To the Graduate Council:

I am submitting herewith a dissertation written by Glendon Tyree entitled "Laser Lap Welding of 80Y90T Steel with Plasma Arc Augmentation." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

John A. Hopkins, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

LASER LAP WELDING OF 80Y90T STEEL WITH PLASMA ARC AUGMENTATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Glendon Tyree
December 1998

DEDICATION

This thesis is dedicated to my parents
for setting the example and to my
little brothers, for simply being
my brothers.

ACKNOWLEDGMENTS

I would like to begin by thanking Mike Sharp, without whose help this thesis would surely have never been completed. His knowledge of laser welding, his friendship, and his ability to work with me as a team have been invaluable during my time at the Space Institute.

My stay here would also not have ever been possible without the funding provided by Johnson Controls, Inc. Specifically, I would like to thank Tom Sanfelippo of Johnson Controls for his guidance and help throughout my study.

As my major professor Dr. John Hopkins has provided me with friendship, guidance, and a steadying hand. With his help I was able to stay more focused on my goals here at the Space Institute. I would also like to thank Dr. Mary Helen McCay for the example she set for me, as a researcher and a leader. Dr. Max Hailey provided me with a good friend and knowledge of design of experiments that I am lucky to have had. Each of you served as educators, friends and leaders during my work and education here.

Being the son of a jack of all trades, I would also like to thank Joe Hane, Ricky Meeker, Gary Payne, Jacob Cashion, and Dean Ferrell. Without the machinists and craftsmen nothing would ever get done. Thanks to all of you for the friends you have been.

Mom and Pop I just want to thank you for raising the three of us the way you did. Whatever the three of us accomplish in life, we owe to you.

Nate Kennedy, Scott Sowles, and Jason Klepper, what can I say? I came here with two brothers and left with five.

ABSTRACT

An experiment is carried out on 80Y 90T steel, a high strength low alloy steel, that is used in lightweight autobody components. Using a CO_2 laser, it is shown that Plasma Assisted Laser Welding (PALW) can provide increased fusion zone width, when compared to conventional CO_2 welding, even in the presence of poor part fit-up. The negative effects of material gap, on PALW and laser only welds, are explained and the methods are compared. The use of plasma arc augmentation to increase the tolerance to gap of a laser welding system is shown. The influence of the plasma torch on the laser welding process is also examined. It is then shown that the plasma arc is able to reduce the effective reflectivity of the metal, when laser welding. Welded samples are sectioned, analyzed and compared according to the dimensions currently used in industry, for laser welds.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A_L	area of metal melted by laser
A_P	area of metal melted by plasma torch
A_{PALW}	area of metal melted by plasma assisted laser welding
LP	lack of penetration in the weld
U	undercutting of the weld
Δ	area of metal melted by the effects of the plasma torch on the laser beam

Abbreviations

FZW	fusion zone width
HAZ	heat affected zone
PALW	plasma assisted laser welding

CHAPTER 1

INTRODUCTION

Laser welding has been shown to be a viable tool for many industry applications, especially in the auto industry (Belforte '94, Breuer '94). The laser is now used to weld body panels, exhaust systems, gears and the many lightweight structures found in today's cars. In fact, today's automobile could not be manufactured without the use of the laser. For many processes the use of laser welding has proven to reduce component weight, component rework through reduced heat input, manufacturing cost and production time (Belforte '94, Darchuk '85, Sun '97).

In our present society greater and greater emphasis is being placed on improving gas mileage in new automobiles. One way of improving gas mileage is to reduce the weight of the automobile itself. Laser welding is often able to reduce the weight of components when compared to those welded by traditional methods. This is achieved because unlike MIG and TIG welding, laser welding rarely requires the use of filler metals. The use of filler metals is often unnecessary because the incident laser beam can actually fuse the materials together. This also eliminates a production cost because filler materials will not need to be purchased.

The reduced rework of components is due to the low heat input of the laser welding process. Though a moderate amount of energy is input into the material during the welding process the actual area over which this energy is input is very small. In many cases the weld track is only a few millimeters wide and the heat affected zone (HAZ) is only slightly larger. The thin seam of the laser weld is also attributable to the high welding speed (Beyer '96). The heat input is reduced to such a degree that rework due to heat distortion is often eliminated. Cooling times before handling are also reduced or eliminated because of this reduced part heating.

Perhaps the greatest advantage of laser welding, when compared to other methods, is reduced production time. It is not uncommon for a laser welding system to be capable of welding at speeds five times greater than those achievable by other methods, for the same application. This is in addition to the reduced production times from quicker cooling times. With added production speed a manufacturer may be able to reduce the amount of floor space needed for a component to be produced. This is because several conventional welding stations may be replaced by only one laser welding station, with the production needs still being met. While it varies with the factory, floor space can be of great value to the manufacturer.

All of these advantages add up to reduce the manufacturing cost for many car components. Gains in all these areas show why the laser is becoming more common in today's automotive factory. Still, one limitation that is keeping more applications from being laser welded is the demands the process puts on joint fit-up (Darchuk '85, Leong '94, Walduck '94).

Joint fit-up refers to the amount of space between the two materials that are to be welded. This empty space, which is often referred to here as material gap, can create a problem when laser welding. At the least, poor joint fit-up can make achieving the weld specifications difficult, at its worst it can make forming a weld impossible. This is a result of the lack of a filler material that can be used to fill the empty space. The industry standard for allowable gap during laser welding is usually taken to be around 10% of the sheet thickness, but a manufacturer's spec for a process may allow more gap (Biffin '97, Johnson '95, Sun '97).

As an example of the types of problems that poor joint fit up can cause when laser welding, the figures 1 through 4 show four sections taken from an automotive component that was laser welded. The sections were taken out of an area only a few inches in length, so it can be seen how rapidly changes in joint fit-up can take place. One might also note the several different phenomena present in only a short length of weld track. In the first section you can see that the gap was such that no weld was made. The second and fourth pictures, show how gap can cause a lack of penetration into the metal and in this case, severe undercutting. In the third photo, one can see that with a smaller amount of gap a seemingly satisfactory weld may be made. However, this weld would still not meet the manufacturer's standards, as the amount of undercut is more than twice what is allowable. The component is made of 80Y90T steel and is part of a lightweight autobody structure that is currently being examined as a possible laser welding application.

As the previous example shows, in order for industry to exploit the many advantages of laser welding it is necessary to minimize the effects of material gap in a welding process. There are several ways to approach this, among them are improved part design, improved stamping, better fixturing of components and adapting the laser welding process to better handle poor joint fit-up (Farson '97, Belforte '94, Leong '94, Darchuk '85). Because of this researchers must find ways to improve the laser welding process, so that the process becomes more tolerable and therefore more user friendly.

The first thing that can be done, from a laser standpoint, is to determine the welding parameters for a process that give the greatest range of gap tolerance. By

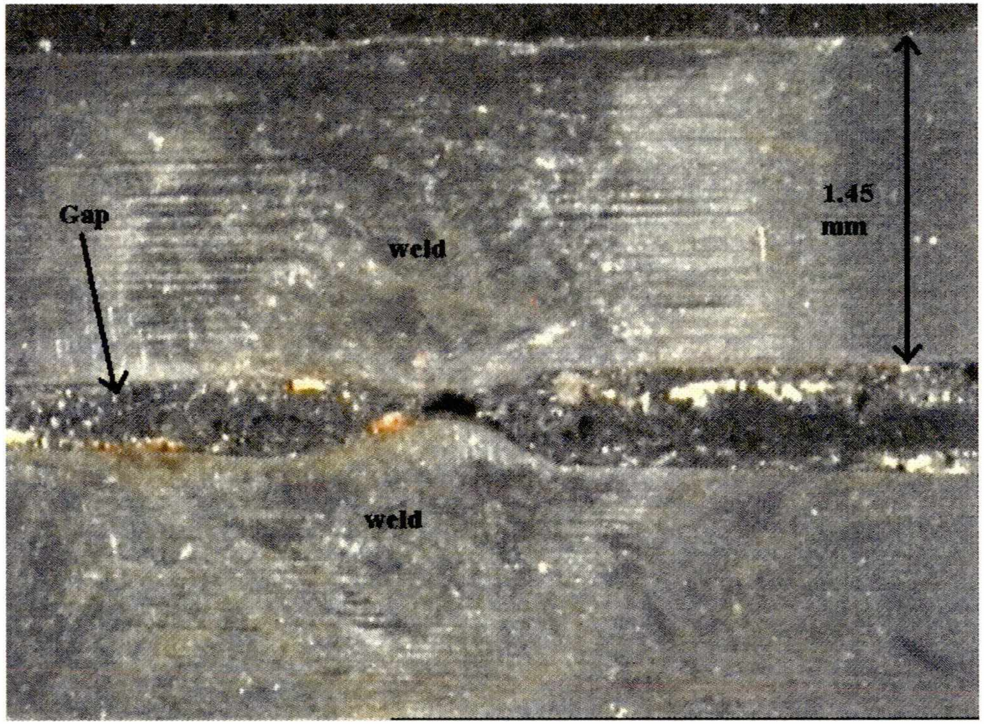

Figure 1. Gap Causing Lack of Fusion. Weld performed on 80Y90T autobody component using a CO_2 laser and helium gas (1850W, 1000mm/min., +1mm focal position).

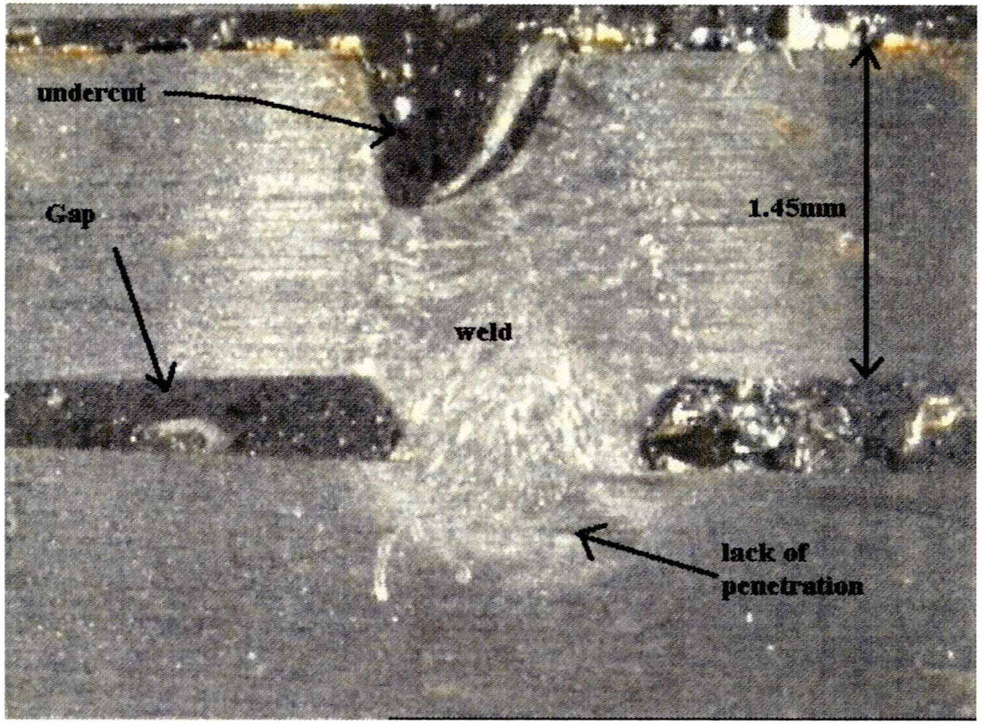

Figure 2. Gap Causing Lack of Penetration and Undercut. Weld performed on 80Y90T autobody component using a CO_2 laser and helium gas (1850W, 1000mm/min., +1mm focal position).

