h \cdot g = 2.352 \times 10^4 Pa(3.4 \ psi) \quad (3-2)$$

Where $r$ is the soil density, $h$ is the depth of the buried pipe, and $g$ is gravitational acceleration. The effect of vehicle weight was determined by assuming an impact loading from the rear tires of two adjacent tracks resulting in two surface loads of 12,000 kgf that are separated by a distance of 100 cm. The resulting pressure can be calculated using the following equation [20]:

28
\[ W_i = \frac{3Q}{2\pi h^2} \left[ 1 + \left( \frac{h}{\sqrt{h^2 + X^2}} \right)^2 \right] \]  \hfill (3-3)

\[ W_i = 0.048 \text{MPa}(7.174 \text{psi}) \]

Where \( Q \) is the impact loading of the rear tire of each vehicle.

Figure 3.2: FEA Model with Applied Internal Pressure (0.4MPa) and Tensile Loading (0.678MPa)

As can be seen from Equations (3-1) to (3-3) the internal pressure is partially balanced by an external pressure at the top of the pipe from soil and vehicle weight. If the pipe is buried at a depth of 120 cm then the internal pressure is much higher than the...
external pressure. Therefore, we will assume that the pipe is loaded primarily by the internal pressure.

Another possible load may be tensile resulting from applying an end cap to the pipe. In this case, one can balance the load resulting from the pressure applied to the end cap with axial stress \((\sigma)\) on the wall as shown in the following equation:

\[
P \times A_{\text{cap}} = \sigma \times A_{\text{wall}}
\]

\[
3.999 \times 10^{5} \text{ Pa} \times \pi (0.023m)^{2} = \sigma \times (\pi (0.029m)^{2} - \pi (0.023m)^{2})
\]

\[
\sigma = 6.78 \times 10^{5} \text{ Pa (98 psi)}
\]

(3-4)

where the inner radius of the pipe is 0.023m and the outer radius is 0.029m. The resulting axial stress in the pipe from the end cap would be 0.678MPa (98psi). Since the pipe is buried in soil, which constrains its axial movement, the axial stress will decay and eventually approach zero. Therefore, in general it is unlikely that we would have axial stress in the pipe from both bending and end cap loading. Therefore, we will assume that the maximum axial stress that would be experienced by the pipe would be 0.678MPa (98psi).

In summary, if a small element from the top of the pipe is considered as can be seen in Figure 3.3, it may be subjected to combined loading with an internal pressure of 0.4MPa (58 psi), an axial stress of 0.678MPa (98psi) and a hoop stress of 1.758MPa (255 psi) calculated by using the stress equations for a cylinder with a thick wall subjected to internal pressure as follows [21]:

\[
\sigma_{h} = \frac{P_{o}r_{o}^{2} - P_{i}r_{i}^{2}}{(r_{o}^{2} - r_{i}^{2})} + \frac{r_{i}^{2}r_{o}^{2}(P_{o} - P_{i})}{r_{i}^{2}(r_{o}^{2} - r_{i}^{2})}
\]
$$\sigma_h = \frac{4 \times 10^2 \times 0.023^2 - 0 \times 0.029^2}{(0.029^2 - 0.023^2)} = \frac{0.023^2 \times 0.029^2 (0 - 4 \times 10^5 Pa)}{0.023^2 (0.029^2 - 0.023^2)}$$

$$\sigma_h = 1.756MPa(254.686psi) \quad (3-5)$$

where Figure $\sigma_h$ is the hoop stress. Figure 3.4 shows a typical contour plot of the von Mises stress distribution in the weld zone for a coupling with 6mm wall thickness. The contour plots of the von Mises stress distribution and z-direction (axial direction) stress distribution for the couplings with 1-6mm thickness are shown in Appendix A. As can be seen in Figure 3.4 the maximum stress is at the weld interface at the outer edge of coupling.

![Figure 3.3: Stress Loading on a Small Element at the Top of the Pipe](image)
Figure 3.4: Von Mises Stress Distribution in the Weld Zone for 6mm Thick Coupling
There are a number of possible failure criteria that are utilized for plastic components. Assuming that the part can be considered isotropic then one can utilize any of the following failure criteria [22]:

1) Maximum stress
2) Maximum strain
3) Stress reaching the yield stress
4) When strain reach 0.5% offset strain
5) Maximum shear stress criterion (more common with metals)
6) Parabolic criterion
7) Conical criterion
8) Maximum distortion energy criterion, which is also known as von Mises criterion, as well as HMH criterion and octahedral shear stress theory

Of these numerous criteria, the von Mises criterion is very effective in predicting the yield stress for ductile materials (e.g. plastics) that are subjected to multi-axial loadings. For the von Mises criteria the equivalent stress is given by the following relation:

\[
\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}
\]  

(3-6)

Where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the principal stresses in the 1, 2, and 3 directions. Figure 3.5 shows that the von Mises criterion (m=1) is more conservative than other criteria and it
works very well for a wide range of polymers that are subjected to biaxial loading and it should just as effective for three dimensional loading conditions.

Figure 3.5: Experimentally Determined Stress at Failure and Calculated Failure Curves for Different Plastics Using the Von Mises Criteria (Taken from Ref 22)
Therefore, the maximum Von Mises stress in the weld zone was compared with regard to couplings with different wall thickness. Figure 3.6 shows the FEA to predict maximum stress as a function of wall thickness. In all cases the maximum stress was near the outer of the coupling. Generally, the maximum stress in the joint increased as the coupling thickness increased because the stress concentration increases with increasing thickness. However, it was demonstrated that the increase in maximum stress is small and not significant compared with the ability to insure that the coupling is thick enough to avoid failure (Section 3.2.1).

![Graph showing maximum Von Mises stress as a function of wall thickness](image)

Figure 3.6: Data Predicted from FEA Model Showing the Effect on the Maximum Stress with Regard to Different Wall Thickness of Coupling on the Welded Zone
3.3 Evaluation of Effect of Coupling Width on Joint Mechanical Performance

The maximum Von Mises stress in the weld zone with regard to different coupling width was evaluated by using elastic finite element analysis (FEA) for a typical tensile loading of the joint. As described in Section 3.2.2, the welding of an end cap for a pressurized pipe results in axial tensile loading of the joint. Therefore, in the model, it will be assumed that the maximum axial stress that would be experienced by the pipe would be 0.678MPa (98psi).

Two different cases for socket joint and combined socket and butt were analyzed. Four models were analyzed with 18, 36, 54, and 72mm wide couplings. Using the symmetric nature of the geometry, half of the welded pipe was modeled and a tensile loading of 0.678MPa (98psi) was applied on right wall area of the pipe and symmetric boundary condition (axial direction) was applied at the left end of half of the welded pipe as shown in Figure 3.2. Figures 3.7 and Figure 3.8 show contour plots of the stress distribution for 18mm wide coupling for socket joint and for combined socket and butt joint respectively. The contour plots of the stress distribution for the couplings with of width of 36, 54 and 72mm are shown in Appendix B. As before the maximum Von Mises stress is in the weld at the outer end of coupling.

Figure 3.9 shows FEA model predictions of the maximum Von Mises stress as a function of coupling width for socket joint and combined socket and butt joint under tensile loading. For socket joint, the maximum stress at the fusion zone decreases with increasing coupling width and the maximum stress level remains nearly constant for widths over 54mm. For combined socket and butt joint, the maximum stress level remains nearly constant for all coupling width, showing that the coupling width has little
impact on the joint strength if the butt joint can be successfully obtained. Therefore, it shows that the lap joint strength depends on the width of the coupling and thus it would be better to have a wider coupling to achieve a stronger lap joint. However, increasing the width of the coupling beyond 54mm would be considered an unnecessary waste of the material. If the butt joint can be successfully and consistently obtained then couplings that are just 18mm wide may be used.

Figure 3.7: Stress Distributions in the Socket Weld Zone for 18mm Coupling Width
Figure 3.8: Stress Distributions in the Combined Socket and Butt Weld Zone for 18mm
Figure 3.9: Maximum Stress in the Joint with Regard to Different Coupling Width
3.4 Evaluation of Effects of Coupling Thickness on IR Transmission and Heat Flow

3.4.1 Experimental Study of IR Transmission

3.4.1.1 Experimental Procedures

The thickness of the coupling will also affect the transmission of IR variation. The thicker the coupling the less IR radiation will reach the black film and it may affect over the ability to produce a butt joint. Therefore, the effect of coupling thickness on IR transmission was measured experimentally for thickness ranging from 1 to 6mm in 1mm increments.

A Model FM Coherent Field Master power/energy meter with power sensor was used to measure the radiation of the IR source. Polyethylene pipe was partially sectioned and a hole of the same size as the sensor of the power meter (radius of 0.9cm) was machined. The power meter was placed on the sectioned pipe such that the circular sensor fit the hole made in the pipe. The hole made in the pipe was located at the bottom of heating chamber as shown in Figure 3.10 and only eight lamps located on the bottom portions of heating chamber were turned on for the power measurements. The experiment was conducted at an 80W power output per lamp and 40 sec heating time. As shown in Figure 3.11(a), initially, the power that reached the power sensor without the presence of coupling was measured. The transmitted IR power was measured at a point where the power sensor is 1.9cm away from the surface of lamps. Second, as shown in Figure 3.11(b), the hole in the pipe was covered with the different thickness couplings. The power that passed through the coupling was then measured.
Figure 3.10: Experimental Setup to Measure the Power Level Absorbed in Coupling
Figure 3.11: Experimental Setup for Measuring Power Absorbed in Black Film

(a) Making a hole with same size as the sensor on the pipe

(b) Covering coupling on the pipe with a hole
3.4.1.2 Results and Discussions

Figure 3.12 shows the measured power transmission for the 1-6mm thick coupling. As expected, the transmission decreased with increasing coupling thickness in what appears to be an exponential decrease. Therefore, it was demonstrated that the thin coupling transferred the higher power into the absorber layer (black film) because the thin coupling had higher IR transmission.

3.4.2 Heat Flow Analysis

Most homogeneous plastics do not reflect a significant amount of electromagnetic radiation, usually between 2 and 8%. This is caused by the fact that most plastics have an index of refraction between 1.4 and 1.6 [23] which closely resembles the index of refraction of air (~1). The fraction of light being reflected (R) for a material with index of refraction m in a medium with index of refraction m is given by the following relation:

\[
R = \frac{(n - m)^2}{(n + m)^2}
\]  \hspace{1cm} (3-7)

Therefore, the amount of reflection on the surface of coupling was estimated to be 5.3% by substituting n=1.6, m=1 in equation (3-7), resulting in the amount of refraction (dispersion) of 17.7% on the surface of coupling if the amount of absorption in 1 mm thick coupling is approximated to 8% based on Figure 3.12.
Expected amount of refraction (dispersion): 100% – 69% (transmission) – 8% (absorption) – 5.3% (reflection) = 17.7%

Figure 3.12: Transmission for Different Thickness of Couplings
The morphology or microstructure in semi-crystalline polymers such as Polyamide (PA), polyethylene (PE), and polypropylene (PP) cause internal refraction and scattering as shown in Figure 3.13 [24]. Each phase, crystalline and amorphous, has a different index of refraction and thus light is refracted as it travels through the sample. In the case of a semi-crystalline polymer such as PE, a light beam will encounter many phase changes within the material.

The amount of refraction is defined by Snell’s law:

$$\frac{\sin \theta_a}{\sin \theta_b} = \frac{n_a}{n_b}$$

(3-8)

where \(n_a\) and \(n_b\) is the index of refraction for material a and b. The internal scattering only affects a material’s weldability when TTIr is used. The scattering causes the electromagnetic radiation to diffuse as it travels through the sample and thus reduce the amount of energy that reaches the absorbing layer. The amount of scatter is defined by Lambert Bouger’s Law,

$$I_t = I_o e^{-(\alpha x)}$$

(3-9)

where \(I_t\) is intensity of the light at a thickness \(t\) with an absorption constant \(\alpha\). Therefore, thicker sample produce more internal scatter. Thus, the energy required to melt the absorbing layer is proportional to the thickness of the sample when welding materials, such as semi-crystalline thermoplastics [25].
The cross section of the socket and butt joint assembly with 6mm thickness of coupling is shown in Figure 3.14. A is the inner radius of pipe and B is the outer radius of pipe, C is the outer radius of the black film or inner radius of coupling, and D is the outer radius of coupling.

Pipes that have a cylindrical geometry can be treated as axisymmetrical elements. Figure 3.15 shows the 2D FEA axisymmetric model for 6mm thick coupling. The internal heat generation rate representing absorbed radiation in the coupling was include for this model and the 6mm thick coupling was divided into six areas and a list of the calculated internal heat generation rate is shown in table 3.1. The power absorbed in each 1mm thick area of the coupling was calculated by multiplying the power transmitted to each element by the absorptivity and then the internal heat generation rate was obtained by dividing the actual power absorbed in each area of coupling with the volume of the each
area of coupling. The procedure used for calculation of the internal heat generation rate in element 1 of coupling showing in table 3.1 is given as the following.

Power density on element 1 = Transmitted Power/Area = \( \frac{7.6W}{3.14 \times 0.9} \text{ cm}^2 = 3.0 \frac{W}{\text{cm}^2} \) (3-10)

Area of element 1 = 1.8 cm \times (3.14 \times 7.22 \text{ cm}) = 40.8 \text{ cm}^2 \hspace{1cm} (3-11)

Total power applied on element 1 = 3.0 \frac{\text{watt}}{\text{cm}^2} \times 40.8 \text{ cm}^2 = 122.4W \hspace{1cm} (3-12)

Total power absorbed on element 1 = 122.4 W \times 0.08 \text{ (absorptivity)} = 9.8W \hspace{1cm} (3-13)

Internal heat generation rate on element 1

\[
\frac{9.8W}{[\text{withs}(0.019) \times \text{thickness}(0.001m) \times L(3.14 \times 0.0722m)]} = 2275126.9 \frac{W}{m^3} \hspace{1cm} (3-14)
\]

The internal heat generation rate decreases as the coupling thickness increases because the transmitted power through the coupling decreases as the coupling thickness increase. The internal scattering in 1mm thick elements was expected to be too small based on Lambert Bouger’s Law and thus it was not considered for this model.

<table>
<thead>
<tr>
<th>Element</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{Q} (\frac{W}{m^3}) )</td>
<td>2,275,126.9</td>
<td>2,005,667.4</td>
<td>1,720,423</td>
<td>1,341,944</td>
<td>1,200,990.5</td>
<td>9,916,231.6</td>
</tr>
</tbody>
</table>

Table 3.1: List of Internal Heat Generation Rate Absorbed in Six Divided Coupling Areas
The temperature-dependent material property data for medium density polyethylene is shown in Figure 3.16 and was tabulated in Table 3.2. The thermal conductivity, specific heat capacity, and density were considered as a function of temperature in the axisymmetric FEA model.

Note:
A (radius of the pipe inner wall): 0.023m
B (outer radius of pipe): 0.029m
C (outer radius of the black or inner radius of coupling): 0.0291m
D (outer radius of coupling): 0.0351m

Figure 3.14: Cross-Section of the Socket and Butt Joint Assembly
Table 3.2: Material Property Data Input for ANSYS [26]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Specific Heat (J/kg·k)</th>
<th>Thermal Diffusivity (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>950</td>
<td>0.40</td>
<td>9.7</td>
<td>2,100</td>
</tr>
<tr>
<td>40</td>
<td>947</td>
<td>0.38</td>
<td>9.0</td>
<td>2,520</td>
</tr>
<tr>
<td>60</td>
<td>940</td>
<td>0.33</td>
<td>8.8</td>
<td>2,940</td>
</tr>
<tr>
<td>80</td>
<td>925</td>
<td>0.32</td>
<td>8.0</td>
<td>3,360</td>
</tr>
<tr>
<td>100</td>
<td>910</td>
<td>0.29</td>
<td>7.7</td>
<td>3,780</td>
</tr>
<tr>
<td>120</td>
<td>885</td>
<td>0.28</td>
<td>7.0</td>
<td>5,460</td>
</tr>
<tr>
<td>122</td>
<td>875</td>
<td>0.28</td>
<td>6.7</td>
<td>7,560</td>
</tr>
<tr>
<td>124</td>
<td>865</td>
<td>0.28</td>
<td>6.7</td>
<td>8,820</td>
</tr>
<tr>
<td>126</td>
<td>850</td>
<td>0.28</td>
<td>6.7</td>
<td>10,080</td>
</tr>
<tr>
<td>128</td>
<td>840</td>
<td>0.28</td>
<td>6.7</td>
<td>12,180</td>
</tr>
<tr>
<td>130</td>
<td>830</td>
<td>0.28</td>
<td>6.7</td>
<td>24,780</td>
</tr>
<tr>
<td>132</td>
<td>775</td>
<td>0.27</td>
<td>6.7</td>
<td>58,800</td>
</tr>
<tr>
<td>134</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>4,620</td>
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<tr>
<td>136</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>3,360</td>
</tr>
<tr>
<td>138</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>2,520</td>
</tr>
<tr>
<td>140</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>2,520</td>
</tr>
<tr>
<td>160</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>2,520</td>
</tr>
<tr>
<td>180</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>2,520</td>
</tr>
<tr>
<td>200</td>
<td>775</td>
<td>0.27</td>
<td>6.5</td>
<td>2,520</td>
</tr>
</tbody>
</table>
Figure 3.16: Thermal Material Properties of HDPE [26]
The absorption and conversion of IR radiation by the black film into heat was represented as an equivalent internal heat generation rate. The internal heat generation rate in the black film for 2, 4, and 6mm thick couplings was calculated based on the experimental transmission measurements. The power density was obtained by dividing the power passing through coupling by the area of power sensor of power meter. The total power absorbed in black film was estimated by multiplying the power density by film area (1.8 cm×19 cm = 34.2 cm²). The internal heat generation rate was obtained by dividing the total power amount by the volume of black film [length (0.19m) × thickness (0.0001 m) × width (0.018 m)]. The internal heat generation rate in the black film for 2, 4, and 6mm thick couplings was 162,900,000 W/ m³, 112,400,000 W/ m³, and 86,000,000 W/ m³, respectively.

As shown in Figure 3.15, the effect of convective cooling from the outer coupling wall and the inner wall of pipe was also included in the model as a boundary condition, i.e., the heat-transfer coefficient was defined at the faces of the elements forming the outer coupling wall and the inner wall of joint. During the welding sequence, the inner wall was cooled by natural convection and the outer wall was cooled through a forced air cooling system with air pressure of 0.6205MPa (90psi). Typical values of heat transfer coefficient for natural convection of gas are 5-12 W/m²K [27]. The heat transfer coefficient for the inner pipe wall was approximated at the minimum value of 5W/m²K because the enclosed space.

The dimensionless Nusselt number is often used to determine the surface heat transfer coefficient,
\[ N_u = \frac{hD}{\lambda} \]  

(3-15)

where \( h \) is the surface heat transfer coefficient, \( \lambda \) is the thermal conductivity of the fluid, \( D \) is the characteristic length (outer coupling diameter), and \( N_u \) is the Nusselt number. The velocity of the air coming out of cooling system hose \((v_2)\) can be estimated from Bernoulli’s equation by assuming that the air is incompressible

\[ P_1 + \frac{\rho v_1^2}{2} = P_2 + \frac{\rho v_2^2}{2} \]  

(3-16)

where

\[ P_1 = 0.6205 \text{MPa} \text{ (90 psi)} \text{ (gauge pressure in cooling system hose)} \]

\[ P_2 = 0 \text{ (atmospheric pressure)} \]

\[ v_1 = 0 \text{ m/sec} \]

By applying \( \rho = 1.29 \text{kg/m}^3 \) (air density), \( P_1, P_2, \) and \( v_1 \) into Equation 3-16, we will get the velocity \((v_2)\) of 980 m/sec of the air existing the cooling system hose. Figure 3.17 shows the variation in the \( N_u \) number as a function angular position for cross flow of air over a cylinder for a wide range of Reynolds numbers. By applying \( v_2 = 18.3 \text{m/sec}, D = 0.07 \text{m} \) (outer coupling diameter), \( \mu = 1.73 \times 10^{-5} \text{ N s/m}^2 \) (air dynamic viscosity), we get the Reynolds number

\[ R_e = \frac{\rho \times v_2 \times D}{\mu} = 5,120,000 \]  

(3-17)
For most technical problems, however, we usually need the average heat transfer coefficient. Therefore, the average Nusselt number of $N_u=495$ was obtained by averaging values for the sixteen points for the Reynolds number of 219,000 from Figure 3.17. By applying the Nusselt number, thermal conductivity of air $\lambda=26.3\times10^{-3}$ W/mK, characteristic number $D=0.07$m into equation (3-9), the convection coefficient ($h$) of 180 W/m$^2$K was calculated and used in the model.

Figure 3.18 shows a contour plot for the temperature for a 6mm thick coupling under 250s heating time, 80W lamp power, and 0.6205MPa (90psi) air cooling pressure. Similar calculations were also performed for 2mm and 4mm thick couplings. Figure 3.19 shows the FE calculated history for the different coupling thickness in the inside end of butt joint. As shown in Figure 3.19, the temperature rise is faster for the 2mm thick coupling because it had the highest transmission resulting in the highest power reaching the absorber layer (black film). However, the difference in the maximum temperature between the 2 and 6mm thick coupling was 11°C at the end of the butt joint, which is not significant. Increasing the power or heating time would enable the formation of a complete butt weld even for the 6mm thick coupling.
Figure 3.17: 2D Circumferential Variation of Nu for Cross Flow of Air over a Cylinder

[27]
Figure 3.18: 2D- Axisymmetric Temperature Distribution for a Welded Sample Resulting from the Finite Element Analysis
Figure 3.19: Predicted Temperature History at the Inside End of the Butt Joint
3.5 Summary

1. The coupling thickness should exceed 5mm to insure pipe failure rather than coupling failure during tensile loading.

2. FE Analysis predicts that the maximum Von Mises stress is in the weld zone at the outer end of coupling. Generally, the maximum stress in the joint increased as the coupling thickness increased due to increasing stress concentration. However, the increase in stress is small and it is balanced by the need to minimize the potential for coupling failure.

3. For socket joint when evaluating the effect of coupling width it was that increasing the width decreased the stress level until it level off for widths of 54mm and higher. On the other hand, for combined socket and butt joint, the maximum stress level remains nearly constant for all coupling widths, showing that the coupling width has no impact on the joint strength if the butt joint can be fully obtained.

4. It was also shown that the temperature rise in the bottom of the butt joint was highest for the 2mm thick coupling. However, after 250s of heating the temperature for 2mm thick coupling was 11°C higher than for the 6mm coupling.
CHAPTER 4

EXPERIMENTAL STUDY OF IR ABSORPTION LAYER THICKNESS
AND COMPOSITION

4.1 Introduction

Several additives are used for the polymer to absorb the IR radiation. Generally, carbon black is most widely used and it absorbs nearly all wavelengths in the near IR range. In this study, the absorber black film that was placed at the interface was PE with a small amount of carbon black added (0.03-0.5% by weight). The IR Absorption in the black film depends on the thickness and carbon black content in the film. Therefore, experimental work was performed to investigate the effect of film thickness on absorption of IR radiation and to find out the concentration of carbon black needed to fully absorb the IR radiation.

4.2 Experimental Procedures

4.2.1 Preparation of Films with Different Thickness with 0.5 wt % Carbon Black

To produce film of different thickness, multiple layer of the film were stacked together and hot plate was pressed to form one thick film. Figure 4.1 shows the hot press, which was used to press the films. The given range of pressures was varied so that the film thickness could be varied. The films were pressed using a hot plate temperature of
240 °C for 10sec. Then the platens were cooled by the pressure was maintained until the film cooled to temperatures below about 50 °C. Films of six different thicknesses varying from 0.09 to 0.58mm were produced from 0.1mm initial thickness.

Figure 4.1: Experimental Setup for Fabricating Absorbing Black Film with Different Thickness

4.2.2 Preparation of Films with Different Carbon Black Content

It was also important to evaluate the effect of carbon content in the film on IR absorption and heating. To make films with different contents of carbon black, thin shavings of a natural HDPE, machined from the HDPE rod, were mixed with shavings of the black film (0.5% carbon content) in appropriate proportions. The mixture was placed in a hot plate with temperature of about 240°C and pressed for 10-20sec, and the forming
cycle was repeated 8-12 times to achieve a uniform dispersion of carbon in the film. Black films with ten different carbon black contents varying from 0.03 to 0.5% were made. The amount of energy generated in black films was evaluated by measuring the temperature of thermocouples that was placed on black films.

4.2.3 IR Absorption Measurements

Polyethylene pipe was partially sectioned and a hole of the same size as the sensor of power meter with radius of 0.9cm was machined. The power meter was placed in the sectioned pipe such that the sensor fit the hole in the pipe. The pipe was placed at the bottom of heating chamber. The black films with dimension of 2 ×2 cm were placed between the coupling and pipe, as shown in Figure 4.2. The film was kept 1.3cm from the lamp surface in the IR heating unit and the transmitted power was measured under each lamp at 75W and 50sec heating time.

In addition, thermocouple was placed on just below black films. The temperature of the thermocouple placed on films was also measured. The temperature was recorded with a computer-controlled data-acquisition system. The configuration of the assembly that includes the lamp, coupling, black film and thermocouple is shown in Figure 4.3.
Figure 4.2: Experimental Setup for Measurements of Transmitted Power for Different Film Thickness

IR lamp (75W per lamp, heating time of 50sec)

Heat-absorbing layer (black film)

6mm Coupling

Thermocouple

Figure 4.3: Configuration of the Lamp, Coupling, Black Film, and Power Meter and Thermocouple
4.3 Results and Discussions

4.3.1 Effect of Film Thickness on Heating Performance

Figure 4.4 shows the power transmission through the films with different thickness. As can be seen, all of the power was absorbed even for the thinnest film with thickness of 0.9mm. Figure 4.5 measured temperature on the back of the film as a function of thickness of the black film. The energy was assessed based on the temperature recorded. The 0.09-mm-thick black film reached 117°C, whereas the temperature of 0.19-mm-thick black film was only 107 °C. The temperature associated with the 0.29-mm-thick black film was only 97 °C and the temperature of 0.49-mm-thick black film was 92 °C. Based on these results, most of the energy absorption in the black film is complete in the 0.09-mm-thick layer. It was also demonstrated that thin black film did generate more internal heat.

4.3.2 Effect of Carbon Content on Heating Performance

Figure 4.6 demonstrates how the IR absorption depends on the content of the carbon black in the 0.09mm thick black film. As the carbon black content increases from 0.03% to 0.07%, by weight, the temperature in the black film continuously increases. On the other hand, the temperature did not change as the carbon black content increased above 0.07%. Therefore, carbon black content of 0.07% provides an almost perfect carbon black content level as contents above this amount did not produce higher heat energy in the absorbed layer. On the other hand, surface heating caused by carbon black may promote several undesired side effects. If all the energy is absorbed at the surface,
the energy density can be so high that the peak temperature can cause polymer degradation. Porosity is another undesired side effect for plastics. The vapor pressure of moisture in plastic solution is proportional to the samples temperature [28]. If the weld-line pressure is below the resulting vapor pressure, porosity will form. The generated porosity may reduce the weld strength. Excessive squeeze flow is the other undesired side effect for plastics. Higher temperatures can cause excessive squeeze flow of the melt because viscosity is inversely proportional to temperature. Excessive squeeze flow can cause undesired molecular alignment which is parallel to the weld joint. This type of molecular alignment can cause high flow induced residual stresses and it reduces the weld strength. Therefore, relatively low carbon black content of 0.07% would produce deeper and more uniform heating within the black film.
Figure 4.4: Transmission for Different Thickness of the Black Film
Figure 4.5: Temperature at the Back of Film as a function of Film Thickness (Carbon Content 0.5% by weight)
Figure 4.6: Temperature at the Back of Film as a function of Carbon Black Content

(0.09 mm thick film)
4.4 Summary

1. Transmission measurements show that all film thickness from 0.09mm and higher absorbed all of the IR energy.

2. Increasing the carbon black content above 0.07% by weight did not increase the back film temperature, indicating that 0.07% carbon black is the nearly ideal quantity to allow IR absorption through the film thickness (volumetric rather than just surface absorption). Increasing the carbon black content beyond this value results in more surface absorption and it can produce higher surface temperatures which may lead to polymer degradation, formation of porosity, and excessive squeeze flow.
5.1 Introduction

The heat transfer during combined socket and butt through transmission infrared welding occurs by radiation, convection, and conduction [29-31]. The infrared radiation passing through the surface of the coupling can be reflected at the surface of coupling and absorbed in the coupling thickness (see region A in Figure 5.1). The transmitted power through the semitransparent coupling is absorbed in the absorbing layer (region B), which includes carbon black. Some of the heat generated in the absorbing layer is conducted into the polyethylene pipe (region C). During radiation heat transfer, forced convection heat transfer caused by cool air is applied on the surface of the coupling and free convection heat transfer occurs along the inside of the pipe.

As shown in Figure 5.1, portions of the infrared radiation may be reflected, absorbed, and transmitted in region A. If we define the spectral irradiation \( G_\lambda \) (W/(m\(^2\) \( \mu \)m)) as the rate at which radiation of wavelength \( \lambda \) is incident on a surface per unit area of the surface and per unit wavelength, the amount of radiation on the coupling is given by the following [32]:

\[
G_\lambda = G_{\lambda, \text{ref}} + G_{\lambda, \text{abs}} + G_{\lambda, \text{tr}}
\]  

(5-1)
where the subscripts ref means reflected, abs means absorbed and tr means transmitted.

In general, the amount of absorption, reflection, and transmission depends on the surface conditions, the wavelength of the radiation, and the composition and thickness of the transparent medium.

![Figure 5.1: Heat Transfer Processes during Combined Socket and Butt through Transmission Infrared Welding for Semitransparent Medium](image)

Uniform cooling for all portions of the coupling surface is another important issue analyzed in this study because the temperature distribution on all sides of the weld zone should be uniform. Forced convection cooling on a circular cylinder in cross flow was considered and the cooling system in the heating chamber was experimentally evaluated and modified in order to provide uniform cooling over the overall joint area.
In addition, a 3-D FEA heat flow model for the socket and butt joint assembly for coupling with 6 mm thickness was developed. The internal heat generation rate in the coupling and absorbing layer were calculated based on experimentally measured IR transmission and absorption. In addition, an analytical solution for heat flow in the pipe was developed. Finally, experimental and theoretical evaluation of the cooling system was performed and the FE model and analytical models were compared with temperature measurements in the butt joint.

5.2 Theoretical Analysis

5.2.1 FEA Model

In order to model the temperature distribution in the butt joint, the experimental measurement of IR radiation absorption in the black absorbent film was needed. However, it is difficult to model the radiation heat transfer with absorptivity not equal to 1; therefore the radiation energy can be approximately included as an internal heat generation rate in the black film. As was described in Section 3.4.2, the internal heat generation rate was calculated based on measurement of the transmitted and absorbed power by black film for IR radiation passing through 6 mm thick coupling. As was discussed in Section 3.4.2, the internal heat generation in the black film was calculated by dividing the power absorbed in black film with its volume giving 86,000,000 W/m$^3$.

Figure 5.2 shows the 3D FEA model geometry for a socket and butt joint assembly with 6 mm thick coupling. As shown in Figure 3.14 in Section 3.4.2, the inner radius of pipe is 0.023mm and the outer radius of pipe is 0.029mm, the thickness of black
film is 0.1mm, and the radius of the coupling is 0.0351, the length of the pipe is 100mm, and the width of the coupling is 18mm.

The IR radiation absorbed in the coupling was also included in the model. The coupling was divided into six section each 1 mm thick and the IR absorption in each section was represented as internal heat generation as shown in Table 3.1 in Section 3.4.2. Also included in the model were the temperature-dependent material property data for high density polyethylene (see Table 3.2) and the initial temperature was set to 20°C.