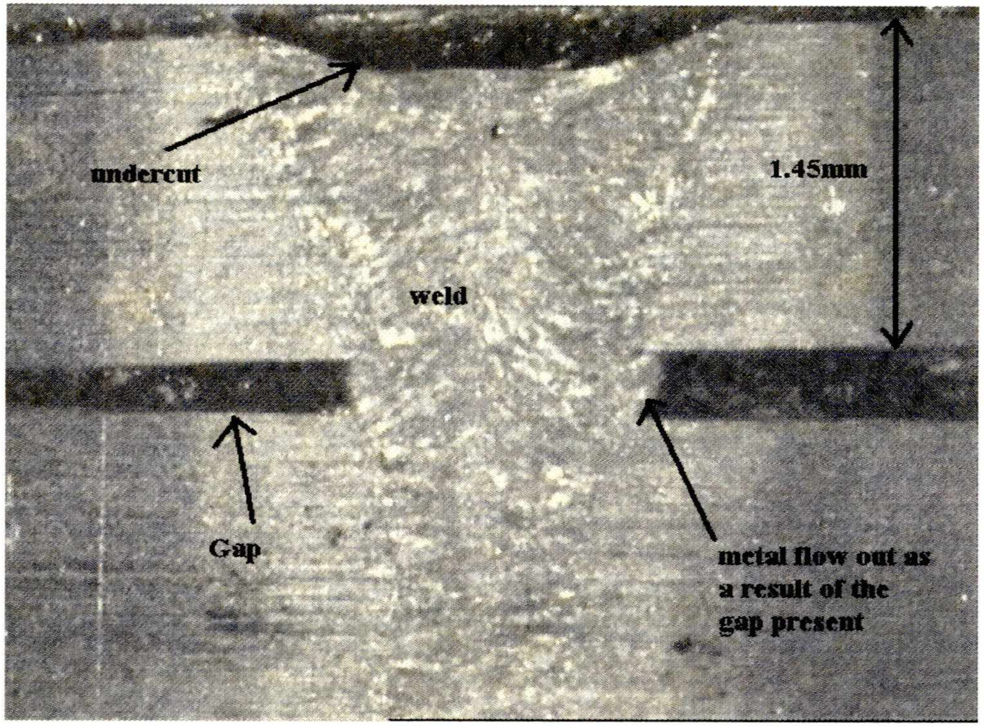

Figure 3. Gap Causing Undercut. Weld performed on 80Y90T autobody component using a CO_2 laser and helium gas (1850W, 1000mm/min., +1mm focal position).

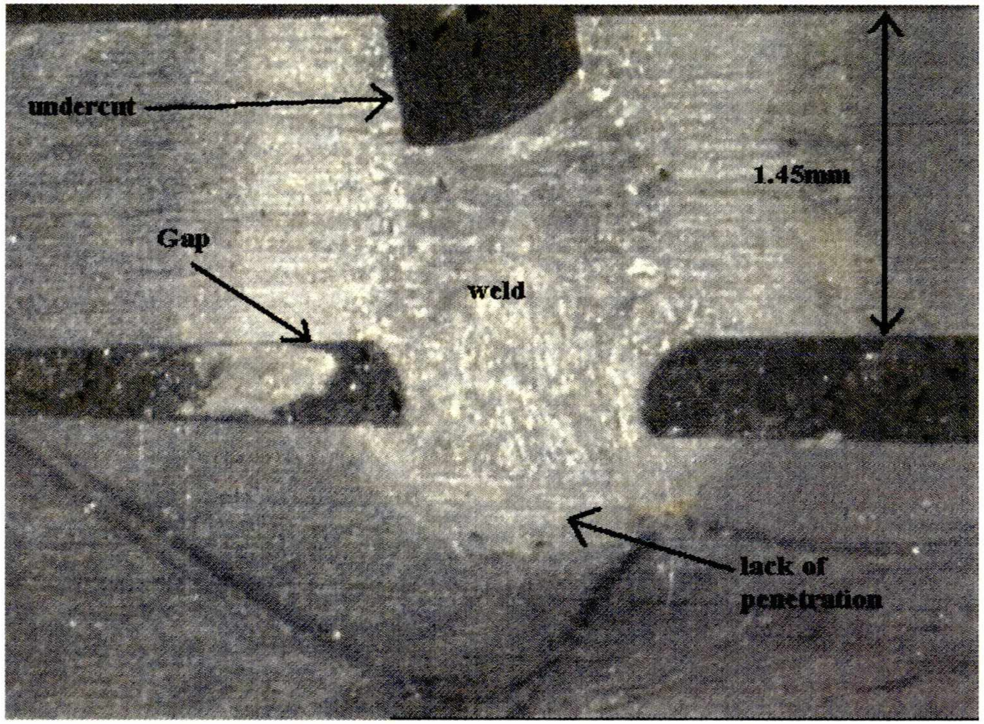

Figure 4. Gap Causing Lack of Penetration and Undercut. Weld performed on 80Y90T autobody component using a CO_2 laser and helium gas (1850W, 1000mm/min., +1mm focal position).

optimizing the welding parameters it should possible to increase the amount of gap tolerance in a welding system and therefore be able to satisfy the welding specifications over a broader range of material gaps. Another option is to look at hybrid welding techniques like Plasma Assisted Laser Welding (PALW), Laser Irradiation of Arc Welding or the addition of a filler material. Research has shown that the use of a plasma torch or MIG arc to augment the laser welding process can greatly increase not only the tolerance to component fit up, and the welding speed but also the important fusion zone width (FZW) (Abe '96, Biffin '97, Walduck '94). This width, is the most important and difficult to obtain factor, in welding specifications.

If methods can be found to improve the tolerance to poor joint fit-up of laser welding systems more applications will be able to take advantage of the many plusses that come with laser welding. This will result in lower manufacturing cost through more efficient production.

The objectives of this study are first to determine the effects of material gap on laser only welding and on PALW. Then it will be determined if PALW can increase FZW, even in the presence of material gap. Next it will be ascertained if PALW provides an increase in tolerance to material gap, when compared to laser only welding. It will also be determined if the use of plasma arc assist results in a higher effective absorptivity for the metal.

CHAPTER 2

BACKGROUND

In this chapter some of the basic concerns and characteristics of laser welding systems and the welds they produce are explained. The purpose is to familiarize the reader with the process and to give an understanding of some of the necessary considerations, when laser welding.

2.1 Laser Welding Considerations

As more manufacturing processes begin to utilize the laser, design engineers must address the differences between laser welding and other joining methods such as MIG and TIG welding. The differences that are of concern include increased sensitivity to joint fit-up, the type of laser, and different manufacturing specifications for laser welds. The choice of which type of laser to use will be discussed later, the rest of these differences are best addressed during the component design process. However, as is often the case, these differences are often only taken into account later in the manufacturing process when it is realized that the laser may be a viable manufacturing option for a certain component. This often occurs when the production capabilities of the current traditional joining process have reached or approached their production limits. In order to meet increased product needs or to reduce production cost the laser is then examined as an alternative to more traditional methods. The laser may also become an option for production if the need for a narrow fusion zone, or reduced cost through the lack of a filler material is important.

The consideration of the laser as a manufacturing tool, early in the design process, is of great importance to allow the full utilization of the laser. Increased efforts are being made to make design engineers, in the automobile industry specifically, more aware of the manufacturing capabilities and requirements of the laser welding system. The laser welding system would include the laser, motion package, beam delivery system and all necessary fixturing. The current tendency to convert components that were designed for conventional welding methods to laser welding, while often successful, does not usually allow full advantage of the laser to be taken. This is because the material, the component design, and the fixturing needs of the component often do not fully lend themselves to laser welding.

2.2 Different Types of Lasers

The laser welding of automotive structures is most commonly done with either a CO_2 laser or a Nd:YAG laser. The choice of lasers depends a great deal on the component to be welded. This is because of the different beam delivery systems of the two lasers and their wavelengths. A CO_2 laser uses parabolic mirrors to focus the beam onto the metal, because the CO_2 wavelength (10.6μm) cannot be transmitted through fiber optics. This is in contrast to the beam of the Nd:YAG, with a wavelength of 1.06μm, which can be transmitted through fiber optics. The use of a fiber optic beam delivery allows for the use of robots and makes the welding of more complex shapes easier. Moving optics can be used to make the CO_2 laser capable of welding complex components but the alignment and care of these systems requires more time than that of a fiber optic cable.

The cost per watt for a Nd:YAG laser is slightly higher than for a CO_2 laser and the CO_2 is available in higher powers. The need for robotic capabilities may however justify the extra investment for a Nd:YAG laser. The need for the extra power of a CO_2 will be determined by the material and the thickness of material to be welded. Added welding speed from increased power may also be an important consideration (Darchuk '85, Leong '94).

2.3 Laser Keyhole Weld

Lap welding of materials with lasers is achieved through a mechanism known as "keyholing". The energy from the laser is coupled into the material, and a vaporized hole is generated. With the beam or material moving with respect to the other, the flow of metal about the keyhole results in a chevron pattern that is characteristic of a laser lap weld (Darchuk '85).

A keyhole occurs when the metal is heated rapidly by the laser to its boiling point, and the vapor pressure opens a cavity in the molten metal. A thermal gradient is formed which is in association with a surface tension gradient. The higher surface tension at the cooler edges causes the molten metal to be pulled from the center of the weld (Powell '94). This allows the energy to penetrate deeper into the metal creating a deeper more penetrated weld. With the motion of the system this keyhole moves through the metal creating the weld track, and thus the metals are fused, under proper conditions (see fig. 5).

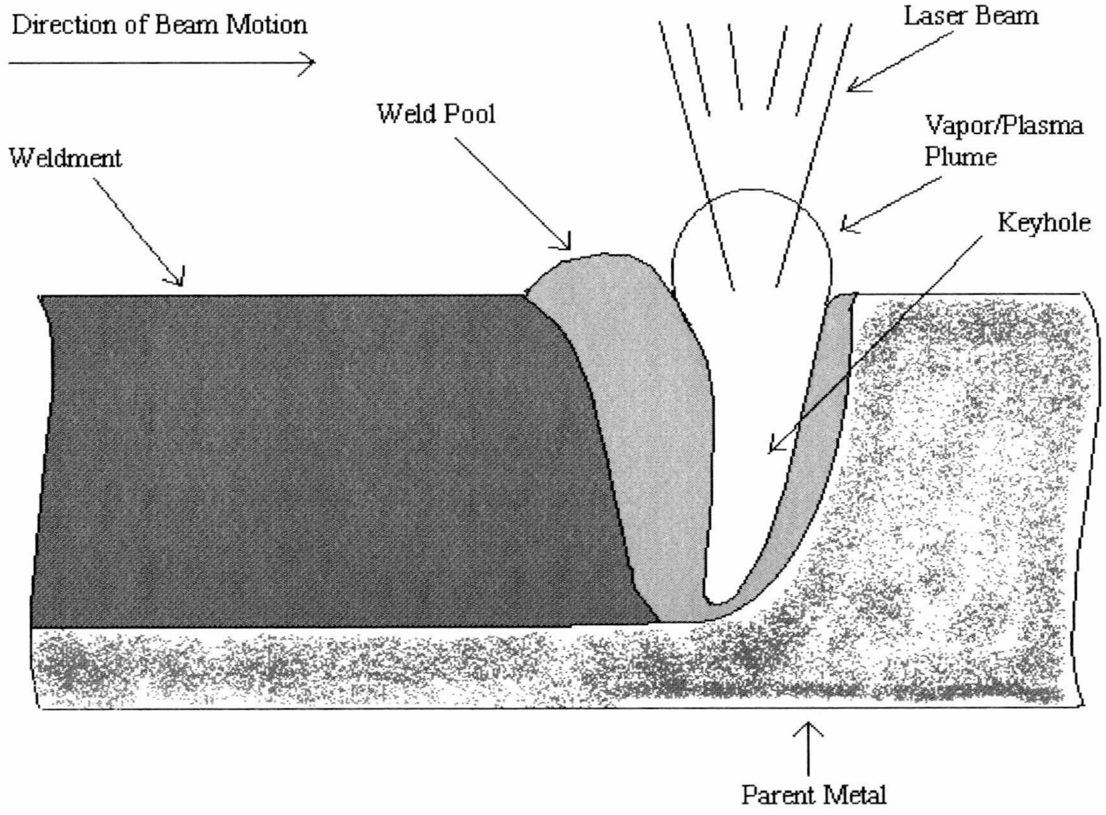

Figure 5. Keyhole Weld.