Figure 5.2: 3D FEA Heat Flow Model for the Joint Assembly with 6 mm Thick Coupling

5.2.2 Analytical Model for Heat Flow in Pipe

A simplified analytical model can be used to predict the temperature distribution in the hollow pipe to determine the degree of butt welding that would develop as well as
to provide general understanding of the heat flow in the combined socket and butt welding process. The heat conduction from the black can be represented in the form of a heat flux on the outer surface of the pipe and on the inside of the pipe convection is considered. On the outer surface of the pipe it is assumed that a fraction (50% and 60%) of the energy absorbed and generated in a absorbing layer flows into pipe while the remaining fraction of the energy flows into the coupling. Therefore, it is possible to calculate the heat flux \( F_o \) from the IR absorption in the black film, which was measured experimentally.

For the model the polyethylene pipe has cylindrical shape having inner radius \( r_a \) and outer radius \( r_b \). Initially the pipe is at the ambient temperature \( T_a \), or \( T(r, 0) = T_a = 20^\circ C \). The boundary condition on the outer surface (at \( r=r_b \)) is the specified heat flux \( F_o \) due to conduction of heat from the black film. At the inner wall (\( r=r_a \)) convection with ambient air at temperature \( T_a \) is considered. This problem would be non-homogeneous because of the boundary conditions and it can be solved using superposition method. A mathematical description of this problem is shown in Figure 5.3.

The governing Equation for conduction in cylindrical coordinates can be simplified to the following assuming axi-symmetry, no variation in the z direction and no internal heat generation rate:
\[
\frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr} = \frac{1}{k} \frac{dT}{dt}
\]  
(5-2)

\[
\lambda w \frac{\partial T}{\partial r} = -F
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) = \frac{1}{k} \frac{\partial T}{\partial t}
\]

\[
T(r,0) = T_a
\]

\[
\lambda w \frac{\partial T}{\partial r} = h(T(r_a, \theta) - T_w)
\]

\[
r=0
\]

Figure 5.3: Mathematical Description for Heat Flow in Pipe

The boundary and initial conditions are

\[
\frac{\partial T}{\partial r} = \frac{h}{\lambda w} \left[ T(r_a, \theta) - T_w \right]
\]  
(5-3)

\[
\frac{\partial T}{\partial r} = -\frac{F_a}{\lambda w}
\]  
(5-4)

\[
T(r,0) = T_a
\]  
(5-5)
To solve this non-homogeneous problem it will be assumed that the solution for $T(r, \theta)$ can be written as follows [33]:

$$T(r,t) = a(r) + b(r,t) \quad (5-6)$$

Substituting this assumed equation into the partial differential Equation 5.2,

$$a''(r) + b_{rr} + \frac{1}{r}[a'(r) + b_r] = \frac{1}{k}b, \quad (5-7)$$

where $a'(r) = \frac{da}{dr}$, $a''(r) = \frac{d^2a}{dr^2}$, $b_r = \frac{\partial b}{\partial r}$, $b''_r = \frac{\partial^2 b}{\partial r^2}$, and $b_t = \frac{\partial b}{\partial t}$.

Substituting the assumed equation into the boundary condition at $r=r_a$ and $r=r_b$ gives,

$$\lambda_w [a'(r_a) + b_r(r_a, \theta)] = h[a(r_a) + b(r_a, \theta) - T_a]$$
$$\lambda_w [a'(r_b) + b_r(r_b, \theta)] = -F_o \quad (5-8)$$

Substituting the assumed equation into the initial condition gives,

$$a(r) + b(r,0) = T_a \quad (5-9)$$
Using the superposition approach we can solve for $a(r)$ and $b(r,t)$ separately and then superpose the solutions. Solving for $a(r)$ by rearranging the $a(r)$ terms from Equations 5-7 and 5-8 gives:

$$a''(r) + \frac{1}{r} a'(r) = 0$$  \hfill (5-10)

$$a'(r_a) = \frac{h}{\lambda_w^2} [a(r_a) - T_a]$$  \hfill (5-11)

$$a'(r_b) = -\frac{F_o}{\lambda_w}$$  \hfill (5-12)

Equation (5-10) may be solved as follows:

$$a'(r) = y$$

$$y' + \frac{1}{r} y = 0$$

$$y = e^{-ln r + C}$$

$$y = C_1 r^{-1}$$  \hfill (5-13)

Substituting Equation 5-12 into Equation 5-13 we can solve for $C_1$ giving,

$$C_1 = -\frac{F_o}{\lambda_w} r_b$$  \hfill (5-14)

Substituting Equation 5-14 into Equation 5-13 gives,
\[ y = -\frac{F_o}{\lambda_w} r_b r^{-1} = a'(r) \quad (5-15) \]

To obtain \( a(r) \) we integrate Equation 5-15

\[
\int \frac{da(r)}{dr} dr = \int -\frac{F_o}{\lambda_w} r_b r^{-1} dr
\]

\[ a(r) = -\frac{F_o}{\lambda_w} r_b \ln r + C \quad (5-16) \]

Combining Equations 5-11, 5-15 and 5-16 one can find \( C \), giving,

\[ a'(r_a) = -\frac{F_o}{\lambda_w} \frac{r_b}{r_a} = \frac{h}{\lambda_w} \left( -\frac{F_o}{\lambda_w} r_b \ln r_a + C - T_a \right) \]

\[ -\frac{F_o}{h} \frac{r_b}{r_a} = -\frac{F_o}{\lambda_w} r_b \ln r_a + C - T_a \]

\[ C = F_o r_b \left( \frac{\ln r_a}{\lambda_w} - \frac{1}{h r_a} \right) + T_a \quad (5-17) \]

To find \( a(r) \), substitute Equation 5-17 into Equation 5-16, giving

\[ a(r) = F_o r_b \left( -\frac{\ln r}{\lambda_w} + \frac{\ln r_a}{\lambda_w} - \frac{1}{h r_a} \right) + T_a \quad (5-18) \]
Next, let's solve for \( h(r,t) \) by separating and rearranging the terms for \( h(r,t) \) from Equations 5-6 to 5-8, giving

\[
b_{rr} + \frac{1}{r} b_r = \frac{1}{k} b_t \tag{5-19}
\]

\[
b_r(r_a, \theta) = \frac{h}{\lambda_w} b(r_a, \theta) \tag{5-20}
\]

\[
b_r(r_b, \theta) = 0 \tag{5-21}
\]

Assuming \( h(r,t) = R(r)\tau(t) \) to separate the variables and substituting into Equations 5-19 to 5-21, gives

\[
\dot{R}(r)\tau(t) + \frac{1}{r} R'(r)\tau(t) = \frac{1}{k} R(r)\dot{\tau}(t) \tag{5-22}
\]

\[
R'(r_a)\tau(t) = \frac{h}{\lambda_w} R(r_a)\tau(t) \tag{5-23}
\]

\[
R'(r_b)\tau(t) = 0 \tag{5-24}
\]

The only way for a function of \( r \) to always be equal to a function of \( t \) is for each function to be equal to the same constant. If this constant is called \(-\lambda^2\), then Equation 5-22 above can be written as two ordinary differential equations by dividing by \( R(r)\tau(t) \) and setting it equal to the constant, giving

\[
\frac{\dot{R}(r)}{R(r)} + \frac{1}{r} \frac{R'(r)}{R(r)} = \frac{1}{k} \frac{\dot{\tau}(t)}{\tau(t)} = -\lambda^2
\]
\[ R^\prime(r) + \frac{1}{r} R^\prime(r) + \lambda^2 R(r) = 0 \]
\[ \tau(t) = e^{-kt} \quad (5-25) \]

The differential equation with respect to \( r \) is multiplied by \( r^2 \) to take the form of Bessel’s equation,

\[ r^2 R^\prime(r) + r R^\prime(r) + r^2 \lambda^2 R(r) = 0 \quad (5-26) \]

whose solution is obtained from the general Bessel equation [34-35] as follows:

\[ R(r) = A J_\alpha(\lambda r) + B Y_\alpha(\lambda r) \quad (5-27) \]

Where \( J_\alpha(\lambda r) \) is the zero order of the Bessel function of the first kind and \( Y_\alpha(\lambda r) \) is the zero order of the Bessel function of the second kind. From Equations 5-23 and 5-24, we get the following:

\[ R^\prime(r_a) = \frac{h}{\lambda_w} R(r_a) \quad (5-28) \]
\[ R^\prime(r_b) = 0 \quad (5-29) \]

Differentiating Equation 5-27, gives

\[ R^\prime(r) = -A \lambda J_1(\lambda r) - B \lambda Y_1(\lambda r) \quad (5-30) \]
Where \( J_1(\lambda r) \) is the first order of the Bessel function of the first kind and \( Y_1(\lambda r) \) is the first order of the Bessel function of the second kind. Substituting Equation 5-30 into Equation 5-28, gives

\[
R'(r_a) = -A \lambda J_1(\lambda r_a) - B \lambda Y_1(\lambda r_a) = \frac{h}{\lambda_w} A J_o(\lambda r_a) + \frac{h}{\lambda_{w}} B Y_o(\lambda r_a)
\]

\[
A \left[ \frac{h}{\lambda_w} J_o(\lambda r_a) + \lambda J_1(\lambda r_a) \right] + B \left[ \frac{h}{\lambda_w} Y_o(\lambda r_a) + \lambda Y_1(\lambda r_a) \right] = 0 \quad (5-31)
\]

Substituting Equation 5-30 into Equation 5-29, gives

\[
R'(r_b) = -A \lambda J_1(\lambda r_b) - B \lambda Y_1(\lambda r_b) = 0
\]

\[
A J_1(\lambda r_b) + B Y_1(\lambda r_b) = 0 \quad (5-32)
\]

The arbitrary constants \( A \) and \( B \) can be found from Equations 5-31 and 5-32 using determinants giving,

\[
A = \begin{vmatrix}
0 & Y_1(\lambda r_b) \\
0 & \frac{h}{\lambda_w} Y_o(\lambda r_a) + \lambda Y_1(\lambda r_a)
\end{vmatrix} \begin{vmatrix}
J_1(\lambda r_b) & Y_1(\lambda r_b) \\
J_o(\lambda r_a) + \lambda J_1(\lambda r_a) & \frac{h}{\lambda_w} Y_o(\lambda r_a) + \lambda Y_1(\lambda r_a)
\end{vmatrix}
\]

\[
\frac{h}{\lambda_w} J_o(\lambda r_a) + \lambda J_1(\lambda r_a) \quad \frac{h}{\lambda_w} Y_o(\lambda r_a) + \lambda Y_1(\lambda r_a)
\]

(5-33)
Both A and B would be zero unless the determinant in the denominator is zero. Since \( A=B=0 \) is trivial solution to the problem without engineering usefulness, we must set the denominator determinant equal to zero. Thus

\[
\begin{vmatrix}
J_1(\lambda a) & 0 \\
\frac{h}{\lambda w} J_o(\lambda r_a) + \lambda J_1(\lambda r_a) & 0 \\
\frac{h}{\lambda w} J_a(\lambda r_a) + \lambda J_1(\lambda r_a) & Y_1(\lambda r_a)
\end{vmatrix} = 0
\]

Therefore, the eigenvalues are determined from Equation 5-35, which can be written as

\[
E(\lambda) = \text{Eigenvalue}
\]

and we can find the zeros for \( r_a=0.023 \) and \( r_b=0.029 \). The curve is shown in Figure 5-4 and the first ten eigenvalues have been found using MathCAD. Therefore, Equation 5-27 can be written as eigenfunction with eigenfunction \( n \) being written as follows:

\[
R_n(r) = A_o J_o(\lambda_n r) + B_o Y_o(\lambda_n r)
\]

or,

\[
R_n(r) = A_o \left[ J_o(\lambda_n r) + \frac{B_n}{A_n} Y_o(\lambda_n r) \right]
\]
\[ \lambda_1 = 125.636 \quad \lambda_2 = 564.004 \quad \lambda_3 = 1069 \quad \lambda_4 = 1586 \quad \lambda_5 = 2106 \]
\[ \lambda_6 = 2627 \quad \lambda_7 = 3149 \quad \lambda_8 = 3672 \quad \lambda_9 = 4195 \quad \lambda_{10} = 4718 \]

Figure 5.4: Plot of Equation (4-34) Showing the First Ten Zeros

It is convenient to redefine the eigenfunction as a function, \( C_k(\lambda_n r) \)

\[
C_k(\lambda_n r) = J_k(\lambda_n r) + \frac{B_n}{A_n} Y_k(\lambda_n r)
\]  

(5-38)
The eigenfunction may be rewritten as

\[ R_n(r) = A_n C_\nu(\lambda_n r) \quad (5-39) \]

The ratio \( \frac{B_n}{A_n} \) in Equation 5-37 may be obtained from Equation 5-32,

\[ \frac{B_n}{A_n} = \frac{J_1(\lambda_n r_b)}{Y_1(\lambda_n r_b)} \quad (5-40) \]

Finally, the solution for \( b(r,t) = R(r)\tau(t) \) from Equations 5-25 and 5-39 can be written as a summation of all the eigenfunctions:

\[ b(r,t) = \sum_{n=1}^{\infty} A_n C_\nu(\lambda_n r) \exp(-k\lambda_n^2 t) \quad (5-41) \]

Using the initial condition by setting \( t=0 \) in Equation 5-41 gives,

\[ b(r,0) = \sum_{n=1}^{\infty} A_n C_\nu(\lambda_n r) \quad (5-42) \]

To determine the \( A_n \), multiply both sides of Equation 5-42 by \( r C_\nu(\lambda_n r)dr \) and integrating from \( r=r_a \) to \( r=r_b \) to obtain
\[
\int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr = \int_{r_a}^{r_b} \sum_{n=1}^{\infty} A_n C_o(\lambda_n r)rC_o(\lambda_m r)dr \tag{5-43}
\]

For \( n \neq m \) we may write

\[
\int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr = A_m \int_{r_a}^{r_b} rC_o^2(\lambda_m r)dr \tag{5-44}
\]

\[
A_m = \frac{1}{\int_{r_a}^{r_b} rC_o^2(\lambda_m r)dr} \int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr = \frac{\int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr}{\frac{1}{2} [r_b^2 C_1^2(\lambda_m r_b) - r_a^2 C_1^2(\lambda_m r_a)]} \tag{5-45}
\]

From Equations 5-9 and 5-18, \( b(r,0) \) is written as

\[
b(r,0) = T_a - a(r) = F_a r_b \left( \frac{1}{\lambda_w} \ln r + \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) \tag{5-46}
\]

To solve \( \int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr \) from Equation 5-44 by substituting Equation 5-46 into it,

\[
\int_{r_a}^{r_b} rC_o(\lambda_m r)b(r,0)dr = \int_{r_a}^{r_b} rC_o(\lambda_m r)F_a r_b \left( \frac{1}{\lambda_w} \ln r + \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right)dr
\]
\[ F_o r_b \int_{r_a}^{r_b} r C_o (\lambda_m r) \left( \frac{1}{\lambda_w} \ln r + \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) dr \]

\[ = F_o r_b \int_{r_a}^{r_b} r C_o (\lambda_m r) \left( \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) dr + \int_{r_a}^{r_b} r C_o (\lambda_m r) \frac{1}{\lambda_w} \ln rdr \]

\[ = F_o r_b \left( \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) \int_{r_a}^{r_b} r C_o (\lambda_m r) dr + F_o r_b \frac{1}{\lambda_a} \int_{r_a}^{r_b} r C_o (\lambda_m r) \ln rdr \]

\[ = - \frac{F_o r_b \left( \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right)}{\lambda_m} [r_b C_1 (\lambda_m r_b) - r_a C_0 (\lambda_m r_a)] + F_o r_b \frac{1}{\lambda_w} \int_{r_a}^{r_b} r C_o (\lambda_m r) \ln rdr \]

\[ (5-47) \]

In order to solve \( \int_{r_a}^{r_b} r C_o (\lambda_m r) \ln rdr \), we will use integration by parts \( \int uv = uv - \int vdu \).