2.4 Shield Gas

Assist gases serve a dual purpose when laser welding. First they protect the keyhole and solidifying metal from oxidation. Second the assist gas protects transmission of the laser beam as it comes into focus on the workpiece. This protection helps to minimize beam expansion and scattering, which can be caused by vapors and gases around the cavity (Dawes '92).

Normally this gas is applied coaxially through the weld nozzle. The most common types of shield gases used are Helium and Argon. These are the two types of gases used in this study, and because of the differences in the two gases, they do affect the welding process.

Helium is generally regarded as the best assist gas for CO_2 laser welding, for several reasons. It has the highest ionization potential, which allows it to absorb the most energy before breaking down and causing undesirable plasma to form. This normally allows for the deepest weld penetration. Because helium is lighter than air it doesn't remain in the weld area too long and degrade (Dawes '92). Helium also allows for greater processing speeds above 2kW of laser power (Migliore '96).

Argon is also known to be a good cover gas, as it also prevents oxidation of the weld, but not as well as helium. Being heavier than air argon can also stay in the weld zone too long and hinder weld penetration (Dawes '92).

Even though argon is inferior to helium with respect to process characteristics, it can be justified in some cases because it is generally cheaper. The cost difference between the two is even more pronounced in Europe and the UK (Dawes '92).

2.5 Types of Welds

There are several different types of welds, among them are lap welds, butt welds and fillet welds. Each of these welds has it's own separate manufacturing specifications and applications. The type of weld covered here is the laser lap weld. As in the name, the two materials are lapped over top of each other. The laser is then used to fuse the top and bottom pieces together (see fig. 6). In a butt weld, the edges of the two materials are placed closely together and the laser is used to fuse the edges together (see fig. 6). A fillet weld refers to the use of a filler material, in the laser welding process. The filler material can then be used to fill the space between the materials, in either a lap or butt configuration (see fig. 6).

2.6 Plasma Assisted Laser Welding

Plasma assisted Laser Welding (PALW) refers to the addition of a plasma torch to the laser welding process. By adding the plasma arc energy to the laser it has been shown that the welding process can be improved. This is due to several factors. The addition of the low cost arc energy increases the total heat input and thus production speeds and/or penetration. The addition of the plasma arc enhances the effective absorptivity of the metal and more energy is then absorbed. Through these mechanisms two limitations of the laser welding process are addressed: the high cost, and the demands for joint fit-up (Abe '96, Biffin '97, Walduck '94).

The effective reflectivity of the metal is reduced because with the plasma torch placed in front of the laser beam, the laser beam is incident on the soft metal, pre-melted by the plasma torch. This results in more efficient use of the laser power. The plasma

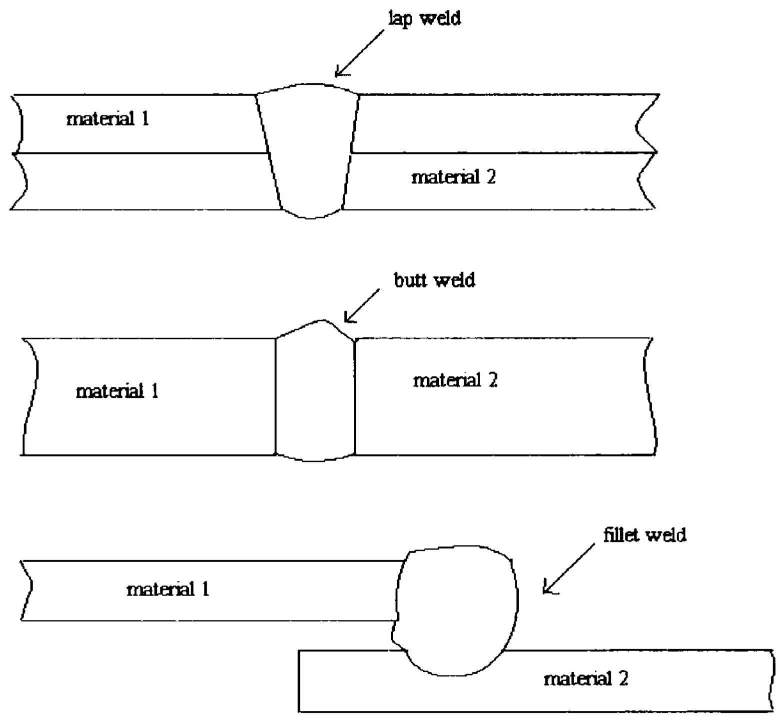

Figure 6. Types of Welds.

torch may also melt a trough shaped cavity into the metal, which reduces the effective sheet thickness (Beyer '96). This would also result in more efficient use of laser power.

2.7 Weld Zone Characterization

In order to be capable of determining what is a quality laser weld, it must be understood how to characterize a laser weld. One of the common areas of confusion is the difference between heat affected zone (HAZ) and the fusion zone. The HAZ refers to all of the area including and outside of the actual weld track that is affected by the heat input of the laser. The fusion zone however, refers only to the area where the melting of material has occurred, resulting in the joining or attempted joining of materials. While the HAZ may provide important information about the heat transfer mechanisms of the weld, it is the fusion zone that is of importance when characterizing laser weld (see fig. 7).

The specifications for the weld are often given as a percentage of the single sheet width and combined sheet width. In this paper both sheets of material are taken to be of the same thickness. The depth of penetration (how deep into the material the fusion zone goes), the FZW (width at the interface of the materials), and the amount of undercut in the fusion zone are the most common methods of characterizing the laser lap weld, these are shown in figure 8. While failure in any of these areas can result in a poor weld, it is the FZW that is of the most importance. This is because, it is the FZW that generates the total fusion area and thus weld strength (Webber '93). Poor joint fit-up can also create an undercut weld, which will affect the FZW. The term undercut is used to describe a laser weld where the laser has begun to form a groove in the top of the welding surface. This

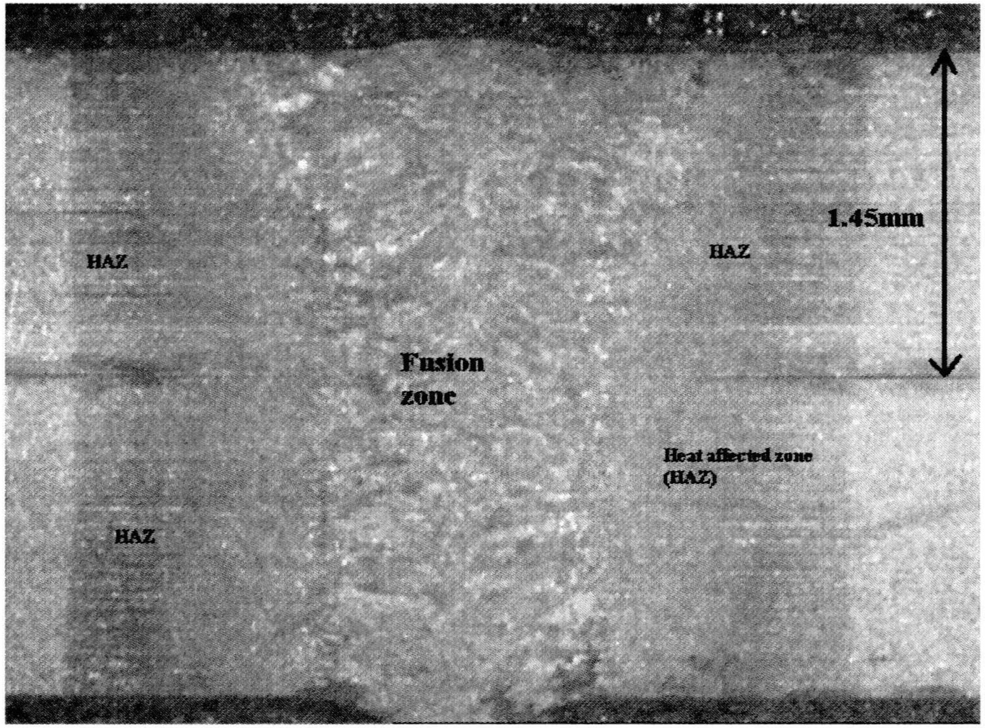

Figure 7. Defining Fusion Zone and HAZ.

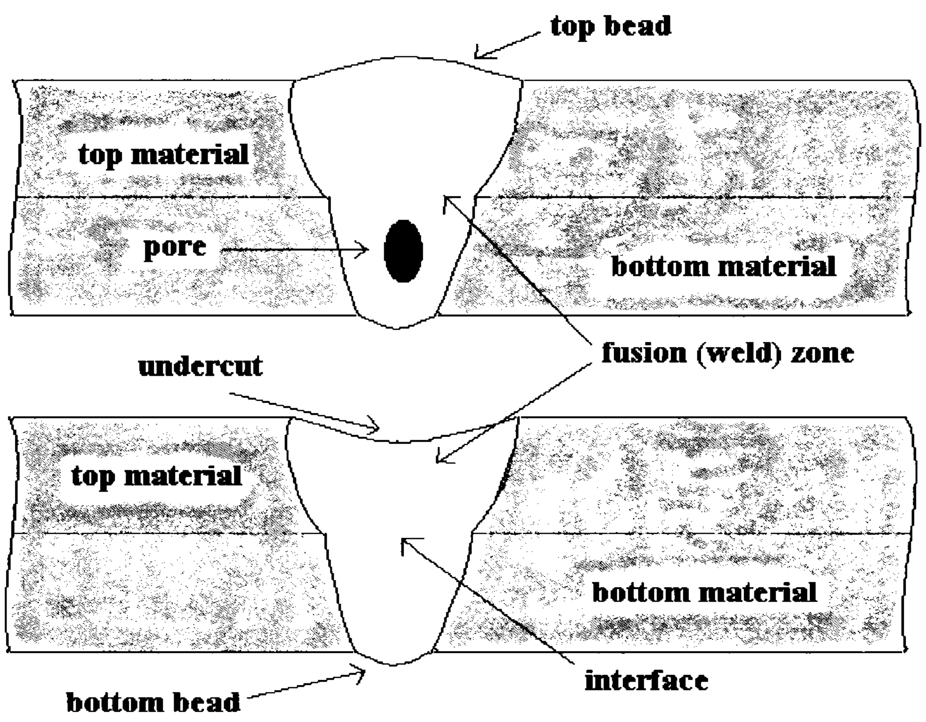

Figure 8. Defining Weld Dimensions.

undercut results from the molten metal flowing from the top of the metal into the material gap. Extreme undercut reduces weld strength and the allowable amount, of undercut, is usually specified in the welding specifications. The flow of the molten metal into the interface can also cause an artificial increase in the FZW. This in turn makes it difficult to make an accurate determination of the weld quality.