Let \( u = \ln r \) and \( dv = r C_o (\lambda_m r) dr \), then \( v = \frac{1}{\lambda_m} r C_1 (\lambda_m r) \) \( du = \frac{1}{r} dr \), giving

\[ \int_{r_a}^{r_b} r C_o (\lambda_m r) \ln rdr = \ln r \frac{1}{\lambda_m} r C_1 (\lambda_m r) - \int \frac{1}{\lambda_m} r C_1 (\lambda_m r) \frac{1}{r} dr \]

\[ = \ln r \frac{1}{\lambda_m} r C_1 (\lambda_m r) - \frac{1}{\lambda_m} \int C_1 (\lambda_m r) dr \]

\[ = \ln r \frac{1}{\lambda_m} r C_1 (\lambda_m r) - \frac{1}{\lambda_m} \lambda_m \left( - \frac{1}{\lambda_m} C_o (\lambda_m r) \right) \]

\[ = \frac{1}{\lambda_m} r \ln r C_1 (\lambda_m r) + \frac{1}{\lambda_m^2} C_o (\lambda_m r) \]

\[ (5-48) \]
Therefore, the solution for \( \int_{r_a}^{r_b} r C_o(\lambda_m r) \ln r \, dr \) will be written as

\[
\int_{r_a}^{r_b} r C_o(\lambda_m r) \ln r \, dr = \frac{1}{\lambda_m^2} r_b \ln r_b C_1(\lambda_m r_b) + \frac{1}{\lambda_m^2} C_o(\lambda_m r_b) - \frac{1}{\lambda_m^2} r_a \ln r_a C_1(\lambda_m r_a) - \frac{1}{\lambda_m^2} C_o(\lambda_m r_a)
\]

(5-49)

Therefore, Equation 5-49 may written as

\[
\int_{r_a}^{r_b} r C_o(\lambda_m r) b(r,0) \, dr = \frac{F_o r_b}{\lambda_m} \left( \frac{1}{h r_a} - \frac{1}{\lambda_m} \ln r_a \right) - \frac{1}{\lambda_m} \left[ r_b C_1(\lambda_m r_b) - r_a C_1(\lambda_m r_a) \right] + F_o r_b \frac{1}{\lambda_m}
\]

\[
\times \left[ \frac{1}{\lambda_m} r_b \ln r_b C_1(\lambda_m r_b) + \frac{1}{\lambda_m^2} C_o(\lambda_m r_b) - \frac{1}{\lambda_m} r_a \ln r_a C_1(\lambda_m r_a) - \frac{1}{\lambda_m^2} C_o(\lambda_m r_a) \right]
\]

(5-50)

Substituting (4-50) into (4-45), we obtain

\[
A_m = \frac{F_o r_b}{\lambda_m} \left( \frac{1}{h r_a} - \frac{1}{\lambda_m} \ln r_a \right) \left[ r_b C_1(\lambda_m r_b) - r_a C_1(\lambda_m r_a) \right] + \frac{F_o r_b}{\lambda_m} \frac{1}{\lambda_m}
\]

\[
\times \left[ \frac{1}{\lambda_m} r_b \ln r_b C_1(\lambda_m r_b) + \frac{1}{\lambda_m^2} C_o(\lambda_m r_b) - \frac{1}{\lambda_m} r_a \ln r_a C_1(\lambda_m r_a) - \frac{1}{\lambda_m^2} C_o(\lambda_m r_a) \right]
\]

(5-51)

We can write the following cylindrical functions:
Substituting this cylindrical function into Equation 5-51 we get,

\[
A_m = \frac{F_o r_b \left( \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) \times [-r_a C_1 (\lambda_m r_a)]}{\frac{1}{2} \lambda_m \left[ -r_a^2 C_o^2 (\lambda_m r_a) \right]} + \frac{F_o r_b}{\lambda_w} \times \\
\left[ \frac{1}{\lambda_m^2} C_o (\lambda_m r_b) - \frac{1}{\lambda_m} r_a \ln r_a C_1 (\lambda_m r_a) - \frac{1}{\lambda_m^2} C_o (\lambda_m r_a) \right]
\]

The solution

Equation 5-41 then becomes (using n for the dummy summation index),

\[
b(r, \theta) = \sum_{n=1}^{\infty} C_o (\lambda_n r) \exp (-k \lambda_n^2 \theta) \times \\
\frac{F_o r_b \left( \frac{1}{hr_a} - \frac{1}{\lambda_w} \ln r_a \right) \times [-r_a C_1 (\lambda_m r_a)]}{\frac{1}{2} \lambda_m \left[ -r_a^2 C_o^2 (\lambda_m r_a) \right]} + \\
\frac{F_o r_b}{\lambda_w} \times \\
\left[ \frac{1}{\lambda_m^2} C_o (\lambda_m r_b) - \frac{1}{\lambda_m} r_a \ln r_a C_1 (\lambda_m r_a) - \frac{1}{\lambda_m^2} C_o (\lambda_m r_a) \right]
\]

Finally, substituting Equations 5-18 and 5-41 into Equation 5-6 to get the final solution: 86
Where $F_o$ is heat flux, $r_a$ is inner radius, $r_b$ is outer radius of pipe, $r$ is position, $T$ is temperature, $t$ is time, $T_o$ is the initial temperature of the joint assembly. $\lambda_w$ is thermal conductivity, $k$ is thermal diffusivity, $h$ is convection heat coefficient, $\lambda$ is eigenvalues obtained from Equation 4-35, and $C_i(\lambda_m r_a)$, $C_o(\lambda_m r_a)$, $C_o(\lambda_m r_b)$ is cylindrical functions obtained from Equation 5-52.

5.2.3 Convection Cooling

The flow characteristics for flow across cylinders is discussed in Section 3.4.2. Figure 5.5 shows experimental data for the local values of the Nusselt Number ($Nu_\theta$) at any angular ($\theta$) position around the cylinder for free-stream Reynolds numbers between 70,000 and 220,000. At $Re < 100,000$, separation occurs near the 80-deg position. At higher Reynolds numbers, where the laminar boundary layer changes to turbulent before
separation occurs, the Nu$_\theta$ curve has two minimum points— the first at the transition to turbulence and the second at the separation point, resulting in Nu$_\theta$ having the lowest value between $80^\circ$ and $100^\circ$. Beyond this point Nu$_\theta$ increases because of the increasing turbulence in the wake as shown in Figure 5.6 [36]. The goal in this work was not to consider the details of the cross flow around the cylinder and its effects on convection but rather to estimate an average value for the convective heat transfer coefficient to use in the models.

Figure 5.5: 2D Circumferential Variation of the Nusselt Number for Cross Flow of Air over a Cylinder (Taken from Ref. 36)
Figure 5.6: Boundary Layer Formation and Separation on a Circular Cylinder in Cross Flow [36]

5.3 Experimental Procedures

5.3.1 Cooling System

Uniform cooling for all portions of the coupling surface was another important issue analyzed in this study. Cooling air was provided through the air inlet T-valve connected to the cooling system hose which was positioned in the bottom of the heating chamber as discussed in Chapter 2 (see Figure 2.4). In order to observe if the air cooling is uniformly provided, thermocouples (36-gauge chromel alumel), which were connected to the computer-controlled data-acquisition system, were secured with Kapton® pressure-sensitive adhesive tape on the different positions at the top, bottom, left, and right
surfaces of the coupling. The temperature distribution on the four surfaces of the coupling was measured for a heating time of 320 sec, lamp power of 90 W per lamp and cooling air pressure of 0.6205MPa (90 psi).

5.3.2 Temperature Measurements in Weld Zone

Temperature monitoring is an important part of this study since the temperature data gathered from different regions of the weld is a key to understanding IR absorption and heat conduction in the joint. Thermocouples from the computer-controlled data-acquisition system were imbedded into the two regions. Thermocouple #1 was fixed at the middle of the butt joint and thermocouple #2 was fixed at the bottom of the butt weld (thermocouple locations are shown in Figure 5.7. The temperature distribution was recorded during welding cycles to observe heating dynamics in the weld zone. The temperature distribution was recorded for a lamp power of 80 W per lamp, 250 sec heating time, and 0.6205MPa (90 psi) cooling air pressure.

5.4 Results and Discussion

5.4.1 Experimental and Theoretical Evaluation of Cooling System

Figure 5.8 shows temperature history at the top, bottom, left and right surfaces of coupling. It was observed that cooling air was not uniform and the temperature at the right and left surfaces of the coupling was much higher than the upper and bottom surfaces of coupling. As a result, the two sides of the coupling melted and deformed during welding. This agrees with the observation in Section 5.2.3 that $N_u$ has the lowest
value at the position between 80° and 100°, which correspond to the left and right surfaces of the coupling.

![Temperature-Monitoring Diagram](image)

**Figure 5.7: Temperature-Monitoring Diagram**

In order to provide uniform cooling over the whole coupling, both side portions of the T-valve were cut for better cooling of the sides and an additional outlet was made in the center of T-valve for better cooling of the bottom (see Figure 2.6(a)). The cooling air was also discharged by air outlet made on upper portion of IR unit as shown in Figure 2.6(b). In order to prevent overheating in the two side portions of the coupling due to non-uniform cooling, the power output of the three lamps on each of the two sides was reduced to 70W. As a result, the temperature distribution was almost uniform, except for the bottom portion of the coupling as shown in Figure 5.9. The bottom portion had
excessive cooling due to airflow directed on the coupling's bottom surface from a hole on the center of the T-valve which results in poor heat conduction to the butt joint in bottom portion. Rather than reduce the cooling of the bottom portion of the coupling the power for a single lamp in the bottom portion was changed from 100W to 150W. This resulted in more uniform cooling as shown in Figure 5.10. It was noted that the power output and heating time would depend on air cooling pressure, and the cooling pressure should be increased as much as possible along with maximizing the power output to reduce the heating time.

Figure 5.8: Temperature History on Four Surface Portions of Coupling (320sec heating time, 90-W power, 0.6205MPa (90 psi) air pressure)
Figure 5.9: Temperature History on Four Surface Portions of Coupling after Changing the Lamp Power Level on Side Portions to 70W and on Bottom Side to 150W (320-s heating time, 90-W power, 0.6205MPa (90psi) air pressure, 6-mm-thick coupling)
Figure 5.10: Temperature History Temperature Distribution on Four Surface Portions of Coupling after Changing the Power Level to 150W in Bottom Portion and to 70W in Side Portion
5.4.2 Comparison of FEA Model with Temperature Measurements

Figure 5.11 shows the experimentally measured temperature history under 80 W per lamp power output, 250 sec heating time, and 0.6205MPa (90 psi) cooling air pressure. In Figure 5.11, thermocouple #1 was fixed at the middle of the butt joint and thermocouple #2 was fixed at the end of the butt weld (thermocouple locations are shown in Figure 5.7).

Figure 5.12 shows contour plots for 3D temperature distribution for a welded sample resulting from the finite element analysis. The computer program for the heat transfer for the combined socket and butt TTIR welding of polyethylene pipe is shown in Appendix A. The maximum temperature (179°C) occurred at the socket weld zone. The maximum temperature of 181°C for 2D axisymmetric model in Chapter 3.4.2 is in good agreement with maximum temperature of this 3D model. Figure 5.13 shows the data for the temperature history in the middle of butt joint and the bottom of butt joint from the FEA modeling and it shows 10~15°C difference from the experimental results as shown in Figures 5.11 and 5.13. It may be because the convection coefficient was theoretically approximated and the temperature dependent material properties applied in FEA modeling was not consistent to actual material properties.
Figure 5.11: Experimental Temperature History in the Joint under 80W Lamp Power and 90psi Cooling Air Pressure
Figure 5.12: Contour Plots for 3D Temperature Distribution Resulting from FEA Numerically Generated using FEA Model for the Socket and Butt Joint Assembly
Based on the experimental and numerical results, it was indicated that the temperature at the middle and end of the butt weld for a heating time of 250 sec was 100 °C, 90 °C respectively, which is below melting temperature (125 °C) of high density polyethylene. It also shows that the temperature at the butt joint increases almost linearly as the heating time increases. Therefore, one needs to increase the lamp power level or heating time to achieve a butt weld. From this numerical analysis, the welding parameter such as lamp power and heating time can be determined and set so as to completely weld the bottom of the butt joint.
Figure 5.14 shows the FEA predictions of temperature distribution for PATH-AB in the butt joint, which is shown in Figure 5.12. The total incident heat flux from the surface layer of the black film into pipe is due to heat transfer from the black film into pipe and it is governed by conduction. The power absorbed in the black film is an important factor in the formation of the butt joint. However, excessive lamp power can cause an increase in the surface temperature of coupling, resulting in the deformation of the coupling and distortions in the joint. In order to keep the temperature of the coupling surface below 120°C, an increase in air-cooling pressure/flow should be accompanied by increases in lamp power level.

It was also demonstrated that the temperature from the socket weld zone to the end of butt weld zone decreases as the distance increases and the temperature at the socket joint area reacts almost immediately to changes in intensity of IR radiation. It was also observed that the temperature difference (81°C) between the socket weld zone and the end of butt weld zone under heating time of 250 sec was very significant because of the low thermal conductivity of polyethylene. Accordingly, these results indicated that temperature of socket weld area can be expected to be about 206°C to obtain at least the melting temperature of HDPE (125°C) at the end of butt weld area. It was also noted that temperature readings of the end of the butt joint can be used to provide the criteria to set the power level and heating time.
5.4.3 Analytical Model Evaluation of Temperature Distribution in Pipe and Comparison with Experiments

As discussed earlier and shown in Equation 5-55, the analytical solution can be thought of having two parts; a steady state portion and a transient portion that decays to zero as time (t) becomes large[37]. To be able to develop this analytical model, it was necessary to ignore the details of the heat generation in the black film and cooling of the coupling. Therefore, it was assumed that 50% and 60% of the energy absorbed and generated in a absorbing layer flows into butt joint as a heat flux ($F_0$), which was calculated based on the experimentally measured absorption in the black film. The heat flux for 60% of the energy going into the pipe can be calculated as follows:
Assuming 60% heat flux flows into pipe

\[ F_o \times 2\pi \times r_m \times w = 0.6 \times W = 0.6 \times (w \times 2\pi \times r_m \times t \times Q) \]

\[ F_o = \frac{0.6 \times w \times 2\pi r_m \times t \times Q}{2\pi \times r_in \times w} = 0.6 \times t \times Q = 0.6 \times 0.0001m \times 86000000 \frac{W}{m^3} = 5160 \frac{W}{m^2} \]

(5-56)

Therefore, it is possible to estimate the temperature profile within the butt joint area by using Equation 5-55 derived through analytical modeling. Figures 5.15 and 5.16 show the temperature history in the pipe assuming 50%, and 60% of the energy absorbed and generated in a absorbing layer flows into butt joint, respectively. The MathCAD file for the analytical solution is shown in Appendix D. The temperature history in the butt joint for the heat flux accounting for 60% of the energy flowing into the butt joint had better agreement with the experimental results than that of 50%. Figures 5.17 and 5.18 show comparison of temperature history in the middle and end of butt joint for FEA model, analytical model, and experimental measurements showing generally good agreement. For the end of the butt joint there is greater deviation between the experimental results and predictions probably due to estimations in the temperature dependent material properties and convective heat transfer coefficient.
Figure 5.15: Analytical Prediction of Temperature History for a Welded Sample Resulting from Mathematical Modeling (assuming 50% heat flux flows into pipe)

Figure 5.16: Analytical Prediction of Temperature History for a Welded Sample Resulting from Analytical Modeling (assuming 60% heat flux flows into pipe)
Figure 5.17: Comparison of Temperature History in the Middle of Butt Joint for FEA Model, Analytical Model, and Measurements
Figure 5.18: Comparison of Temperature History in the End of Butt Joint for FEA Model, Analytical Model, and Measurements
5.5 Summary

1. Based on the experimental and numerical result, it was found that the temperature at the end of the butt weld for a heating time of 250 sec was 100 °C, 90 °C respectively, which is below melting temperature (125 °C) of polyethylene and the results show that the temperature at the butt joint increases almost linearly as the heating time increases.

2. In order to allow for modeling refinement, 2D finite element analysis axisymmetric model and 3D model were compared to the experiment results, showing good agreement.

3. The temperature distribution from the socket weld zone to the end of the butt weld zone decreases as the distance increases and resulting in a temperature difference of 81 °C between the socket weld zone and the end of butt weld zone under heating time of 250 sec, power of 90 W per lamp, and cooling pressure of 0.6205MPa (90 psi) due to the low thermal conductivity of polyethylene.