2.8 Manufacturers Laser Weld Specifications

As an example of the standards now present in industry, one prominent automaker uses the following specifications, for a laser lap weld. The FZW must be 75% of the thickness of the lightest gage member, and the weld must penetrate 80% of the total thickness of the members to be joined. Undercutting in the weld must be no deeper than 5% of the thickness of the lightest gage member. These specifications are diagramed in figure 9. Any porosity present in the weld may not be greater than 25% of the total weld surface. In addition to the specifications for the weld itself there are standards for the amount of material gap that is allowed before welding. After components are clamped, the gap may not exceed one-half the laser beam width or 15% of the material thickness, whichever is less. For this study, the 15% would be applicable because of the thickness of the metal to be welded.

2.9 "Humping" Effect

If the laser welding parameters are set improperly so that there is not sufficient power to match the processing speed, an effect known as "humping" may occur. This is because at high speeds, without sufficient power, the keyhole becomes unstable. Instead

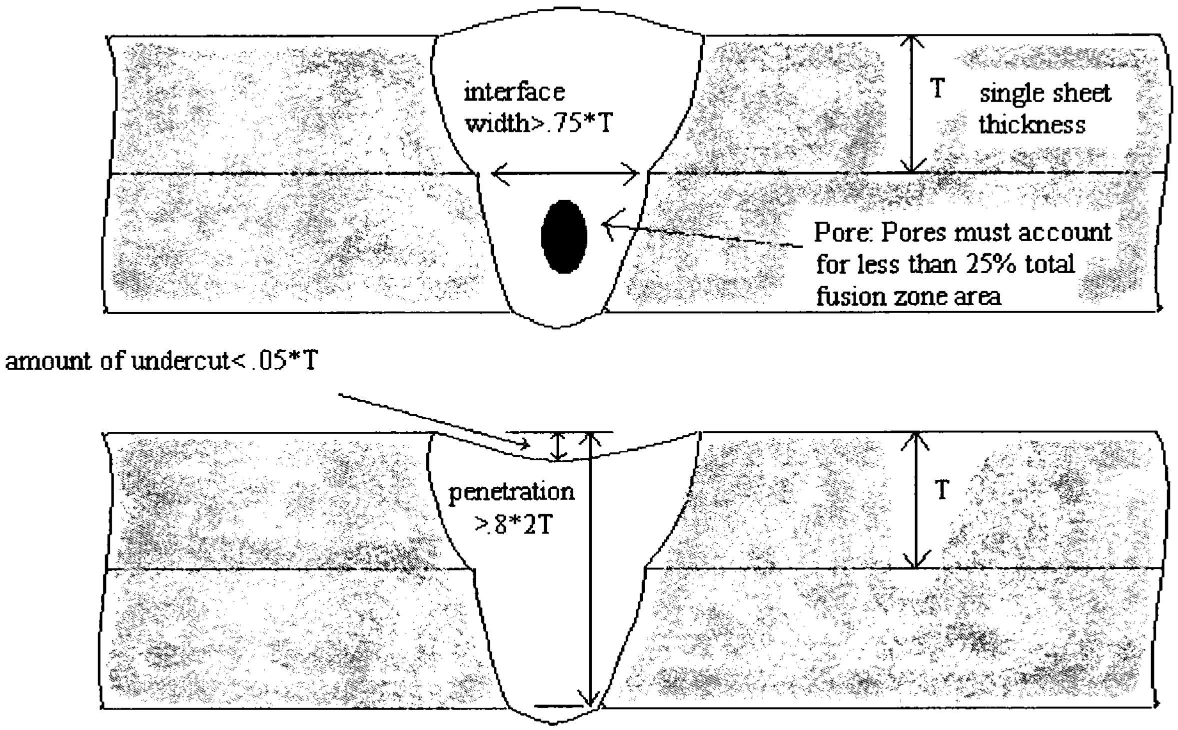

Figure 9. Manufacturer's Specifications.

of a weld track, of continuous width and dimensions being formed, one with irregularities will be formed. That is, there will be alternating areas of narrow fusion zones and wide fusion zones. This can make weld zone characterization difficult because several sections from the same weld sample will have varying dimensions in the fusion zone. Thus a weld may appear narrow in one area and then meet the specifications in another. One important thing to remember, when this humping effect is encountered, is that it is indicative of improper laser welding parameters. So while it is difficult to characterize, when it is found it is a sign that the parameters need to be adjusted, no matter what a single section may reveal about the fusion zone.

2.10 Material

All of the welds in the study are performed on 80Y 90T steel. This falls under the category of SAE980 steel. The only difference being, the chemistry of the 80Y90T steel is more rigidly defined. This steel is categorized as a high-strength low alloy steel.

CHAPTER 3

EQUIPMENT

This section covers the type of equipment used to perform this research. The type of laser system and plasma torch used to perform the welding is covered, as is the digital imaging equipment used to photograph the samples once they were welded. The fixture used to hold the metal samples is also discussed.

3.1 CO_2 Laser

All welding was done with a Rofin Sinar RS3000 fast axial flow CO_2 laser; this also includes the PALW trials. The laser has a maximum power output of 3000 Watts, and the laser beam has a wavelength of 10.6μm. The optics used had a focal length of 150mm, and the TEM_{10*} mode was used. Welding was done using a quasi-continuous mode, where the pulses were stacked closely together to create continuous power output. The welding nozzle allows for applying the shield gas in a coaxial manner.

3.2 Motion System

An Aerotech Unidex 16 motion package with laser controller card was used to weld all of the samples in this study. The package provides motion in three dimensions. In this study, the workpiece moved, while the laser welding head remained stationary. This system allows for accurate control of the processing speeds and the focal height of the laser system.

3.3 Plasma Torch

A Thermal Arc 2A Plasma Welding Torch was used in this study. It is designed for direct current plasma arc welding of ferrous and non-ferrous metals using the transfer arc plasma process and is manufactured by Thermal Dynamics Corporation. The plasma torch is part of a welding system that includes a control console, a direct current power source, a coolant source, and a gas supply (Thermal Dynamics Corporation '83). The Thermal Dynamics WC 100B Welding Console was used to operate the plasma torch. Cooling was supplied by a Miller Coolmate 4 Water Coolant System.

The plasma torch has a max current output of 75 amps and uses Argon gas or a mixture of Argon and Hydrogen.

3.4 Fixture

The welding fixture was made of copper. It consisted of a base plate, with a groove, of the same width as the samples. A relief groove was then machined below this placement groove to provide relief under the weld track. The metal samples were then clamped to the base plate using two smaller pieces of copper. Clamping pressure was applied using two bolts on each of the clamps. The clamps were machined so that the pressure would be directed down on the edges of the metal samples. The fixture can be seen in figure 10.

3.5 Digital Imaging

A Nikon SMZ-U Zoom 1:10 microscope was used to magnify the image of the samples. Then an ELMO Color CCD TV camera was used to form the digital image.

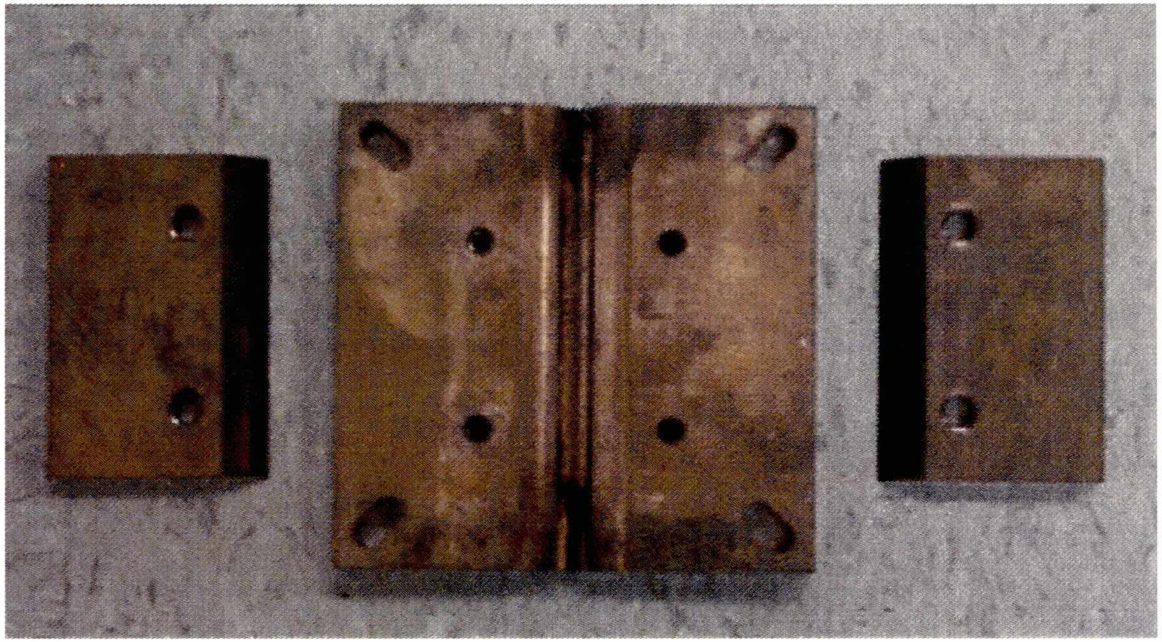

Figure 10. Welding Fixture. This copper welding fixture was used to clamp the metal samples for the study. It is shown here with the clamps removed so that the base plate may be viewed fully.

This image was then routed through a Panasonic S-VHS VCR to a computer. The images were then grabbed using Matrox Inspector 2.0, an image tool designed by Matrox Electronic Systems Ltd. Digital images were then analyzed using either the Matrox Inspector 2.0 software, or Image Tool for Windows version 1.2.3, designed by The University of Texas Health Science Center in San Antonio.

CHAPTER 4

EXPERIMENTAL PROCEDURE

Here the procedures used to prepare the metal samples before welding are covered, along with the welding processes and the sample analysis techniques.

4.1 Basic Design of Experiment

The basic design was a three factor, three level matrix resulting in twenty-seven coupons for each trial. As is discussed in more detail later, two data points were gathered from each coupon, resulting in fifty-four total data points from each run. The matrix was repeated using three different material gaps and the same set of laser parameters for each separate material gap.

With a material gap held constant for each matrix, the three controlled variables were laser power, welding speed and the focus of the laser system. Table 1 shows the matrices for the laser only welding using helium gas. These three factors were chosen as the variables because they are the key process parameters for laser welding (Farson '97). The powers used in each matrix were determined by looking at the capabilities of the laser. The speeds were chosen so as to be appropriate for the power range of the laser. The powers and speeds must be considered together as they have a direct effect on each other. This is because one of the limiting factors of production speed is the available power of the laser system. The three different focal points used were chosen to be 2mm into the material, 1mm into the material and focused at the surface of the material. These three focal positions were chosen because it has been shown that the best penetration

Table 1. Experimental Matrices.