4. The analytical model that was developed can be used for predicting temperature distributions for a hollow pipe welded using transmission infrared welding with convection boundary conditions and would be useful for better understanding of the heat transfer. By using above equation, we can determine the melt layer thickness and estimate the size of the heat-affected zone and the type of morphology that may be expected. In addition, the temperature distribution may be used for estimating thermal expansion and distortion and the thermal stress and residual stress levels in the welded parts in the future.
CHAPTER 6

COMBINED SOCKET AND BUTT WELDING OF POLYETHYLENE GAS PIPE

6.1 Introduction

Combined socket and butt pipe welding is a process for joining pipes using through transmission infrared welding technique. The combined socket and butt TTIR technique could be used for welding polyethylene pipes for the water and natural gas utilities. The combined socket and butt welding process can use a coupling socket with absorbing layer such as polyethylene with a small amount of carbon black added. Socket coupling can be made in sizes ranging from 16 mm to 710 mm. The black film is inserted between the pipe and coupling. This technique can make a lap joint between the inner surface of coupling and outer surface of the pipe and produce a butt joint between the pipes so that a combined socket and butt joint could be made at the same time, resulting in a stronger weld.

One major difference between combined socket and butt TTIR and electro-fusion joining techniques is that combined socket and butt TTIR welding can use less expensive coupling as compared to electro-fusion welding. Combined socket and butt TTIR welding process is much simpler than hot plate butt welding with less expensive welding unit. In addition, non destructive evaluation may be possible through observation of the
formation of the inner weld bead in the butt joint (please note that access to the inner weld bead may not always be possible or it may require special equipment). Therefore, it is expected that combined socket and butt TTIR welding could be extensively used for a wide range of industries in the future. This chapter describes experimental studies of the welding of medium density polyethylene pipes and evaluation of the weld strength through various destructive tests. From the FEA and analytical models along with previous experimental work it was determined that the near optimum welding conditions have been identified to be power of 90W per lamp (150W for bottom lamp and 70W for side lamps), heating time of 320sec, forced cooling air pressure of 0.6205MPa (90 psi). Joints made under these conditions were evaluated through tensile tests and other various destructive tests.

6.2 Welding Procedures

6.2.1 Materials

The pipes that were used in this study were made from yellow high density polyethylene (HDPE) and had a 60-mm OD and a standard dimension ratio (SDR—specifies the minimum OD divided by the minimum wall thickness of the pipe) of 11. The material properties for these gas pipes are given in Table 6.1 [38].

<table>
<thead>
<tr>
<th>Pipe Type</th>
<th>Outside Diameter of pipes(mm)</th>
<th>Wall Thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Melt Flow Index(g/10min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50A PE pipes (Yellow color)</td>
<td>60.0</td>
<td>6</td>
<td>0.933-0.939</td>
<td>0.15-0.4</td>
</tr>
</tbody>
</table>

Table 6.1: Typical Material Properties for 50A PE Pipes
Couplings (18-mm wide × 6-mm thick) with a 60.5-mm inner diameter (ID) were machined from natural HDPE rods (density: 0.937kg/cm²). The ID of the couplings was 0.5-mm larger than the OD of the pipes to allow room for the insertion of absorbing layer (black film) between the pipe and the coupling. The geometry and dimensions for the coupling are given in Chapter 3 (see Figure 3.14).

Sheets of PE-absorbing film with a 0.5% by weight carbon black level, 0.1-mm thickness, and length 10-mm longer than the inner ID of coupling were cut into 18-mm-wide stripes. The width was the same as the width of the coupling to prevent melting due to direct heating by IR. They were prepared by being placed in a hot press where the platens were heated to a temperature of 240°C. After heating, the film was placed between two cold Al plates and pressed several times for cooling, to minimize shrinkage of the black film during the welding process.

6.2.2 Welding Trials

Two pieces of approximately 150-mm-long pipes were squared with a woodworking band saw (Model JWBS-14CS) and the pipe alignment was checked. Then, the coupling made from a natural HDPE was positioned above the center of the joint. Lines were marked at those positions on the pipes in order to secure the center of the coupling at the joint area. The black film was inserted between the pipe and coupling and then the assembly was mounted in the IR welding unit. The diameter of the pipes and clamps was slightly different, because the clamps were made for 63-mm-diameter pipe. Therefore, 1-mm-thick Scotch Brand® tape was rolled around the pipe to compensate for the difference in diameters between the pipes and the clamps. The pipes
were then secured with the clamping device. The joint area of the assembly was centered in the middle of the IR welding unit. The experimental setup is shown on Figure 6.1. The welding parameters varied in this process were lamp power, heating time, and cooling air pressure. The amount of radiant energy was controlled by adjusting the power controller in the IR welding unit. Increasing power levels allowed for reduced heating time and for heat conduction into the butt joint to melt material over the whole joint area. Therefore, most of the welds were conducted at relatively high output power levels of 80-90 W per lamp.

Figure 6.1 Experimental Setup for Combined Socket and Butt Welding
During initial experiments, the cooling air pressure was adjusted, depending on the lamp power output and heating time. Much effort was expended to determine the most appropriate cooling pressure (0.6205MPa) with 90-W per lamp power. As the power output and heating time were increased, air pressure was also increased. During the heating phase, air-cooling was necessary to prevent the melting and deformation of the coupling due to the absorption of IR energy. Maintaining the structural integrity of the coupling was also necessary to develop the weld pressure in the lap joint by thermal expansion of the film, outer surface of the pipe and inner surface of the coupling.

6.3 Joint Evaluation

For the many welding trials with different welding parameters, destructive tests were conducted to assess the optimum weld parameters. Four destructive tests were conducted; sustained pressure test, crush test, three bend test, and tensile test. Four specimens for the tensile tests and two specimens for the bend tests were cut from each welded sample. The specimens for tensile tests were taken from every 90 degrees of the pipe circumference. The specimens for bend tests were taken from every 180 degrees of the pipe circumference.

6.3.1 Tensile testing

While conducting the tensile test, the ASTM D 638 standard procedure [39] was generally followed; however, the specimen geometry per this standard is not appropriate for the butt/lap joint. Following ASTM D 638 for joint quality assessment of the hot-plate-welded PE, dumbbell specimens are made to reduce the weld area so that the failure
happens in the weld zone, not in the parent material. The use of such specimens with reduced weld area in the tensile test is recommended by a number of European standards, DVS 2203 [40] and ISO standards for the cases when the failure is not achieved in the weld area. However, in case of the butt and lap joint specimens, through initial tensile tests during weld trials, it was demonstrated that the specimens with no formation of an inner bead showed weakening of the weld area, and thus it was not necessary to reduce the weld area to create the failure in the weld zone. Therefore, Phase 1 was conducted with specimens with no reduction at the joining area. The specimen dimensions are detailed in Figure 6.2. Four welded specimens which were located in the upper, bottom, right, and left portions were cut perpendicular to the welded joint with the bond area being at the middle of the strap (Figures 6.3). Tests were performed at room temperature, using a crosshead speed of 20 mm/min on an Instron model 4468 tensile testing machine. In these specimens, the failure location and mode were noted and for each specimen with failure in the weld area, maximum failure load, energy-to-break, and extension-at-break were measured.
Figure 6.2: Geometry and Dimensions for Tensile Test Specimen for Phase 1

Figure 6.3: Tensile Test Specimens before Testing
In order to provide a more accurate joint quality assessment of the welds with the formation of the inner bead, Phase 2 testing was conducted. This testing was expected to be more sensitive than other short-term destructive testing methods. In the specimens used for this tensile test, a hole was made to initiate failure in the weld zone, not in the parent material. The specimen dimensions are detailed in Figure 6.4 and typical specimens before testing are shown in Figure 6.5. The tensile tests conducted for specimens with a reduced weld area are more sensitive in distinguishing between welds made under standard and nonstandard conditions than other short-term destructive testing methods.

![Figure 6.4: Geometry and Dimensions for Tensile Specimen for Phase 2](image-url)
6.3.2 Sustained Pressure Test

According to the ASTM D1599 [41], for pipe sizes of 150 mm (6 inches) or less, the specimen length between the end closures shall be not less than five times the outside diameter of the pipe. Based on the standard, the specimen length used in this test was 254 mm (10 inches), which is more than five times the outside diameter of the pipe. The test was conducted at 25°C. Figure 6.6 shows the sustained pressure test apparatus. The end of the specimen was sealed using an aluminum plate with rubber sheet. In order to introduce the compressed air into the specimen through a polyethylene tube (1/8 in), a hole was machined at the end of the specimen. The compressed air pressure was set by the pressure regulator which was connected between the air supply and the specimen and the pressure was measured using a pressure gage. The air pressure was increased uniformly and continuously until the internal pressure reached 0.9997 MPa (145 psi),
which is 2.5 times the maximum usage pressure (0.3999 MPa) and then the pressure was maintained for one hour. After one hour, the sample was checked for leaks in the joint area using soap spray. According to the ASTM D1599, it is considered as a failure if there is any pressure loss and leakage at the weld zone. Leakage in the vicinity of the end caps on the specimen was ignored. Figure 6.7 shows the experimental set up.

Figure 6.6: Sustained Pressure Test Apparatus
6.3.3 Crush Test

The crush test is used to evaluate the joint strength for the electro-fusion PE fittings. It was carried out based on ASTM F1055 [42] except that the specimen was loaded using an Instron tensile testing machine instead of vise jaws. The whole welded pipe was tested instead of testing two section cut from the welded sample. Figure 6.8 shows the crush test arrangement. The center of the load was applied 32mm (1¼ inches) away from the outer weld zone as shown in Figure 6.9(a). To simulate loading by a vise jaw, a rectangular steel plate was used to apply the load.

The load was applied on the specimen until the inner walls of the pipe met as shown in Figure 6.9(b). According to ASTM F1055 “standard specification for
eletrofusion type polyethylene fittings for outside diameter-controlled polyethylene pipe and tubing”, separation of the coupling from the pipe at the fusion interface was considered a failure. Minor separation at the lap-joint area of up to 15% of the fusion length was acceptable and not defined as a failure. The load-displacement curve was recorded to see if any separation at the fusion interface occurred.

Figure 6.8: Experimental Setup for Crush Test
Figure 6.9: Typical Deformation for Crush Test
6.3.4 Bend Test

While conducting the bend test, CEN standard prEN 12814-1 [43] procedures was followed, except that the specimen dimensions were changed as shown in Figure 6.10. The schematic diagram of the test is shown in Figure 6.11. In order to carry out this test, four 20mm wide sections were cut perpendicular to the welded joint with bond area being at the middle of the strap. Tests were performed at room temperature, using a ram rate of 100mm/min. The tests were terminated at a maximum bend angle, $\alpha$, of 80°. For each test, it was observed if fracture occurred in the weld zone.

![Figure 6.10: Specimen Dimensions for Three-Point Bend Test](image-url)
Figure 6.11: Schematic Diagram for Three-Point Bend Test
6.4 Results and Discussions

6.4.1 Welding Trials

During the welding cycle, an inner bead is formed in the butt joint. The formation of the bead was monitored visually. Visual observation of the inner bead forming in the butt joint provided evidence of uniform fusion taking place between the pipes. Therefore, the formation of an inner bead provided the criteria for setting the optimum power level and heating time. Excessively high power caused an increase in the surface temperature of the coupling, resulting in the deformation of the coupling around 120 °C as shown in Figure 6.12.

Figure 6.12: Coupling Deformation due to Excessive Temperature
In order to maintain the temperature of the coupling surface below 120°C, it was necessary to adjust the cooling air pressure when the lamp power output was increased. Figure 6.13 shows the cross sections of the combined socket and butt joint and it shows non-uniform melting between the pipes in the butt joint. The low heat generated by the absorbing layer in the lap joint caused non-uniform heating of the butt joint, resulting in no melting of the inner wall of the butt joint.

In case that excessive heating time was applied, even though the welds had acceptable appearance all around the pipe, cracks occurred on the inner surface of the butt joint as can be seen in Figures 6.14 and 6.15. Excessive heating caused over melting of the lap-joint surface of the pipes and thus it caused the coupling to overheat and collapse and displace into the interface of the butt joint, resulting in cracks in the butt-joint interface.

It was observed that a minimum inner bead started to form when the temperature of the bottom of the butt joint was about 10°C lower than melting temperature of HDPE (125°C). Figure 6.16 shows the formation of inner bead for different heating times. A full inner bead was formed at the heating times of 320 s and 350 s for 90W, but the specimens made under 380 s and 420 s heating times with this power output had cracks at the butt joint interface due to excessive heating. Based on these results the pipes could be evaluated by examination of the inner bead and formation of cracks. Figure 6.17 shows a good joint made without deformation of the coupling, no cracks in the butt joint, and with minimum inner bead. It was made under 90W per lamp power, 320 s heating time, and 0.6205MPa (90psi) cooling air pressure. Figure 6.18 shows fairly uniform appearance all around the welded pipe without significant deformation of the coupling. It
was indicated that observation of the inner bead could be used as a monitoring tool during the joining process and for the purposes of joint inspection. In production observation of the inner bead would likely require a video camera to be inserted into the pipe.

Figure 6.13: Specimen made under 90W, 260sec (bottom of butt joint is not welded)
Figure 6.14: Specimen made under 90W, 380s (This joint was overexposed to the heating; material has melted excessively and displaced from the interface to the bottom of the butt joint)

Figure 6.15: Specimen Made under 90W, 420sec (Crack occurred in the butt joint interface due to excessive heating time)
Figure 6.16: Formation of Inner Bead for Different Heating Times

Figure 6.17: A Good Joint Made with Formation of Inner Bead around Butt Joint
6.4.2 FEA Stress Models for Combined Socket and Butt Joint

Finite element stress analysis was performed for combined socket and butt joints with 18mm coupling width and 6mm thickness. Figures 6.19-6.22 show the contour plot for stress distribution in the weld zone for socket joint, socket and 1/3 butt joint, socket and 2/3 butt joint, and socket and complete butt joint for an internal pressure of 0.4MPa (58psi) and the tensile load of 3.447MPa (500psi), 6.895MPa (1000psi), and 10.34MPa (1500psi) applied. As shown in Figure 6.23 the maximum stress in the weld zone decreases as the fraction of the butt joint is increased. It is also indicates that a full and uniform butt joint should be considered more important as the tensile loading is increased. It is concluded that the visual observation of the formation of an inner bead can be used as a criteria for setting the optimum welding conditions.
Figure 6.19: Stress Distributions in the Socket Weld Zone for 18mm Coupling Width Under Internal Pressure of 0.4MPa (58psi) and Tensile Loading of 6.895MPa (1000psi)
Figure 6.20: Stress Distributions in the Socket and 1/3 Butt Joint for 18mm Coupling Width under Internal Pressure of 0.4MPa (58psi) and Tensile Loading of 6.895MPa (1000psi)
Figure 6.21: Stress Distributions in the Socket and 2/3 Butt Joint for 18mm Coupling Width under Internal Pressure of 0.4MPa (58psi) and Tensile Loading of 6.895MPa (1000psi)
Figure 6.22: Stress Distributions in the Socket and Complete Butt Joint for 18mm Coupling Width under Internal Pressure of 0.4MPa (58psi) and Tensile Loading of 6.895MPa (1000psi)
6.4.3 Joint Evaluation

Tables 6.2-6.4 shows the tensile test results for specimens made under power outputs of 80 and 90 W per lamp. The results show that the specimens made with insufficient or excessive heating time failed through the butt joint or the lap joint (see Figure 6.24). Figure 6.25 shows the tensile test results for specimens made with 560-s heating time with 80-W per lamp power, and specimens made with 320, 350, 380, and 410 s heating time using 90-W per lamp power; these specimens did not fail through the weld zone.
For the specimens that did not fail through the joint, it was necessary to use the phase 2 tensile testing with the reduced area at the weld through the introduction of a hole. Figure 6.26 shows the tensile test specimens after Phase 2 testing. As expected, due to the introduction of the hole all specimens failed through the weld area. The results for all conditions are shown in Figure 6.27, 6.28, and 6.29. It appears that the welding condition of Sample 1 from Table 6.4 would be the best welding condition among the four welding conditions tested. It was indicated that the quality of Sample 1 was better compared to other samples because there was a significant increase in failure load, extension at break, and energy to break compared to the other samples. The energy to break values for Samples 2, 3, and 4 were lower than for Sample 1 due to non-uniform heating of the butt joint due to the deformation of the coupling by excessive heating.

A possible reason for the energy to break value for the right portion of the Sample 1 being lower than that of Sample 2 could be because the temperature distribution in the absorbing layer along the circumference of the pipe was not completely consistent. This would tend to produce less melt at the right side of the pipe, so that the energy to break value recorded for the right side of Sample 1 would be lower than that of Sample 2.
<table>
<thead>
<tr>
<th>Sample</th>
<th>POSITION Around Weld</th>
<th>Welding Condition</th>
<th>Failure Load (kN)</th>
<th>Extension at Break (mm)</th>
<th>Energy to Break (J)</th>
<th>Failure Mode</th>
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</tr>
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Table 6.2: Tensile Test Results (Phase 1) at 90 W
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<th>Energy to Break (J)</th>
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<td>No failed at joint area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom (270 degrees)</td>
<td></td>
<td></td>
<td></td>
<td>No failed at joint area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left (270 degrees)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>Top (0 degrees)</td>
<td>80 W, 610 s</td>
<td></td>
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</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Bottom (270 degrees)</td>
<td></td>
<td></td>
<td></td>
<td>No failed at joint area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left (270 degrees)</td>
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<td></td>
<td></td>
<td>No failed at joint area</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Top (0 degrees)</td>
<td>80 W, 660 s</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
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Table 6.3: Welding Conditions and Tensile Test Results (Phase 1) at 80 W
<table>
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<tr>
<th>Sample</th>
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<th>Welding Condition</th>
<th>Failure Load (KN)</th>
<th>Extension at break (mm)</th>
<th>Energy to break (J)</th>
<th>Failure Load</th>
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<td>Top (0 degrees)</td>
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<td>Ductile</td>
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<tr>
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<td>15.9</td>
<td>16.9</td>
<td>Ductile</td>
</tr>
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<td>Bottom (180 degrees)</td>
<td></td>
<td>1.4</td>
<td>18.3</td>
<td>20.2</td>
<td>Ductile</td>
</tr>
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<td>Left (270 degrees)</td>
<td></td>
<td>1.2</td>
<td>20.7</td>
<td>18.1</td>
<td>Ductile</td>
</tr>
<tr>
<td>2</td>
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<td>90W, 350sec</td>
<td>0.9</td>
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<td>Ductile</td>
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<td>1.0</td>
<td>13.7</td>
<td>12.0</td>
<td>Ductile</td>
</tr>
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<td></td>
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<td></td>
<td>1.0</td>
<td>10.7</td>
<td>14.3</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>Left (270 degrees)</td>
<td></td>
<td>1.2</td>
<td>14.0</td>
<td>17.0</td>
<td>Ductile</td>
</tr>
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<td>0.7</td>
<td>12.3</td>
<td>6.8</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
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<td>10.1</td>
<td>11.1</td>
<td>Ductile</td>
</tr>
<tr>
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<td>13.5</td>
<td>5.3</td>
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</tr>
<tr>
<td>4</td>
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<td>1.5</td>
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<td>1.0</td>
<td>8.2</td>
<td>6.1</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
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<td>6.4</td>
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<tr>
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<td>0.9</td>
<td>7.2</td>
<td>0.9</td>
<td>Ductile</td>
</tr>
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</table>

Table 6.4: Welding Conditions and Tensile Test Results (Phase 2)

Figure 6.24: Ductile Failure Mode of Specimens after Tensile Testing (All specimens made with heating time below 320sec for 90 W failed through the joint)
Figure 6.25: Tensile Test Specimens after Testing (All specimens made with heating time over 320-s and 90-W per lamp power did not fail at the joint.)

Figure 6.26: Tensile Test Specimen after Testing (Phase 2)
Figure 6.27: Tensile Failure Load for Phase 2 Testing
Figure 6.28: Extension at Break for Phase 2 Testing
Figure 6.29: Energy to Break for Phase 2 Testing
For the sustained pressure and crush tests no differentiation between welding conditions was possible because all the specimens passed these tests. In the crush test no separation of the welded region was observed. A typical load displacement curve is shown in Figure 6.30. The load reached about 10 kN when the inner walls of the pipe met. For all four samples we did not observe any sudden increase of displacement or decrease of load that can be cause by separation in the welded region. Visual observation of the sample following testing also showed that no separation occurred.

![Load-Displacement Curve for Crush Test](image)

**Figure 6.30**: Load-Displacement Curve for Crush Test
Figure 6.31 shows the geometry of the 3D FEA modeling of the crush test which was done to compare to the experimental results. The welded joint pipe is symmetric so that half of the sample was modeled and symmetric boundary condition was applied at the end of the pipe in the axial direction (z-direction). The displacement load was applied 32mm away from the outer weld zone.

Non-linear elastic-plastic finite element analysis was used to determine the stress distribution and deformation in the lap joint area for a typical crush test. As shown in Figure 6.32, maximum Von Mises stress was observed at the outer fusion interface among weld zone, which is the region where separation of the coupling from the pipe is likely. The stress at the outer fusion interface was 18.62MPa (2700psi) as shown in the contour plot in Figure 6.32. It indicates that any fracture or separation at the lap-joint area would not occur since the yield stress of the HDPE is 17.65MPa (2560 psi) and the calculated stress is just slightly higher. Therefore, the FEA results are in good agreement with the experiments indicating that no separation would occur. Both the FEA model and the experimental results show that the yield stress will occur at the outer fusion interface thereby decreasing the bending stiffness but any fracture at the weld zone would not occur if the lap joint is made under the near optimum welding condition.

Typical bend test specimens after testing are shown in Figure 6.23. None of the specimens failed or showed any cracking in the weld joint area when the specimens were taken to a maximum bend angle of 160 degrees. From these results it appears that no failure in any specimen made under the near optimum welding condition was not generated. These results suggest that the bend test can be used for evaluating the joint performance for the combined socket and butt joint in PE pipes.
Figure 6.31: FEA Model with Applied Displacement Load at 32mm away from the Outer Weld Zone
Figure 6.32: Non-Linear Elastic-Plastic Finite Element Analysis for Stress Distribution in the Joint for a Typical Crush Test
Figure 6.33: Three-Point Bend Test Specimens after Testing
6.5 Summary

1. Combined socket and butt TTIR welding method for polyethylene gas pipe has been shown to make strong joints.

2. By varying the welding parameters such as lamp power, heating time, and cooling pressure, near optimum welding conditions may be obtained.

3. The formation of an inner bead provides the criteria for setting the optimum power level and heating time.

4. Excessive heating caused over heating and melting of the coupling resulting in collapse of the coupling and cracks in the butt-joint interface.

5. In order to maintain the temperature of the coupling surface below 120°C, it is necessary to adjust the cooling air pressure when the lamp power output is increased.

6. Under the welding conditions of a 90-W per lamp power, 320-s heating time, and 90-psi cooling air pressure, highest joining strength is achieved without deformation of the coupling, no cracks in the butt joint, and with minimum inner bead.

7. Sustained pressure test has been conducted under the internal pressure of 0.9997MPa (145 psi), which is 2.5 times the maximum usage pressure, showing that no leakage occurred for all joints.

8. Similarly, for the crush tests no separation of the welded region was observed. This was in agreement with FEA modeling of the crush test.
9. For the bend test, none of the specimens failed or showed any cracking in the weld joint area when the specimens were taken to a maximum bend angle of 160 degrees.

10. The destructive testing methods used in this study for polyethylene gas pipes can be developed as standard test procedures for evaluating joint quality when combined socket and butt joints are produced.
CHAPTER 7

COMBINED SOCKET AND BUTT TTIR WELDING OF PVDF PIPE

7.1 Introduction

Polyvinylidene fluoride (PVDF) offers the stable characteristics of a fluoropolymer in addition to abrasion resistance, mechanical strength and toughness, an inherent high purity, chemical compatibility, UV and radiation resistance, and low permeability. As compared to polyethylene or polypropylene, PVDF also has good stability at high temperatures up to 166 °C. Therefore, PVDF has been widely used as a material for pipes in many industries such as semiconductor, pulp and paper, pharmaceutical, nuclear waste processing, chemical processing, food processing, and laboratory facilities. The semiconductor and pharmaceutical industries especially need to use high purity materials such as PVDF.

For a long time, PVDF pipe has been welded by a various welding method such as hot plate welding, electro-fusion welding, and infrared welding. However, the demand for high purity water flowing through the pipes requires removal of inner bead to prevent accumulation of particles or growth of bacteria on the bead. Therefore, there is a need to modify existing methods or to develop new methods that allow for high purity and elimination of the inner weld bead. Combined socket and butt joint may offer one such
welding process. Based on recent research [18, 44] in through-transmission infrared (TTIR) welding techniques, the feasibility study of combined socket and butt joints for PVDF pipes was conducted using TTIR method. However, it was demonstrated that it is very difficult to completely make the butt weld between the pipe ends. In this study, the welding conditions for TTIR process have been experimentally evaluated with 63mm outer diameter PVDF pipes. In order to evaluate the joint quality, welding parameters such as lamp power, heating time, and cooling air pressure were evaluated. This study provides experiment data necessary for optimization of the socket and butt joint for different sizes of PVDF pipes in addition to the 63mm size studied here. This work also indicated how uniform heating in the butt joint area without deformation of the coupling was critical with regards to the joint quality and cycle time and how the joint quality could also be initially verified by visual observation of the formation of an inner bead. Much effort was devoted to making weld with full butt joints but without the inner bead which could be caused by contamination of flowing liquid in the pipe.

7.2 Welding Procedures

7.2.1 Material

The pipes that were used in this study were made from natural HP PVDF and had an outer diameter (OD) of 63mm and wall thickness of 4mm. They were AGRU products, made from SUPER PROLINE brand HP PVDF and the material properties are given in Table 7.1. Couplings (18mm wide and 4mm thick) with inner diameter (ID) of 63.5mm were machined from PVDF rods with natural color. The ID of the couplings was
0.5mm bigger than the outer diameter of pipes to allow room for the absorbing layer (black film) between pipe and the coupling.

Sheets of PVDF absorbing film with 0.5% carbon black content, a 0.1mm thickness, and length 10mm longer than the inner ID of coupling were cut into 18mm wide stripe. This width was the same as the width of the coupling to prevent the melting due to direct heating by IR. They were hot pressed at a temperature of 300°C. After heating, the film was placed between two cold aluminum plates and pressed several times for cooling, in order to prevent shrinkage of the black film during the welding process.

7.2.2 IR Transmission Measurements

The transmission of infrared power passing through coupling is very important issue for the combined socket and butt TTIR welding. Therefore, the transmission and absorption is important to determine the welding conditions such as heating time and cooling pressure on the surface of coupling. The IR power transmitted through couplings of different thickness (1,-2-, 3- 4-, 5- and 6-mm) was measured. A Model FM Coherent Field Master power/energy meter with power sensor was used to measure the transmission. The experimental setup for measuring the transmission is shown in Figure 7.1.

The transmission experiments were performed using 90 W per lamp power output and 40 s heating time. Initially, the power that reached the power sensor without the coupling was measured. Then, the sensor of the power meter was covered with PVDF plates (3- ×3-cm) of different thickness (1-, 2-, 3-, 4-, 5-, and 6m) and the power reaching the sensor was measured. The plate was made of the same material as the couplings.
<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
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<td>%</td>
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<td>ASTM D-638</td>
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<td>ASTM D-2240</td>
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<td>ASTM D-3418</td>
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<td>psi</td>
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<td>Limiting Oxygen Index (%)</td>
<td>%</td>
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<td>Flame Spread</td>
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<td>ASTM F-1673</td>
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Table 7.1: Physical Properties of PVDF Pipe
7.2.3 Welding Trials

Two pieces of pipes, approximately 150mm long, were squared with a woodworking band saw (Model JWBS-14CS) and the pipe alignment was established using Widos butt welding machine. Much effort was made to exactly align the pipe surfaces because alignment of the pipes was critical to prevent a gap in the butt joint and to prevent the black film from being displaced into the inner wall of pipe and become a possible contamination source. Then, the coupling made from a natural PVDF was positioned above the center of the joint. Lines were marked on the pipes at those positions in order to locate the center of the coupling over the joint area. The black film was inserted between the pipe and coupling and then the assembly was mounted in the IR welding unit. The joint area of the assembly was centered in the middle of the IR welding unit. The experimental set up is shown on Figure 7.2. The welding parameters varied in this process were lamp power, heating time, and cooling air pressure.

Figure 7.1: Experimental Setup to Measure Transmission for PVDF Coupling
The amount of radiant energy was controlled by adjusting the power controller in IR welding unit. Increasing power level allowed for reduced heating time and for heat conduction into the butt joint to melt the material over the whole joint area. Therefore, most of the welds were conducted at relatively high output power level of 90W.

To make beadless joints, which is very important for transportation of high purity water and other liquids, a silicon balloon (shown in Figure 7.3) was inserted into the pipe and Kapton® pressure-sensitive adhesive tape was rolled up on the silicon tube in order that the joint area is smoothly formed. It was located just below the center of the joint and the pressure controller used to adjust the air pressure in the balloon. Significant effort was made to set up appropriate inner air pressure. The system and experimental set for beadless welding of PVDF pipe is shown in Figures 7.4 and 7.5.

![Experimental Setup for Combined Socket and Butt Joint for PVDF Pipe](image)

**Figure 7.2: Experimental Setup for Combined Socket and Butt Joint for PVDF Pipe**
Figure 7.3: Silicon Tube and Pressure Controller for Beadless Welding of PVDF Pipe

Pressure.

Figure 7.4: Silicon Tube System for Beadless Welding of PVDF Pipe
Joint Evaluation

Tensile tests were conducted with several weld trials with different welding parameters. Based on the European standards, DVS 2203 and ISO standards, a hole was made in the center of weld zone to initiate the failure in the weld zone. The specimen in the test was made with cross-sectional area of about 20mm by 8mm as shown in Figure 7.6. Figure 7.7 shows the typical specimens before testing. Two welded specimens were cut perpendicular to the welded joint with the bond area being at the middle of the strap. The specimens for tensile tests were taken from every 90 degrees of the pipe circumference. Tests were performed at the room temperature, using a crosshead speed of 20mm/min on the Instron (model # 4468) tensile testing machine. The failure location
and mode were noted and for each specimen with failure in the weld area, maximum failure load, energy-to-break, and extension-at-break were measured.

![Diagram](image)

Figure 7.6: Geometry and Dimensions for Tensile Specimen for Phase 2

![Image](image)

Figure 7.7: Tensile Test Specimens before Testing (natural PVDF pipe)
7.4   Results and Discussions

7.4.1   IR Transmission Measurements

The power transmission was found to be 42.6-, 39.2-, 36.1-, 33.2-, 29.6-, and 27.2% of the input power for the 1-, 2-, 3-, 4-, 5-mm-, and 6-mm thick coupling. Figure 7.8 shows the transmission as a function of PVDF coupling thickness. Figure 7.9 shows the comparison of transmission between PVDF and PE coupling. The transmission of PVDF coupling was lower than that of PE coupling but the transmission of PVDF decreases more slowly than that of PE. Therefore, it is indicates that the absorption of PVDF is lower than that of PE coupling. Thus, the air cooling pressure on the surface of PVDF coupling could be decreased compared with that used for PE.