	Laser only using helium			
Variables	Values			Units
Laser Power	1850	2500	3000	Watts
Processing Speed	1000	1375	1750	mm/min.
Focal Position	0	1	2	mm into surface
		Matrix		
Constants	1	2	3	Units
Shield Gas	Helium	Helium	Helium	-
Shield Gas Flow	24.8	24.8	24.8	L/min.
Material Gap Intoduced	0%	5.20%	8.60%	% single sheet thickness
		PALW		
Variables	Values			Units
Laser Power	1850	2500	3000	Watts
Processing Speed	1000	1375	1750	mm/min.
		Matrix		
Constants	1	2	3	Units
Torch Gas	Argon	Argon	Argon	-
Material Gap Introduced	0%	5.2%	8.6%	% single sheet thickness
Focal Position	1	1	1	mm into surface
Torch Current	75	75	75	Amps
Torch Gas Flow	1.4	1.4	1.4	CFH
Torch Alignment	tangent	tangent	tangent	-

occurs when the laser is focused below the surface (Darchuk '85). It was decided here to include the focal point as a variable to determine if it had some effect on the tolerance of the system to material gap. The gas flow for the laser only experiments using helium was held constant at 24.8L/min. For the laser only welds the gas flow was 7.8L/min. The type of gases used is explained later in this section.

The laser variables remained much the same for the plasma assisted matrices. The same range of laser powers was used. One exception was that the addition of the plasma torch to the system did not allow for the focus to be moved deeper than 1mm, into the surface. Because of this the focal position for PALW was set to always be 1mm into the surface. This is taken into account when comparing the laser only case to PALW by only comparing PALW to laser only cases where the focal position was also at 1mm, into the surface. Additionally some data was taken using higher processing speeds for the PALW method. This was done because the use of plasma torch allowed for full penetration at higher speeds than the laser only case. These additional speeds and the limitations on focal position account for the differences between the experimental matrices for PALW and laser only welding. The PALW matrices are shown in Table 1 with the laser only matrices. The higher processing speeds, that were performed in addition to those shown, are not included here but are included in the results.

The additional parameters introduced by the PALW process are the plasma torch current, the gas flow through the torch, and the alignment of the torch with the laser. Each of these parameters was held constant, and then the laser parameters were varied in a like manner to the laser only welds, with the exceptions of the aforementioned focal position and higher processing speeds. The max current of the plasma torch system was used, 75 amps. At the 75 amps of current the voltage of the plasma torch was 28 volts, this corresponds to 2100 Watts of added power. The gas flow was set to 1.4 cubic feet hour, and argon was used.

Laser only welds were performed predominantly with helium because it was desired to compare laser only, in its best case scenario, to PALW, in its best case scenario. A limited amount of data was also gathered for the laser only case using argon as the shield gas. This was done to show that it did not account for the majority of the changes observed in the weld dimensions when using PALW and argon gas. Additionally, it is well documented that helium is considered to provide the best weld quality for the laser only case, on the type of material studied here (Abbot '94,Dawes '92, Migliore '96).

4.2 Preparation of Metal

The samples of 80Y 90T to be welded were prepared in the following manner before being welded. The material, of 1.45mm thickness, was cut into coupons measuring approximately 2.5cm by 8.9cm using an industrial shearing machine. All edges were then belt sanded to remove any burs or rough edges that might later hinder part fit up. After this all samples were cleaned with acetone to remove any grease and oil. While this oil and grease would likely be present in an industrial situation, it would have created an uncontrolled variable in this study. Samples were also thoroughly checked for any warping or curvature that would create a problem once the samples are mounted in the welding fixture.

4.3 Laser Welding Samples

Laser welds were performed using the fixture and Rofin RS3000 laser, with motion system, outlined in the apparatus section. Metal samples were clamped securely in the fixture and then welded. For those samples where a material gap was introduced, metal shims were placed in between the metal sheets, before clamping, to create the desired material gap. The shims were placed on the edges of the clamped pieces so as to prevent their interference with welding process. The gaps that were chosen for the study were no gap, 5.2% gap and 8.6% gap (where the gaps are expressed as a percentage of the single sheet thickness). The no gap condition was chosen so as to provide a base condition for comparison to the gapped conditions. The 5.2% gap was chosen because it represents almost half of the 10% gap that is normally accepted as the limiting gap when lap welding. The 8.6% gap was introduced as the next step above the 5.2% case. Higher gaps were not introduced because the 8.6% gap proved to be limiting factor here. Though 10% gap is the generally accepted limit for laser welding, the manufacturer's specifications for laser welding were applied here and served to reduce the amount of gap that could be tolerated, and still remain within the specifications.

The power was set according to the reading on the laser and the processing speed was controlled by the motion system. The focus was set by measuring from a permanent datum that corresponded to being focused on the surface of the material. Focal changes were then measured with respect to this position.

4.4 PALW Samples

PALW data was gathered in a similar method to the laser only samples. The plasma torch had to be aligned properly with the laser spot. For this work it was determined that the best configuration would be to have the plasma spot and laser spot just slightly past being tangent to each other. This alignment position can be seen in figure 11, and in figure 12 a poorly aligned condition is shown. This position was chosen through preliminary trials and from studying the PALW work of John Biffin and the MIG arc assist work of Nobuyuki Abe. The torch was fixed at an angle of 45° from the laser welding nozzle, which was perpendicular to the work piece.

The alignment is found by using the plasma torch and laser to melt spots on the metal, and then comparing their relative positions under a microscope, which is how figures 11 and 12 were created. The alignment was checked before each PALW matrix to insure the torch has been properly positioned.

The dual clamps, on the fixture used, did not allow enough room for the plasma torch to pass through. Because of this, large washers were used to clamp the metal samples on one side. The washers were placed on the same nuts that had held the original clamp. Because data was only collected at points corresponding to where these nuts are located, for both PALW and laser only welding, the clamping pressure should have been similar.

The addition of the torch also prevented the use of the coaxial weld nozzle on the CO2 laser. With the plasma torch providing the shield gas in PALW the nozzle would have served only in a protective mode. In an industry setting a smaller nozzle could be

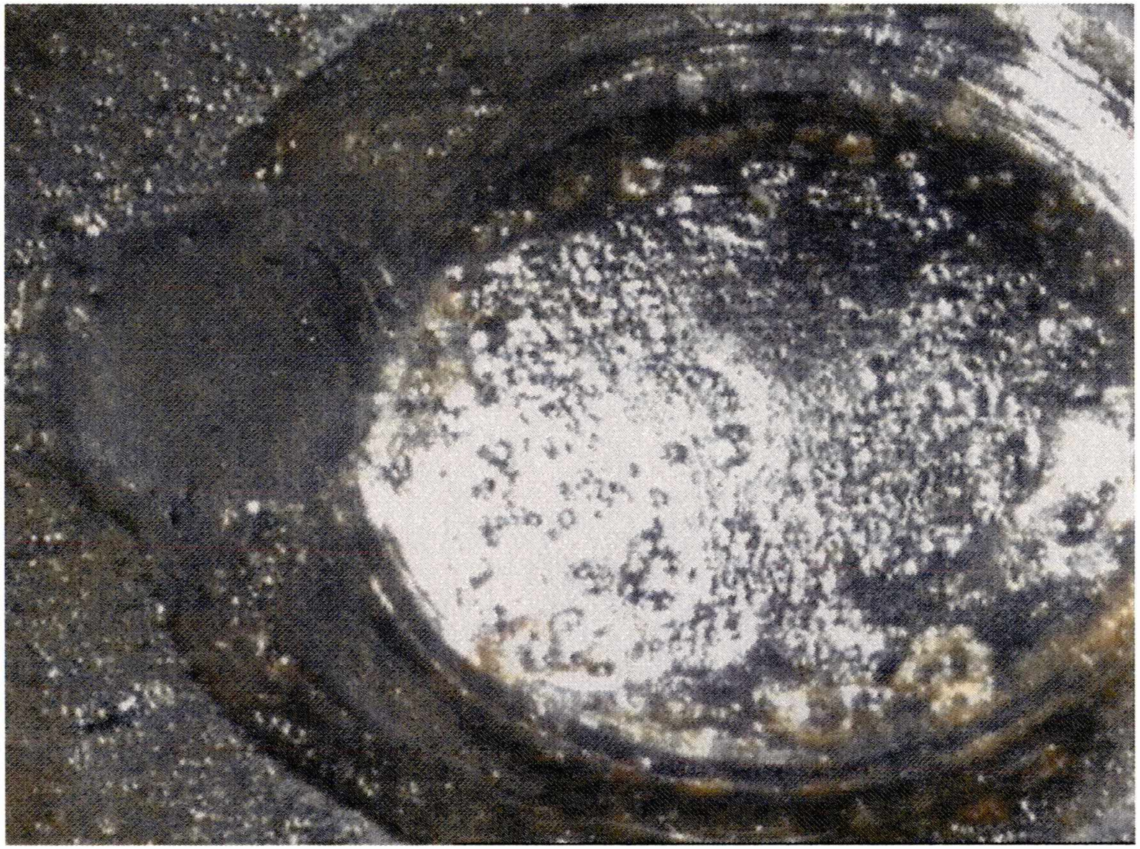

Figure 11. Proper Alignment of Plasma Torch with Laser.

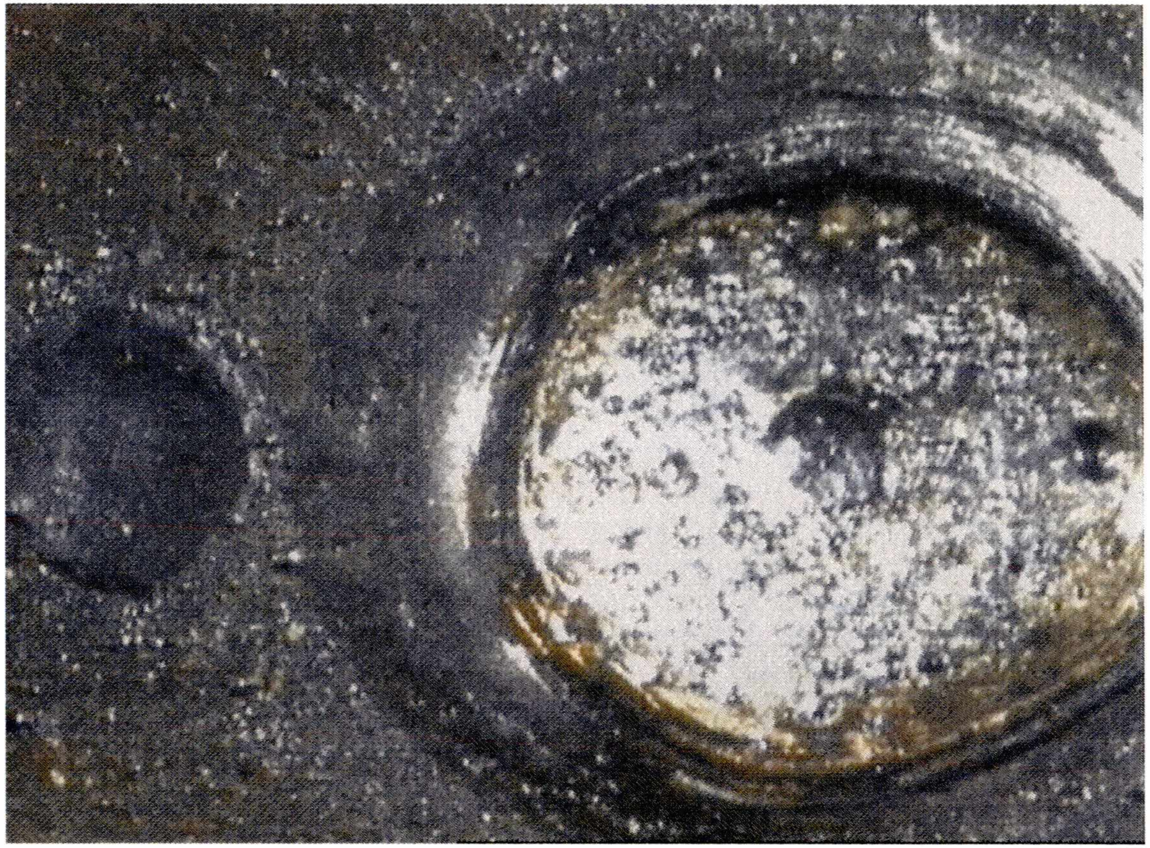

Figure 12. Improper Alignment of Plasma Torch with Laser.

fitted to the laser to provide protection, but for this study the removal of the weld nozzle should not have affected the welding process.

4.5 Plasma Only Samples

Samples were also gathered using only the plasma torch on the same material. The same 75 amps of current were used and the processing speeds, used in the other matrices, were repeated. The plasma torch was placed on the laser in the same way and all other factors were the same as for PALW. This data was gathered to show how the plasma torch performs without the laser and to show that the enhancement that occurs during PALW is greater than the simple addition of the two powers.

4.6 Welded Sample Preparation

As the coupon pairs were welded together they were marked with a number coding system in order to track them. The samples were then sectioned. Two sections were taken from each welded coupon. The sections were taken from the same two places on each coupon, corresponding to the location of the bolts, which apply the clamping pressure in the welding fixture. Each of these sections was also marked with the numeric code that allowed them to be traced to the original sample. Then the sections were mounted, with the two sections from each coupon mounted together. The sectioned and mounted samples were then polished and etched. The etchant used was 85% percent H2O, 15% nitric acid and 5% ethanol.

4.7 Die Penetrant Application and Methodology

On those samples where there was little or no gap present during welding it can be difficult to determine the exact FZW without a method for determining exactly where the fusion zone at the interface ends. A die penetrant was used on these samples. The penetrant was sprayed onto the mounted samples and allowed to dry thoroughly. A cleaner/remover solution, that comes with the penetrant, was then used to clean the excess penetrant from the surface of the mounted sample. At this point, through the use of a microscope, it may be possible to determine where the fusion begins at the interface. If this is still not possible, then a developer solution is then applied to the mount. This brings out any penetrant remaining on the coupon. Places where penetrant remains, show where the un-fused areas of the section occur, allowing the FZW to be analyzed.

The use of the die penetrant differs here slightly from its more common use, where it is used to only determine the presence of cracks in materials. Because it was necessary to be able to make a rather exact determination of where the interface begins and ends the normal method of spraying on the developer was not always sufficient. It was found here that the use of cotton swabs to apply the developer (and at times the penetrant itself) in small amounts produced much clearer results. It is also noted that the developing process may need to be repeated several times to produce the desired affect.

4.8 Sample Analysis

Digital photos of the mounted samples were taken using a digital imaging system mounted on a microscope. The photos were taken to determine the fusion zone width using image analysis software. Because the FZW specifications are given as a percentage of the single sheet thickness, the width of the interface can be determined by comparing it to the sheet thickness in the image. This gives the interface expressed as a percentage of the single sheet thickness, and allows the quality of the weld to be determined. This method removes any errors due to images taken at slightly different magnifications. The digital images were also analyzed to provide information about the amount of undercut, penetration, and the presence of any porosity in the samples.

4.9 Sources of Error

There are several sources of error when producing laser welds and analyzing the sections from these welds. These include variations in the weld due to inconsistencies in the metal, or contamination on the metal surface. The weld dimensions can also change rapidly, especially in the large material gap case, due to the inherent variations in the fluid flow of the molten metal.

This variation in the weld track can introduce error when sectioning the weld sample. Sections from one area may not accurately reflect the dimensions of the rest of the weld track. It is for this reason that samples here were taken from two different places in the weld track. Additionally, care must be taken to insure that the welds are sectioned perpendicular to the weld track. If not then the fusion zone may appear wider than it actually is.

The most prominent source of error would likely be in the measuring of the weld images to determine the weld dimensions. In order to take into account any variations in the thickness of the metal, the dimensions were determined as percentages of the sheet thickness as it appeared in the image being measured. Using this ratio method, this source of error should have been minimized, as should any error due to variations in the magnification of the images. The next source of error during measurement, and the major one, was determining where the fusion began and ended in the metal. This can be especially difficult on those welds where little gap was introduced. On those samples, where little or no gap was present, it can be hard to determine where fusion stops. The die penetrant was utilized to make this determination easier. The measurements on a sample proved to be reproducible, thus any error introduced should have been of a consistent amount throughout the sample analysis. Two different image analysis tools were also used to compare their results. Through this, it was found that the measurements were consistent and did not depend upon the image analysis software package used.

Error could also have been introduced from day to day variations in the laser power or beam quality. To counteract this, a base set of welding parameters was used to check the laser. Because the results of these welding parameters were known prior to the study we were able to check the laser by seeing if the previous result could be reproduced. To also counteract day to day variations in the laser, as much data was gathered as possible on each testing run.

The plasma torch also had to be checked, before each run, to be sure that its nozzle did not become clogged and cause inconsistencies in its gas flow. Still, error may have been introduced through any variation in the plasma arc produced by the plasma torch.

CHAPTER 5

RESULTS

In Chapter 5 the results of the laser only welding, PALW trials, and plasma torch only runs are presented. These results include the FZW, the amount of undercut, weld penetration and the presence of porosity in the welds. The joining methods are compared and the additional effects of adding the plasma torch to the laser welding process are examined.

5.1 Laser Only Results

Data was taken for the laser only case using helium and additionally with argon shield gas. The majority of the data taken was with helium, for the reasons stated previously.

Table 2 shows the FZW that were measured for the different laser welding parameters, using helium shield gas. The FZW is expressed as a percentage of the single sheet thickness. The table show the FZW for the no gap, 5.2% and 8.6% gap conditions, respectively. The material gaps are stated as percentages of the single sheet thickness. There are two FZW presented for each weld condition corresponding to the two sections taken from each welded coupon.

From the data, it can be seen that the introduction of the material gaps introduces a great deal of variation in the results, for laser only welding, using helium. However, the FZW is often smaller in the 5.2% gap when compared to the no gap condition, and the

Table 2. Laser Only Results, using Helium.

			No gap condition						5.2% gap condition						8.6% gap condition					
			FZW*						FZW*						FZW*					
Power (Watts)	Speed (mm/min.)	Focus (mm)	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration
3000	1000	2	78	80	2	79.0	-	-	65	63	2	64.0	-	-	81	73	8	77.0	-	-
3000	1375	2	63	59	4	61.0	-	-	62	55	7	58.5	-	-	74	79	5	76.5	U	-
3000	1750	2	57	51	6	54.0	-	-	72	72	0	72.0	-	-	74	69	5	71.5	U	-
2500	1000	2	78	82	4	80.0	-	-	69	67	2	68.0	-	-	84	86	2	85.0	U	-
2500	1375	2	58	67	9	62.5	-	-	56	57	1	56.5	-	-	62	74	12	68.0	U	-
2500	1750	2	61	53	8	57.0	-	-	58	68	10	63.0	-	-	81	73	8	77.0	U	-
1850	1000	2	71	77	6	74.0	-	-	66	67	1	66.5	-	-	81	75	6	78.0	U	-
1850	1375	2	57	54	3	55.5	-	LP	63	70	7	66.5	-	-	66	67	1	66.5	U	-
1850	1750	2	47	48	1	47.5	-	LP	54	46	8	50.0	-	LP	60	54	6	57.0	U	LP
3000	1000	1	72	69	3	70.5	-	-	60	61	1	60.5	-	-	76	76	0	76.0	U	-
3000	1375	1	55	54	1	54.5	-	-	67	60	7	63.5	-	-	82	73	9	77.5	-	-
3000	1750	1	53	47	6	50.0	-	-	70	73	3	71.5	-	-	68	71	3	69.5	U	-
2500	1000	1	71	75	4	73.0	-	-	55	64	9	59.5	-	-	79	84	5	81.5	U	-
2500	1375	1	64	60	4	62.0	-	-	61	66	5	63.5	-	-	80	84	4	82.0	U	-
2500	1750	1	67	78	11	72.5	-	-	46	57	11	51.5	-	-	80	78	2	79.0	-	-
1850	1000	1	78	80	2	79.0	-	-	69	66	3	67.5	-	-	76	73	3	74.5	U	-
1850	1375	1	58	58	0	58.0	-	-	58	56	2	57.0	-	-	76	77	1	76.5	U	-
1850	1750	1	41	42	1	41.5	-	LP	50	53	3	51.5	-	LP	54	55	1	54.5	U	LP
3000	1000	0	60	69	9	64.5	-	-	60	58	2	59.0	-	-	81	84	3	82.5	U	-
3000	1375	0	63	56	7	59.5	-	-	60	62	2	61.0	-	-	81	79	2	80.0	-	-
3000	1750	0	76	60	16	68.0	-	-	74	50	24	62.0	-	-	69	72	3	70.5	U	-
2500	1000	0	80	76	4	78.0	-	-	59	57	2	58.0	-	-	79	76	3	77.5	U	-
2500	1375	0	70	67	3	68.5	-	-	68	61	7	64.5	-	-	74	73	1	73.5	-	-
2500	1750	0	69	58	11	63.5	-	-	80	73	7	76.5	-	-	87	85	2	86.0	U	-
1850	1000	0	83	78	5	80.5	-	-	74	72	2	73.0	-	-	83	89	6	86.0	-	-
1850	1375	0	67	59	8	63.0	-	-	52	50	2	51.0	-	LP	90	89	1	89.5	U	LP
1850	1750	0	64	69	5	66.5	-	LP	63	65	2	64.0	-	LP	65	60	5	62.5	U	LP
			Avg.	Diff.	5.3						4.9						4.0			

*FZW is expressed as a percentage of the single sheet thickness

FZW are largest when the 8.6% gap is introduced. This increase in FZW for the largest gap condition is caused by the flow of the molten metal out into the material gap. It is important to note here that a fusion zone that has been widened by this metal flow may not posses the structural strength of a weld where the width is not due to metal flow into the gap. The welding parameters that have resulted in a FZW that meets the specifications (75%) for the no gap condition give the best example of what effect the 5.2% gap has on FZW. For these cases the FZW no longer meets the specification once gap has been introduced.