7.4.2   Heating Process Evaluation and Monitoring

First, it was critical to have sufficient heating to generate melting in the bottom of the butt joint. Figure 7.10 shows the experimentally measured temperature history for 90 W per lamp power output and 0.4137MPa (60 psi) cooling air pressure. It shows that 90 W per lamp power output and 210 s heating time were sufficient to generate melting (175°C) at the butt joint region. It was observed that the minimum inner bead started to form when the temperature of the bottom of the butt joint was about 10°C lower than melting temperature of PVDF (175°C). A full inner bead was formed for a heating time of 210 sec with 90 W per lamp power. Excessively high power output caused an increase of the surface temperature of coupling, resulting in the deformation of the coupling around 170 °C (Figure 7.11). In order to maintain the temperature of the coupling surface
below 170°C, it was necessary to adjust the cooling air pressure when the lamp power output was increased. Excessive heating also caused collapse of the coupling. In cases when excessive heating around the joint was made, the black film in lap joint between coupling and pipe was discolored into a golden yellow color. Visual observation of forming of the inner bead of the butt joint and discoloration of the black film of the lap joint helped identify conditions for uniform fusion taking place in joint area. Figure 7.12 show an example of insufficient heating resulting in non-uniform heating of the butt joint and no weld forming near the bottom of the joint.

![Transmission for Different Thickness of PVDF Coupling](image)

Figure 7.8: Transmission for Different Thickness of PVDF Coupling
Figure 7.9: Comparison of Transmission between PVDF and PE Coupling
Figure 7.10: Experimental Temperature Distribution under Welding Condition of 90-W Lamp Power, 60-psi Cooling Air Pressure
Figure 7.11: Coupling Deformation due to Excessive Temperature

Figure 7.12: Specimen Made under 90 W, 190-s (This joint was insufficiently heated; bottom of butt joint not welded and inner bead of butt joint is not formed)
During initial experiments, the cooling air pressure was adjusted, depending on the lamp power output and heating time. Much effort was expended to determine the most appropriate cooling pressure (0.4137MPa) with 90-W per lamp power. As the power level and heating time increased, it was necessary to increase the air pressure. During the heating phase, cooling air was necessary to prevent the melting and deformation of the coupling due to the absorption of IR energy.

During the welding cycle, different air pressures were applied to the silicon balloon, which was pressed against the inner wall of the pipe in order to prevent formation of the inner bead. Excessive air pressure in the silicon balloon caused the cross sectional area of the pipe to be reduced because it excessively pressed the weld area during heating process in addition to removing the inner bead. Figures 7.13 and 7.14 shows the cross section of socket joint area made under different air pressures of 0.2413MPa (35psi) and 0.3103MPa (45psi) in silicon balloon. The weld sample made under air pressure of 0.3103MPa (45psi) showed the most serious reduction of cross sectional area. On the other hand, Figure 7.15 shows the cross section of a good joint without excessive heating and with air pressure of 0.1724MPa (25psi) in silicon balloon. Figure 7.16 shows the inside of the pipe for a good joint with no reduction of cross section of weld area and no visible inner bead when using 0.1724MPa (25psi) air pressure in the silicon balloon. Figure 7.17 shows uniform outer appearance all around the pipe made under near optimum welding conditions of 90W per lamp power, 210 s heating time, 0.4137MPa (60psi) air cooling pressure, and 0.1724MPa (25psi) silicon balloon air pressure. It shows no deformation of coupling and no discoloration of the black film in the lap joint.
Figure 7.13: Specimen Made under 90W per lamp power, 230 s heating time, and 0.2413MPa (35psi) Silicon Air Pressure

Figure 7.14: Specimen Made under 90W per lamp power, 230 s heating time, and 0.3103MPa (45psi) Silicon Air Pressure
Figure 7.15: Cross Section of a Good Joint Made under 90W per lamp power, 210 s heating time, and 0.1724MPa (25psi) Silicon Air Pressure

Figure 7.16: Inner Appearance of a Good Joint under 0.1724MPa (25psi) Air Pressure in Silicon Tube (Inner bead was removed and cross-section area was not reduced)
Figure 7.17: Uniform Appearance All around the Pipe (4mm thick coupling, 90 W per lamp power, 210 s heating time, 0.4137MPa (60 psi) cooling air pressure, 0.1724MPa (25psi) air pressure in silicon tube

7.4.3 Joint Evaluation

Tensile test was first conducted with specimens with no reduction in the joining area. The specimens made with 190-s, 210-s, and 230-s heating time using 90-W lamp power did not fail through the weld zone but in the pipes as can be seen in Figure 7.18. Figure 7.19 shows the tensile test specimen with the reduced joint area after testing. As expected, due to the reduced area all specimens failed in the weld area. From Figures 7.20-7.22, it appears that the welding condition of 90-W per lamp power and 210-sec heating time would be an the best welding condition among those evaluated because there is showed a significant increase in energy to break and a slight increase in both the failure load and the extension at break.
Weld Line
(Bond line is the butt area could not be detected by visual observation)

Figure 7.18: Tensile Test Specimens Made under Heating Time of 210sec and 90 W Lamp Power

Figure 7.19: Tensile Test Specimens after Testing
Figure 7.20: Tensile Failure Load with Regard to Different Heating Time
Figure 7.21: Extension at Break with Regard to Different Heating Time
Figure 7.22: Energy to Break with Regard to Different Heating Time
7.5 Summary

1. The combined socket and butt TTIR welding for PVDF pipe is easier than PE pipe because lower air cooling pressure could be applied to prevent melting of PVDF coupling due to lower absorption in PVDF.

2. Excessive heating around the joint made the black film discolor into a golden yellow color. Visual observation of forming of the inner bead of the butt joint and discoloration of the black film of the lap joint provided indicators for appropriate welding conditions.

3. During the welding cycle, air pressure of 0.1724MPa (25psi) was applied to a silicon balloon, which was pressed against the inner wall of the pipe in order to prevent formation of the inner bead. Excessive air pressure in silicon tube caused reduction of the cross section area of pipe that could reduce the joining strength.

4. Combined socket and butt welding method for PVDF for high purity water quality polyethylene has been shown to successfully make strong joint without inner weld bead to prevent water contamination.

5. Under the welding conditions of a 90W per lamp power, 210 s heating time, 0.4137MPa (60psi) cooling air pressure, and 0.1724MPa (25 psi) silicon balloon pressure it was possible to achieve the highest joining strength without deformation of coupling, no discoloration of the black film, and elimination of the inner bead.
CHAPTER 8

FEASIBILITY STUDY FOR COMBINED SOCKET AND BUTT WELDING OF POLYETHYLENE GAS PIPES USING LASER SOURCE

8.1 Introduction

A laser heat source has been used for welding materials that need high energy density heat input. While laser welding has been experimented with for many years in polymer welding, actual industrial use came about more recently due to the availability of low cost laser diodes decreases [45]. As with IR heating, laser radiation is absorbed by some materials and converted into heat energy. Most of lasers used in the polymer joining are in the visible or infrared portion of the electromagnetic spectrum. Due to its coherency characteristic, the beam has very small divergence and can be transmitted over long distances through mirrors or fiber optics with minimal loss of beam quality [46].

Diode lasers or semiconductor lasers are commonly used in polymer joining process [47]. The beam is in visible or near infrared range and it can be transmitted through fiber optics. Laser diode welding systems are compact and cost effective and they can include stacking of diode lasers to achieve high power levels. The wavelength can be optimally designed for specific applications and the typical wavelengths are in the range of 808 to 940 nm with additional wavelength lasers being developed. However, the
beam quality for laser diodes is not as good as that of solid state lasers, such as Nd: YAG and Fiber lasers.

Nd: YAG and Fiber laser are ones of the most popular solid state lasers which are commercially available [48]. The beam quality of Nd: YAG and Fiber lasers is excellent and it can be used where beam quality is critical. The wavelength of Nd: YAG laser is 1064nm, which is within the near infrared region. The Fiber laser has similar wavelength to Nd: YAG, but it varies depending on amount of doped medium. Due to its excellent beam quality, it can be more focusable than diode laser and it can be used for precision welding. In this experiment, Nd: YAG laser has been selected for the feasibility test. Due to limitation of available power (50watt), only spot welding tests were performed to determine feasibility only.

8.2 Experimental Procedures

8.2.1 Experimental Setup

A diode pumped Nd: YAG laser, Tornado Laser (TN-50) by Spectra Physics was used for the feasibility tests. The system can generate a maximum power of 50watt and it can be operated in either CW (continuous wave mode) or pulsed mode (up to 80 kHz). The detail specification is summarized in Table 8.1. As shown in Figure 8.1 [49], the system is composed of power supply unit, laser head, beam delivery system, and work table. The raw beam was expanded and defocused on the surface of coupling to control beam diameter and thus adjust heating area. The total distance between the focus lens and the base frame was set at 215mm and the distance between focal spot and the surface of the coupling, or the defocus length, was set to 30 mm and 45 mm. Through initial
experiments, the spot size was varied to find suitable beam diameter, which was then
fixed at 10mm.

<table>
<thead>
<tr>
<th>Type</th>
<th>Nd:YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>TN-50</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1064 nm</td>
</tr>
<tr>
<td>Power</td>
<td>&gt;35W@10kHz</td>
</tr>
<tr>
<td>Pumping</td>
<td>By Diode Laser (808nm)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Random</td>
</tr>
<tr>
<td>Pulse width</td>
<td>120nm @10kHz</td>
</tr>
<tr>
<td>M²</td>
<td>max 15</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Single hot to 80kHz</td>
</tr>
</tbody>
</table>

Table 8.1: Characteristics of Diode Nd:YAG Laser

![Experimental Setup for Nd-YAG Laser](image)

Figure 8.1: Experimental Setup for Nd-YAG Laser
8.2.2 IR Transmission Measurements

The laser power should be transmitted to the absorbing black film as efficiently as possible without heat loss such as absorption by the coupling and reflection on the surface of coupling. The laser power amount transmitted through different thickness couplings (1,-2-, 3- 4-, 5- and 6-mm) was measured. A Model FM Coherent Field Master power/energy meter with power sensor was used to measure the power of the Nd: YAG laser source. As shown in Figure 8.2, initially, the laser power that reached the power sensor without coupling was measured and then the power was measured after the sensor was covered with different thickness (1, 2, 3, 4, 5, and 6mm) HDPE plates (3-×3-cm). The experiment was conducted at 10-s heating time and power outputs of 15W, 20W, and 25W.

8.2.3 Spot Welding Test

In this experiment, only feasibility tests were conducted due to limitation of available power (50watt) so that only spot test was performed. First, a small piece of the black film was inserted between the pipe and coupling and then the assembly was placed on the working table with the joint area being at the center of the defocused laser beam (see Figure 8.3). All experiments were performed using CW mode and the welding parameters varied in this process were defocus distance, laser power, and heating time. Most of the welds were conducted at relatively high output power levels of 35-40 W.

During initial experiments, the defocused distance was adjusted, depending on the laser power output and heating time. The defocused distance was important to prevent
burning of black film and to produce as large a weld zone as possible. Once the power output and defocused distance were set up then the heating time was varied.

Figure 8.2: Experimental Setup to Measure Transmission of Polyethylene Coupling

Figure 8.3: Experimental Setup for Combined Socket and Butt joint
8.3 Results and Discussions

8.3.1 IR Transmission Measurements

The experimental results for transmission at 15-, 20-, and 25W are shown in Table 8.2 and the average transmission was found to be 64-, .52-, 41-, 32-, 25- , and 17% for the 1-, 2-, 3-, 4-, 5-mm-, and 6-mm thick coupling. It was interesting to observe that the transmission of 6mm thick coupling for Nd: YAG laser source was much lower than that of the Infrared lamp as show in Figure 8.4.

<table>
<thead>
<tr>
<th>Coupling Thickness (mm)</th>
<th>Measured Power (watt)</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 watt</td>
<td>20 watt</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>1</td>
<td>64%</td>
<td>64%</td>
</tr>
<tr>
<td>2</td>
<td>52%</td>
<td>53%</td>
</tr>
<tr>
<td>3</td>
<td>41%</td>
<td>40%</td>
</tr>
<tr>
<td>4</td>
<td>32%</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>6</td>
<td>18%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Table 8.2: Transmitted Power for Different Thickness of Couplings
Figure 8.4: Transmission for PE Coupling for IR Lamp and Nd:YAG Laser
8.3.2 Spot Welding Test

During spot welding experiments, heating times were varied under fixed settings of defocus distance and laser power level, as shown in Table 8.3. As shown in Figure 8.5, for a defocused distance of 30mm the black film was overheated resulting in a hole because the power density was too high so that even laser powers of 35W and heating time of 5sec resulted in overheating. Figure 8.6 shows that a gap developed at the interface between the black film and pipe as the black film decomposed. Changing the defocused distance to 45mm, resulted in reducing the power density sufficiently to melt the black film. As the heating time increases, a joint had formed between the surface of the pipe and the coupling, and the black film that melted in was displaced into butt joint area as shown in Figure 8.7 (heating time of 110sec, defocused distance of 45mm, and laser power of 35W). This was probably due to the high level of power at the center of the beam resulting in more significant melting in the center and the pressure forcing the melted film into the gap between the two pipes. Decreasing the power density further and getting more of a top hat laser power distribution will probably resolve this problem. Figure 8.8 shows the cross section of the joint made under heating time of 110sec, the defocused distance of 45mm, and laser power of 35W. Even though the laser beam was defocused, longer heating times resulted in melting of the surface of the coupling. Therefore, it is necessary to use cooling air over the surface of the coupling for laser welding as well.
<table>
<thead>
<tr>
<th>Defocus Distance (mm)</th>
<th>Power Level(W)</th>
<th>Frequency(Hz)</th>
<th>Heating Time(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30mm</td>
<td>35W</td>
<td>CW</td>
<td>5sec</td>
</tr>
<tr>
<td>30mm</td>
<td>35W</td>
<td>CW</td>
<td>10sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>20sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>25sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>40sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>50sec</td>
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<tr>
<td>45mm</td>
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<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>70sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>80sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>100sec</td>
</tr>
<tr>
<td>45mm</td>
<td>35W</td>
<td>CW</td>
<td>110sec</td>
</tr>
</tbody>
</table>

Table 8.3: Experimental Results for Spot Welding

Figure 8.5: A Hole Made on Black Film Caused by Defocused Distance of 30mm
Figure 8.6: A Gap Made at Socket Joint Area under the Defocused Distance of 30mm, Laser power of 35W, and Heating time of 10sec.

Figure 8.7: Melted Black Film Displaced into the Butt Joint by Focused High Laser Power
8.4 Summary

1. The transmission of polyethylene to Nd: YAG laser radiation was lower than for the IR lamp.

2. For short defocused distances the power density of the beam was too high resulting in degradation of the black film. With selection of an appropriate defocused distance it was possible to prevent burning of the absorbing layer.

3. Under appropriate conditions it was possible to produce a spot weld between the coupling and the pipes as well as a partial butt weld. Increasing the laser power and the spot size along with getting a more uniform power density distribution should help improve the weld quality.
4. Laser has been shown to be a suitable alternative heat source for combined socket and butt TTIR welding. Depending on the pipe material such a system could be, more compact than Infrared lamp sources and it may reduce the need to cool the coupling.
CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

Welding of polyethylene (PE) pipes of different diameters is critical for the infrastructure of natural gas transmission as well as for numerous industrial applications. Presently, most of the plastic pipes are joined by either hot-plate (butt fusion) welding or electro-fusion welding. Both butt fusion and electro-fusion welding can produce high quality welds. However, butt fusion welding is a slow and complicated process and electro-fusion welding has an expensive consumable cost of the coupling and potential flaws including incomplete insertion of the pipe into the socket and deviation of the resistive wire. Therefore, it would be beneficial for the gas and water industry if a convenient, safe and faster joining method could be developed. Therefore, in this study, the new combined socket and butt welding method using the basic concept based on through transmission infrared welding was applied to welding polyethylene gas pipes. This combined socket and butt welding process also has benefits such as reduction of process time, cheaper equipment and coupling compared to conventional pipe welding methods, and a simple welding process.

A combined socket and butt welding unit using TTIr welding technique was developed for plastic pipes. All the welding experiments were conducted using this unit. It was found to provide a uniform heating and cooling pattern over the entire joint area.
Theoretical and experimental studies were performed to evaluate the effects of coupling thickness and width on stress distribution and IR transmission and heat flow during welding. From finite element studies of the effect of coupling thickness on stress distribution, it was found that the maximum Von Mises stress is in the weld zone at the outer end of coupling and that the maximum stress in the joint increased as the coupling thickness increased due to increasing stress concentration. However, the increase in stress is small and it is balanced by the need to minimize the potential for coupling failure. On the other hand, from experimental studies of IR transmission, it was also shown that thin couplings had higher transmissions allowing higher power IR radiation to reach the absorber layer (black film). However, despite the increased IR transmission, the temperature rise in the bottom of the butt joint did increase significantly as the coupling thickness decreased.