Table 2 also shows the existence of undercutting and the penetration of the laser only welds, with helium gas. A U marks the welds, in which the undercut is deeper than 5% of the single sheet thickness. LP marks Welds in which the total penetration was less than 80% of two-sheet thicknesses, for lack of penetration. These values were chosen because they are the values used in current manufacturer's specifications, for these dimensions. From these tables it can be seen that the presence of the gap had little effect on the ability of the laser to fully penetrate the metal sheets. It can also be seen that undercutting is not a problem for the no gap and 5.2% gap cases, but is very prevalent in the 8.6% case. The undercutting is present for only that gap because of the metal that flows into the gap at the weld interface. With the metal flowing into the interface there is no longer as much metal at the top of the weld and thus an undercut weld is created. The presence of undercutting in the 8.6% case offsets the gains in FZW at that gap, because while width at the interface does generate weld strength, undercutting creates a weak point in the top of the weld.

Any porosity that was found in the laser only welds was also measured. No porosity was found to be of significant size. Current weld specifications allow for 25% of the weld surface to be covered by porosity. None of the laser welds were found to have porosity larger than 6% of the weld surface and most were less than 2%.

Table 3 shows the data gathered for the case where argon shield gas was used. Those conditions marked with an "x" denote data points that were not taken. Again laser work with argon shield gas was limited for the aforementioned reasons. Similar results to the helium shielded welds can be seen for the FZW and undercutting when using argon gas. However the FZW are smaller and there was a much greater difficulty in generating properly penetrated welds. It is also important to note that no FZW was generated with argon for the 3000 Watt case. The plasma absorbed the bulk of the laser energy, at this power level, and made the laser unable to fuse the two pieces of metal. Porosity was also not substantial for laser welding with argon gas.

5.2 PALW Results

Data for the PALW is presented in a manner similar to the laser only results. The torch current, which was held constant, at 75 amps, is included. The results for the FZW, undercutting, and penetration of the PALW, are shown in table 4. The same conventions and values were used, as in the laser only case.

In looking at the FZW for the PALW runs it can readily be seen that increases in speed had a very negative effect on the FZW, for all sizes of gap. A good example of this is the degree to which the FZW changes between 1000mm/min. and 1375mm/min. The

Table 3. Laser Only Results, using Argon.

			No gap condition						5.2% gap condition						8.6% gap condition					
			FZW*						FZW*						FZW*					
Power (Watts)	Speed (mm/min.)	Focus (mm)	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration
3000	1000	1	0	0	0	0.0	-	LP	x	x	###	###	x	x	x	x	###	###	x	x
2500	1000	1	58	74	16	66.0	-	-	x	x	###	###	x	x	x	x	###	###	x	x
1850	1000	1	49	48	1	48.5	-	-	60	55	5	57.5	-	LP	76	73	3	74.5	-	-
1850	1375	1	x	x	###	###	x	x	47	43	4	45.0	-	LP	81	70	11	75.5	U	LP
1850	1600	1	x	x	###	###	x	x	60	49	11	54.5	-	LP	56	60	4	58.0	U	LP
1850	1750	1	x	x	###	###	x	x	42	47	5	44.5	-	LP	38	43	5	40.5	-	LP
			Avg.	Diff.	5.7						6.3						5.8			

*FZW is expressed as a percentage of the single sheet thickness

Table 4. PALW Results.

Power (Watts)	Speed (mm/min.)	Torch Current (Amps)	Focus (mm)	No gap condition						5.2% gap condition						8.6% gap condition					
				FZW*						FZW*						FZW*					
				Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration	Run 1	Run 2	Difference (|R1-R2|)	Avg. of Runs	Under cut	Pene-tration
3000	1000	75	1	115	108	7	111.5	-	-	126	115	11	120.5	U	-	155	128	27	141.5	-	-
3000	1375	75	1	81	74	7	77.5	-	-	75	76	1	75.5	-	-	100	107	7	103.5	U	-
3000	1600	75	1	61	62	1	61.5	-	-	59	65	6	62.0	U	-	86	92	6	89.0	-	-
3000	1750	75	1	58	55	3	56.5	-	-	66	62	4	64.0	U	-	79	70	9	74.5	-	-
3000	2000	75	1	37	33	4	35.0	-	-	46	45	1	45.5	U	-	58	66	8	62.0	U	-
3000	2250	75	1	56	47	9	51.5	U	-	44	42	2	43.0	-	-	53	56	3	54.5	U	LP
2500	1000	75	1	114	119	5	116.5	-	-	118	122	4	120.0	-	-	153	146	7	149.5	U	-
2500	1375	75	1	79	66	13	72.5	U	-	74	70	4	72.0	-	-	104	99	5	101.5	U	-
2500	1600	75	1	68	52	16	60.0	-	-	59	58	1	58.5	-	-	87	85	2	86.0	-	-
2500	1750	75	1	54	54	0	54.0	-	-	53	57	4	55.0	-	-	69	80	11	74.5	-	-
2500	2000	75	1	46	48	2	47.0	U	-	48	51	3	49.5	-	-	65	60	5	62.5	U	-
1850	1000	75	1	109	100	9	104.5	U	-	107	102	5	104.5	-	-	116	119	3	117.5	U	-
1850	1375	75	1	60	63	3	61.5	-	-	62	60	2	61.0	-	-	85	75	10	80.0	-	-
1850	1600	75	1	47	50	3	48.5	U	-	48	41	7	44.5	-	-	70	64	6	67.0	-	-
1850	1750	75	1	42	35	7	38.5	U	-	44	45	1	44.5	U	-	53	60	7	56.5	U	-
				Avg. Diff		5.9						3.7						7.7			

*FZW is expressed as a percentage of the single sheet thickness

flow of the metal into the material gap for the 8.6% gap can also be seen, as it was for the laser only case.

Achieving proper penetration was a problem for only one of the conditions for the PALW process. It was found here that a fully penetrated weld could be achieved at higher processing speeds using plasma arc assist, for the same laser power. This shows that if a fully penetrated weld is desired the use of PALW can increase production speed.

Undercut welds can be found for all the tested gaps, for PALW. The occurrence of undercut, for the PALW process at all the gaps, may be explained by the increased amount of energy input into keyhole. For PALW, the top bead of the weld tends to rise above the surface of the metal, to a level that creates grooves on either side of the top bead. At times the grooves are substantial enough to create an undercut weld. In the 8.6% gap case, some of the undercutting can again be attributed to the flow of metal into the material gap, as in the laser only case.

The PALW had porosity of similar size to the laser only welds, with no pores approaching the 25% level. The welds done with the plasma assist however did have a much higher occurrence of pores, with most of the welds having at least a small pore. In most cases these pores did account for less than 1% of the total weld surface.

5.3 Comparison of Joining Methods

Figures 13 through 15 show the FZW vs. the laser power at all introduced gaps, for the three respective processing speeds, for both the laser only case, using helium gas, and PALW. Only those laser only welds where a +1mm focal position was used are included, so as to be able to compare them to PALW. Here both data points for each

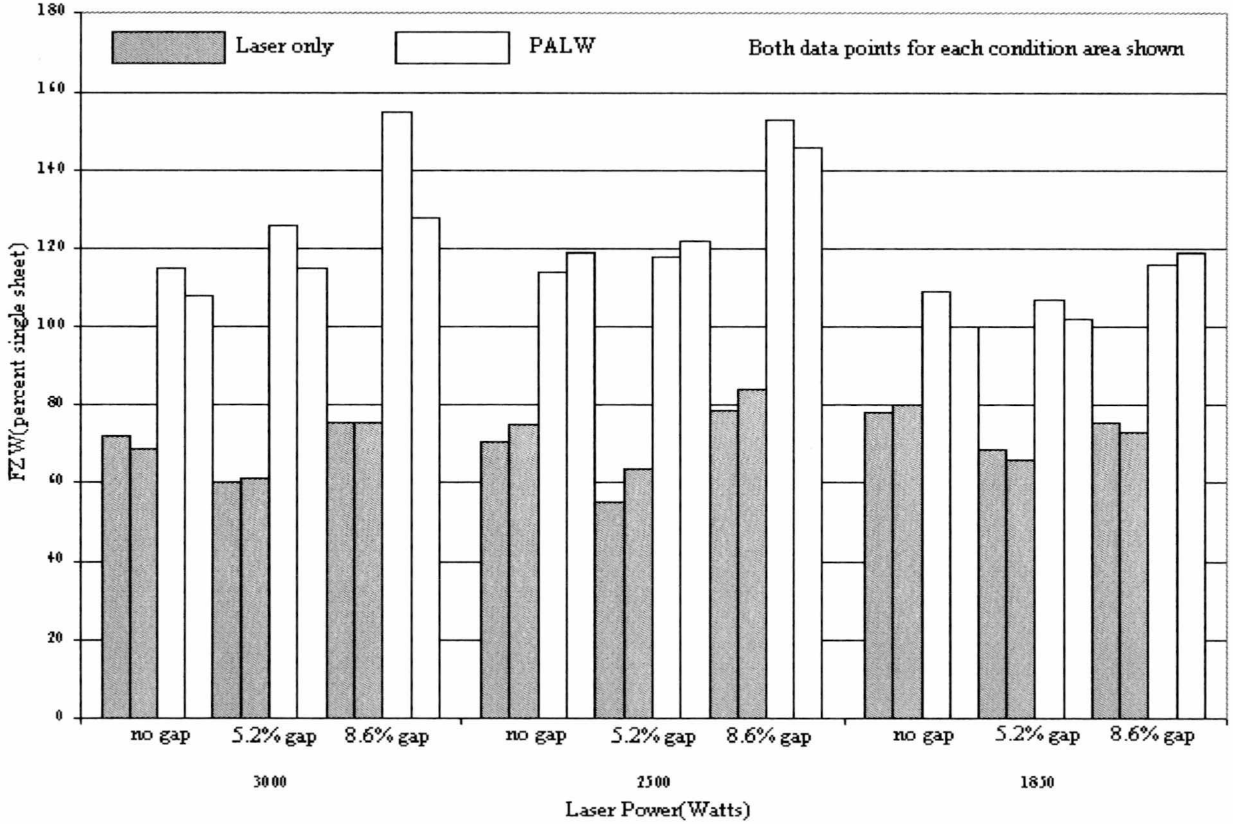

Figure 13. FZW vs. Laser Power, for Laser Only and PALW, 1000mm/min. Laser only data taken with helium gas. All welds were performed at +1mm focal position.