From the finite element studies of coupling width, the maximum stress level remains nearly constant for all coupling widths, showing that the coupling width has no impact on the joint strength if the butt joint can be fully obtained. However, when only a socket joint is considered, increasing the width decreased the stress level until it level off for widths of 54 mm and higher.

From experimental work to investigate the effects of film thickness and carbon black content on IR absorption, it was found that all film thickness from 0.09mm and higher absorbed all of the IR energy. It was also found that 0.07% carbon black is the nearly ideal quantity to allow IR absorption through the film thickness. Increasing the carbon black content beyond this value results in more surface absorption and it can
produce higher surface temperatures which may lead to polymer degradation, formation of porosity, and excessive squeeze flow.

Finite element analysis of heat flow during welding was used to predict the temperature history in the butt joint. In the analysis IR absorption was replaced by an equivalent internal heat generation rate for the coupling and black film. The variation of the thermal properties with temperature and convection losses due to the cooling air on the outside of the coupling and natural convection on the inside of the pipe were also included. Generally, the temperature history in the middle and end of the butt joint showed good agreement between experimental and FEA results. However, for the end of the butt joint there was greater deviation between the experimental results and predictions probably due to estimations in the temperature dependent material properties and convective heat transfer coefficient.

An analytical model for heat transfer in the pipe during combined socket and butt welding was developed. In this case, the heat conducted from the black film into the pipe was represented as a heat flux boundary condition on the outside of the pipe; calculations were performed for two cases assuming that 50% and 60% of the energy absorbed by the black film would transfer to the pipe. On the inside of the pipe natural convection was considered. It was found that using 60% of the energy absorbed by the black film had better agreement with the experimental and FEA results. This is reasonable since the coupling temperature increased due to partial IR absorption, resulting in a smaller temperature gradient between the black film and the coupling, and therefore, lower heat conduction to the coupling as compared to the cooler pipe.
The combined TTIR socket and butt welding method was evaluated for polyethylene gas pipe and it has been shown to be a new welding technique to make strong joints. Joints were evaluated using several destructive tests such as tensile test, sustained pressure test, crush test, and three bend tests. For near optimum welding conditions it was possible to produce high quality joints that successfully passed all of these tests. It is suggested that these destructive evaluation methods could also be used to evaluate the welding strength and optimize the welding conditions for other plastic pipe materials and sizes in the future.

The combined TTIR socket and butt welding method was also successfully applied to PVDF pipes for high purity water applications where the inner bead must be eliminated to avoid contamination. It was demonstrated that the combined socket and butt TTIR welding for PVDF pipe is easier than PE pipe because lower air cooling pressure could be applied to prevent melting of PVDF coupling due to lower absorption in PVDF. During the welding cycle, air pressure of 0.1724MPa (25psi) was applied to a silicon balloon, which was pressed against the inner wall of the pipe in order to prevent formation of the inner bead. Excessive air pressure in silicon tube caused reduction of the cross section area of pipe, which could reduce the joint strength.

A feasibility study using a Nd:YAG laser source instead of lamps showed that it was possible to produce a spot weld between the PE coupling and pipes as well as a partial butt weld. It was proposed that by increasing the laser power and the spot size along with getting a more uniform power density distribution, laser sources could also be used to produce high quality welds.
It is recommended to continue studies of laser transmission welding using fiber coupled laser diodes which could be arranged around the circumference of the coupling to simultaneously illuminate the whole joint area. The use of monochromatic laser sources offers the potential or reducing or eliminating absorption in the coupling thereby eliminating the need for cooling the outside of the coupling. It is also recommended that methods for injection or compression molding of the coupling with the black layered incorporated onto the inner surface be investigated. This will make it easier to prepare the pipes and coupling for welding. Additional theoretical and experimental work needs to be performed on other pipe materials and sizes to determine the applicability of this new method to other applications. Also, existing test methods should be re-evaluated along with development of new test methods and standards for use on combined socket and butt joints. Ultimately this will lead to further development and much wider range of applications for this new approach of combined socket and butt welding of plastic pipes using through transmission infrared welding.
APPENDIX A

FEA CONTOUR PLOTS FOR THE COUPLINGS WITH 1-MM, 2-MM, 3-MM, 4-MM, AND 5-MM THICKNESS
Figure A.1: Von Mises Stress Distribution in the Weld Zone for 1mm Thick Coupling
Figure A.2: Von Mises Stress Distribution in the Weld Zone for 2mm Thick Coupling
Figure A.3: Von Mises Stress Distribution in the Weld Zone for 3mm Thick Coupling
Figure A.4: Von Mises Stress Distribution in the Weld Zone for 4mm Thick Coupling
Figure A.5: Von Mises Stress Distribution in the Weld Zone for 5mm Thick Coupling
Figure A.6: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 1mm Thick Coupling
Figure A.7: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 2mm Thick Coupling
Figure A.8: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 3mm Thick Coupling
Figure A.9: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 4mm Thick Coupling
Figure A.10: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 5mm Thick Coupling
Figure A.11: Axial Direction (Z-direction) Stress Distribution in the Weld Zone for 6mm Thick Coupling
APPENDIX B

FEA CONTOUR PLOTS FOR THE COUPLINGS WITH
32-MM, 54-MM, AND 72-MM WIDTH
Figure B.1: Von Mises Stress Distributions in the Socket Weld Zone for 32mm Coupling Width
Figure B.2: Von Mises Stress Distributions in the Socket Weld Zone for 54mm Coupling Width
Figure B.3: Von Mises Stress Distributions in the Socket Weld Zone for 72mm Coupling Width
Figure B.4: Von Mises Stress Distributions in the Combined Socket and Butt Weld Zone for 36mm Coupling Width
Figure B.5: Von Mises Stress Distributions in the Combined Socket and Butt Weld Zone for 54mm Coupling Width
Figure B.6: Von Mises Stress Distributions in the Combined Socket and Butt Weld Zone for 72mm Coupling Width
APPENDIX C

HEAT TRANSFER PROGRAM FOR COMBINED SOCKET AND BUTT TTIR WELDING OF POLYETHYLENE PIPE
/PREP7
ET, 1, PLANE55
KEYOPT, 1, 1, 0
KEYOPT, 1, 3, 1
KEYOPT, 1, 4, 0
KEYOPT, 1, 8, 0
KEYOPT, 1, 9, 0
MPTEMP, 1, 20
MPTEMP, 2, 40
MPTEMP, 3, 60
MPTEMP, 4, 80
MPTEMP, 5,100
MPTEMP, 6,120
MPTEMP, 7,122
MPTEMP, 8,124
MPTEMP, 9,126
MPTEMP, 10,128
MPTEMP, 11,130
MPTEMP, 12,132
MPTEMP, 13,134
MPTEMP, 14,136
MPTEMP, 15,138
MPTEMP, 16,140
MPTEMP, 17,160
MPTEMP, 18,180
MPTEMP, 19,200
MPDATA, KXX, 1,, 0.4
MPDATA, KXX, 1,,0.38
MPDATA, KXX, 1,,0.33
MPDATA, KXX, 1,,0.32
MPDATA, KXX, 1,,0.29
MPDATA, KXX, 1,,0.28
MPDATA, KXX, 1,,0.28
MPDATA, KXX, 1,,0.28
MPDATA, KXX, 1,,0.28
MPDATA, KXX, 1,,0.27
MPDATA, KXX, 1,,0.27
MPDATA, KXX, 1,,0.27
MPDATA, KXX, 1,,0.27
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MPDATA, KXX, 1,,0.27
MPDATA, KXX, 1,,0.27
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MPTEMP, 7,122
MPTEMP, 8,124
MPTEMP, 9,126
MPTEMP, 10,128
MPTEMP, 11,130
MPTEMP, 12,132
MPTEMP, 13,134
MPTEMP, 14,136
MPTEMP, 15,140
MPTEMP, 16,160
MPTEMP, 17,180
MPTEMP, 18,200
MPDATA, DENS, 1,,950
MPDATA, DENS, 1,,947
MPDATA, DENS, 1,,940
MPDATA, DENS, 1,,925
MPDATA, DENS, 1,,910
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MPDATA, DENS, 1,,775
MPDATA, DENS, 1,,775
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CYL4, 0, 0, 0.029, ,0.0291, ,0.009
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CYL4, 0, 0, 0.0301, ,0.0311, ,0.009
CYL4, 0, 0, 0.0311, ,0.0321, ,0.009
CYL4, 0, 0, 0.0321, ,0.0331, ,0.009
CYL4, 0, 0, 0.0331, ,0.0341, ,0.009
CYL4, 0, 0, 0.0341, ,0.0351, ,0.009
FLST, 2, 8, 6, ORDE, 2
FITEM, 2, 1
FITEM, 2,-8
VGLUE, P51X
ANTYPE, 4
TRNOPT, FULL
LUMP, 0
OUTRES, ALL, ALL
TIME, 250

FLST, 2, 36, 5, ORDE, 20
FITEM, 2, 1
FITEM, 2, -2
FITEM, 2, 5
FITEM, 2, -6
FITEM, 2, 8
FITEM, 2, -10
FITEM, 2, 15
FITEM, 2, -16
FITEM, 2, 21
FITEM, 2, -22
FITEM, 2, 27
FITEM, 2, -28
FITEM, 2, 33
FITEM, 2, -34
FITEM, 2, 39
FITEM, 2, -40
FITEM, 2, 45
FITEM, 2, -46
FITEM, 2, 49
FITEM, 2, -65
SFADELE, P51X, 1, CONV

BFADELE, 8, HGEN
ICDELE
TREF, 20,
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 9
/GO

FLST, 5, 8, 6, ORDE, 2
FITEM, 5, 9
FITEM, 5, -16
CM, _Y, VOLU
VSEL, , , P51X
CM, _Y1, VOLU
CHKMSH,'VOLU'
CMSEL,S, _Y
VMESH, _Y1

SFA, P51X, 1, CONV, 180, 25
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SFA, P51X, 1, CONV, 5, 25

BFV, P51X, HGEN, 86000000
FLST, 2, 1, 6, ORDE, 1
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BFV, P51X, HGEN, 9916231.6
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 11
/GO

BFV, P51X, HGEN, 1200990.5
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 12
/GO

BFV, P51X, HGEN, 1341944
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 13
/GO

BFV, P51X, HGEN, 1720423
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 14
/GO

BFV, P51X, HGEN, 2005667.4
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 15
/GO

BFV, P51X, HGEN, 2275126.9

SOLVE
FINISH
/POST1
/TITLE, 3D Heat Transfer
APPENDIX D

COMPUTER PROGRAM FOR TEMPERATURE DISTRIBUTION FROM ANALYTICAL SOLUTION
°C = K

\[ F_0 := -5160 \frac{W}{m^2} \]
\[ k := 2 \cdot 10^{-7} \frac{m^2}{s} \]
\[ T_a := 20°C \]
\[ r_a := 0.023\pi \]
\[ r_b := 0.029\pi \]
\[ \lambda := 0, 1..500°C \]
\[ h := 55 \frac{\text{watt}}{m^2 K} \]
\[ \lambda_w := 0.4 \frac{\text{watt}}{mK} \]

\[ E(\lambda) := \left[ J_1(\lambda \cdot r_b) \left( \frac{h}{\lambda_w} \cdot Y_0(\lambda \cdot r_a) + \left( \lambda \cdot Y_1(\lambda \cdot r_a) \right) \right) \right] - \left[ Y_1(\lambda \cdot r_b) \left( \frac{h}{\lambda_w} \cdot J_0(\lambda \cdot r_a) + \left( \lambda \cdot J_1(\lambda \cdot r_a) \right) \right) \right] \]
\[ \lambda := 200 \]

Given

\[ J_l(\lambda \cdot r_b) \left( \frac{h}{\lambda_w} \cdot Y(\lambda \cdot r_a) + \lambda \cdot Y_l(\lambda \cdot r_a) \right) - Y_l(\lambda \cdot r_b) \left( \frac{h}{\lambda_w} \cdot J_0(\lambda \cdot r_a) + \lambda \cdot J_l(\lambda \cdot r_a) \right) = 0 \]

Find \( \lambda = 2.106 \times 10^3 \)

\[ \lambda_{\text{array}} := \begin{pmatrix} 125.636 \\ 564.004 \\ 1069 \\ 1586 \\ 2106 \\ 2627 \\ 3149 \\ 3672 \\ 4195 \\ 4718 \\ 5241 \end{pmatrix} \]

\[ J_l(\lambda_{\text{array}} \cdot r_a) - \left( \frac{J_l(\lambda_{\text{array}} \cdot r_b)}{Y_l(\lambda_{\text{array}} \cdot r_b)} \cdot Y_l(\lambda_{\text{array}} \cdot r_a) \right) = \begin{array}{c|c}
0 & 0 \\
0 & 0.325 \\
1 & -0.052 \\
2 & -0.055 \\
3 & 0.036 \\
4 & 9.472 \times 10^{-3} \\
5 & 5.413 \times 10^{-3} \\
6 & 4.818 \times 10^{-3} \\
7 & 7.764 \times 10^{-3} \\
8 & -0.038 \\
9 & -4.343 \times 10^{-3} \\
10 & -2.331 \times 10^{-3} \\
\end{array} \]
\[
\begin{align*}
J_0(\lambda_{\text{array } a}) &= \frac{J_1(\lambda_{\text{array } b})}{Y(\lambda_{\text{array } b})} \cdot Y(\lambda_{\text{array } a}) \\
J_0(\lambda_{\text{array } b}) &= \frac{J_1(\lambda_{\text{array } b})}{Y(\lambda_{\text{array } b})} \cdot Y(\lambda_{\text{array } b})
\end{align*}
\]

\[
C_{\lambda rb} := J_1(\lambda_{\text{array } b}) \cdot \frac{J_1(\lambda_{\text{array } b})}{Y(\lambda_{\text{array } b})} \cdot Y(\lambda_{\text{array } b})
\]

\[
C_{\lambda ra} := J_1(\lambda_{\text{array } a}) \cdot \frac{J_1(\lambda_{\text{array } b})}{Y(\lambda_{\text{array } b})} \cdot Y(\lambda_{\text{array } a})
\]
\[ C_{0ra} := J_0(\lambda_{array} r_a) - \frac{J_1(\lambda_{array} r_b)}{Y(\lambda_{array} r_b)} \cdot Y(\lambda_{array} r_a) \]

\[ C_{0rb} := J_0(\lambda_{array} r_b) - \frac{J_1(\lambda_{array} r_b)}{Y(\lambda_{array} r_b)} \cdot Y(\lambda_{array} r_b) \]

\[ A_m := \frac{F_o r_b}{h r_a} \left( \frac{1}{\lambda_w} - \frac{\ln(r_a)}{r_a C_{0ra}} \right) - \frac{1}{\lambda_{array}} \left( r_a \ln(r_a) C_{0ra} - \frac{1}{2} \lambda_{array}^2 \right) \]

\[ a(r) := F_o r_b \left( \frac{-\ln(r)}{\lambda_w} + \frac{\ln(r_a)}{\lambda_w} - \frac{1}{h r_a} \right) + T_a \]
\[ C_{0 \lambda}(t) := J_0(\lambda_{\text{array}} r) - \frac{J_1(\lambda_{\text{array}} r_b)}{Y(\lambda_{\text{array}} r)} \cdot Y_1(\lambda_{\text{array}} r) \]

\[ b(r, \theta) := \left[ \frac{1}{\text{length}(\lambda_{\text{array}})} \sum_{n=0}^{\text{length}(\lambda_{\text{array}})-1} \left( A_m \cdot C_{0 \lambda}(t) \cdot \exp\left[ -k(\lambda_{\text{array}})_n^2 \cdot \theta \right] \right) \right] \]

\[ \theta := 0, 10, \ldots, 250 \]

\[ T(r, \theta) := a(r) + b(r, \theta) \]
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