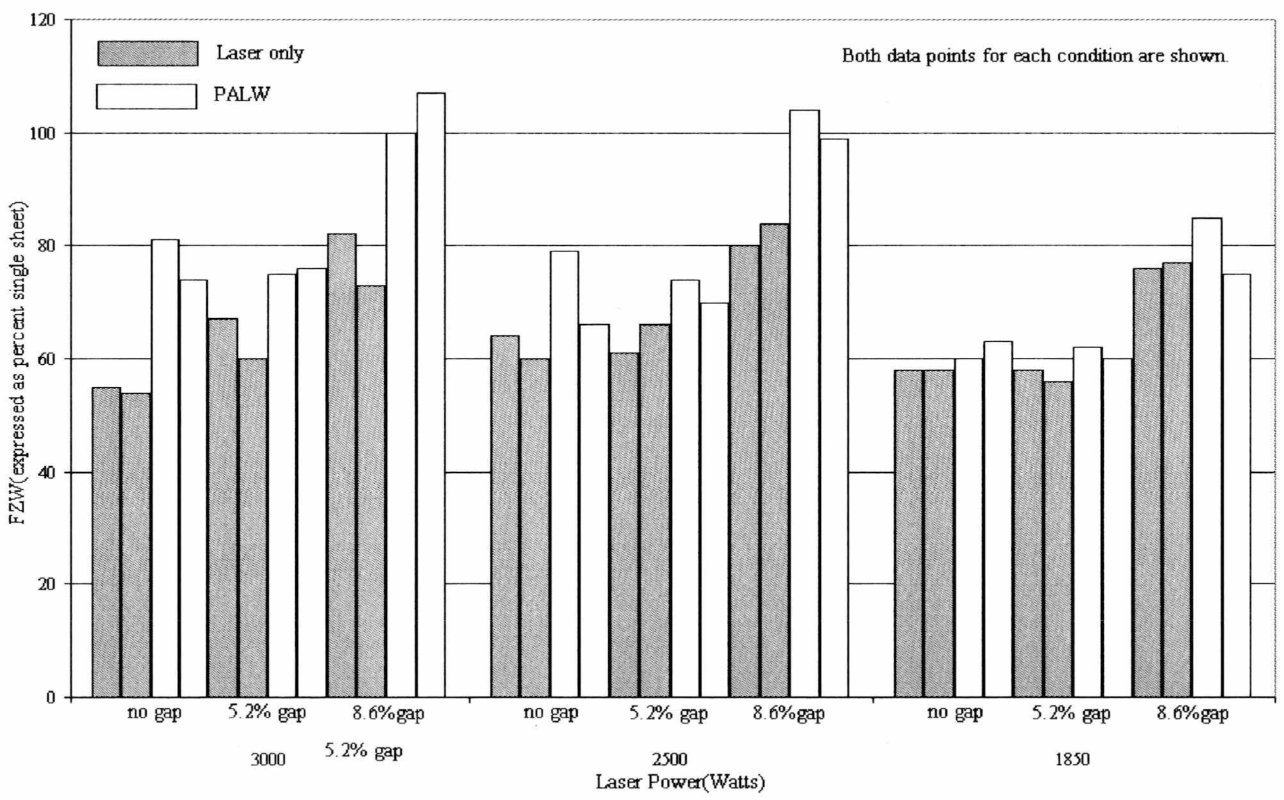

Figure 14. FZW vs. Laser Power, for Laser Only and PALW, 1375mm/min. Laser only data taken with helium gas. All welds were performed at +1mm focal position.

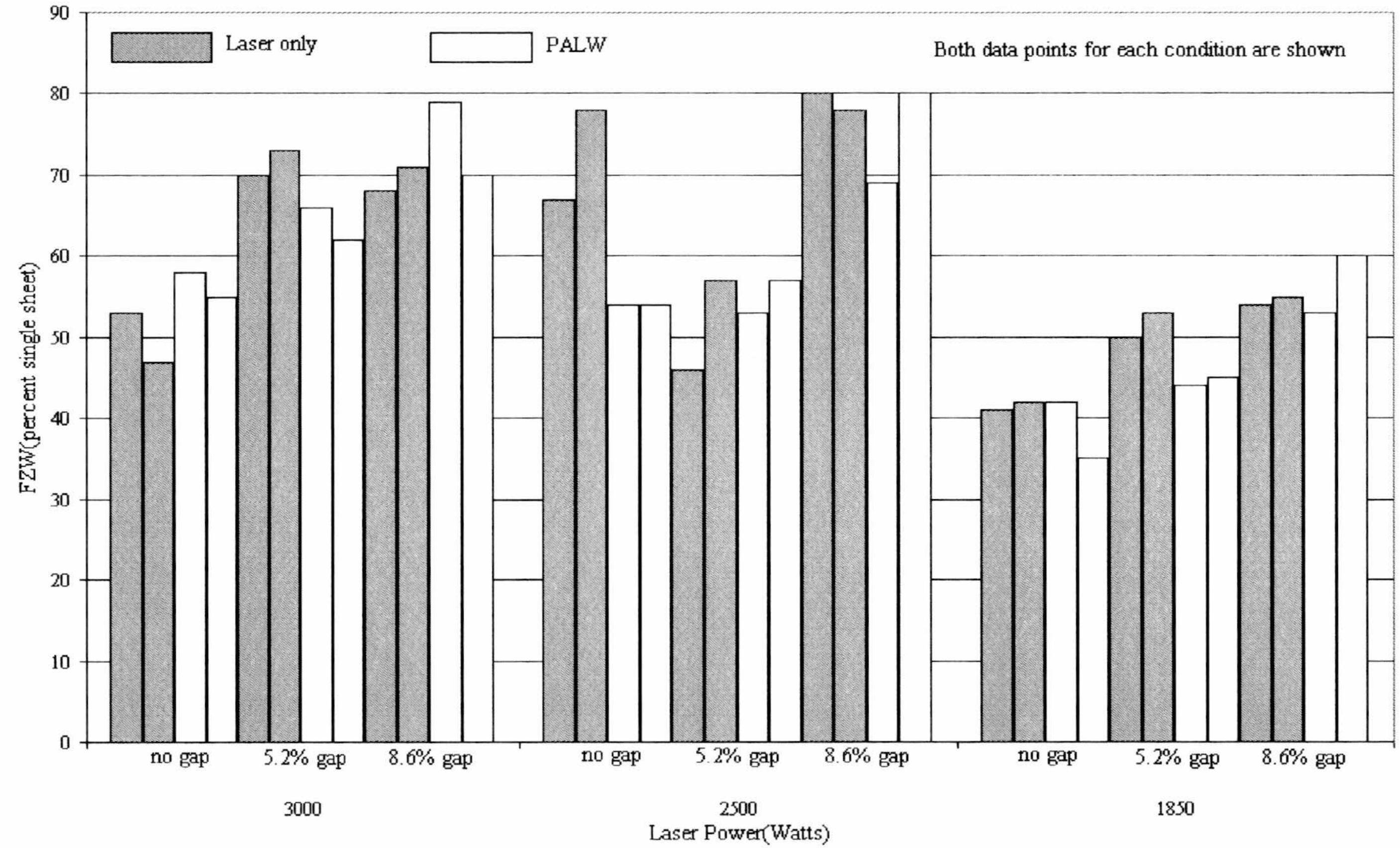

Figure 15. FZW vs. Laser Power, for Laser Only and PALW, 1750mm/min. Laser only data taken with helium gas. All welds were performed at +1mm focal position.

separate set of processing parameters is shown. As a note, the results show an average FZW width of 35% for the PALW case where 3000W, 75A and a processing speed of 2000mm/min. were used. This data point is considered here to be an outlying point. The data point was checked, and while the measurements were correct, the data point is taken here to be the result of some error in the processing system and not valid data.

In the tables for 1000mm/min. and 1375mm/min., if the FZW's are compared between the laser only case and PALW, for the same gap, it can be seen that for most of the cases the FZW is much greater. Many of the cases show increases of 20% or more in the FZW for the PALW trials compared to the laser only trials. However in the 1750mm/min. table it can be seen that the FZW's of the laser only case are greater or at least very comparable to those of the PALW trials. This is a reflection of the impact processing speed has on PALW. In his work with MIG arc assisted laser welding, Abe found that speed also had a decidedly negative effect on the welds.

The tables presented in the earlier this chapter showed that with the addition of the plasma torch achieving the necessary penetration is much easier. This is a result of the shielding effects of the plasma torch and the power it adds to the welding process. Penetration may also not have been a problem here because of the thickness of the material being welded. In work on much thicker plates (12mm), with MIG arc assist, Abe found that penetration was affected at higher speeds. The shielding effects and increased power absorption due to the plasma torch are explained further later on this text.

Compared to the laser only case, PALW has a much greater occurrence of undercutting in the welds than the laser only case. The undercutting occurs in more cases and is of a more severe type than the laser only case. When the laser only welds are undercut they tend to be undercut across the entire top bead, unlike the PALW case where the welds are undercut only to the sides of the top bead. Examples of these two different types of undercutting can be seen in figures 16 and 17. Because the undercut is more spread out in the laser only case, the undercut tends to not be as deep and therefore not as damaging. With the PALW case having grooves on both sides of the top bead, two separate areas of weakness in the weld are created. This undercutting problem for the PALW case could be the result of several factors. Among these is too much energy being put into the weld cavity, less than optimal alignment between the plasma torch and laser, and the use of argon gas in the torch. The use of a lighter gas, like helium, might serve to remedy some of this problem, because it doesn't remain in the weld cavity as long. These explanations are in addition to the undercutting problem created by larger gaps, found in both laser only welding and PALW.

Plasma torch only runs, at the same processing speeds as PALW, also show the same type of undercutting in the top bead of the weld. Because of this, it is believed that most of this undercutting is due to how the plasma torch is implemented here, and not necessarily to the addition of the torch to the laser welding process. An example of the undercut present in the plasma torch only runs is shown in figure 18.

As mentioned in the section on the laser only results, it is difficult to find a trend for the laser only welds when the FZW results are plotted because of the variation that the introduction of the gaps brings to the process. However by looking at figure 19, it can be seen that with PALW these variations due to gap can be overcome. In figure 19 the FZW is plotted versus the processing speed. From the plots it can be seen that the 5.2% gap

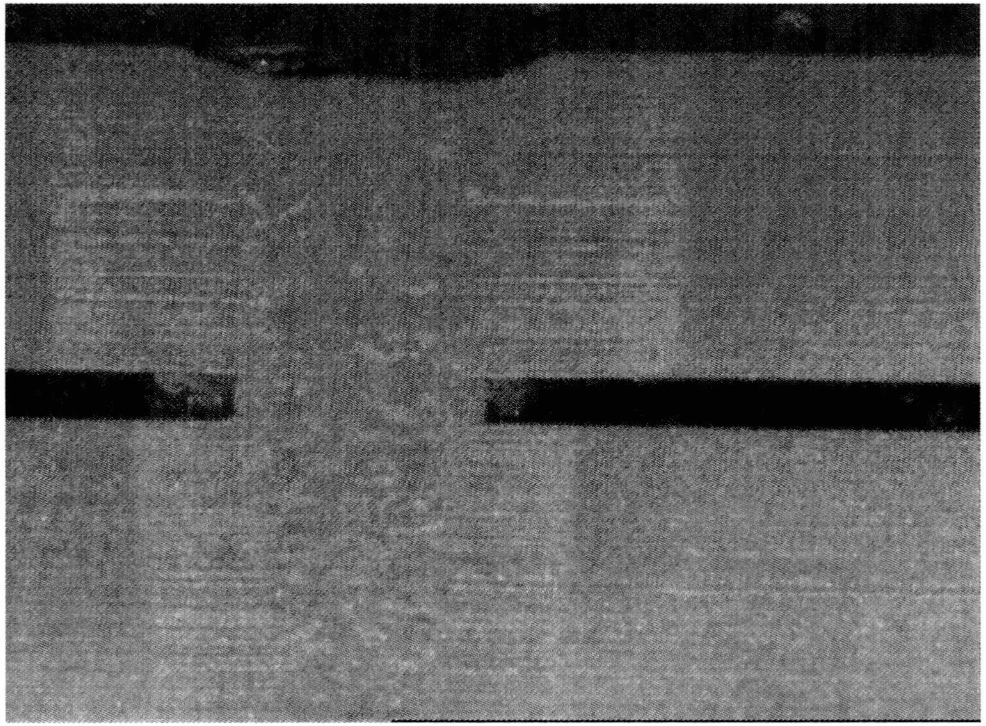

Figure 16. Laser Only Undercut Example. Weld performed on 80Y90T with a CO2 laser using helium gas (1850W, 1000mm/min., +1mm focal position, 8.6% gap).

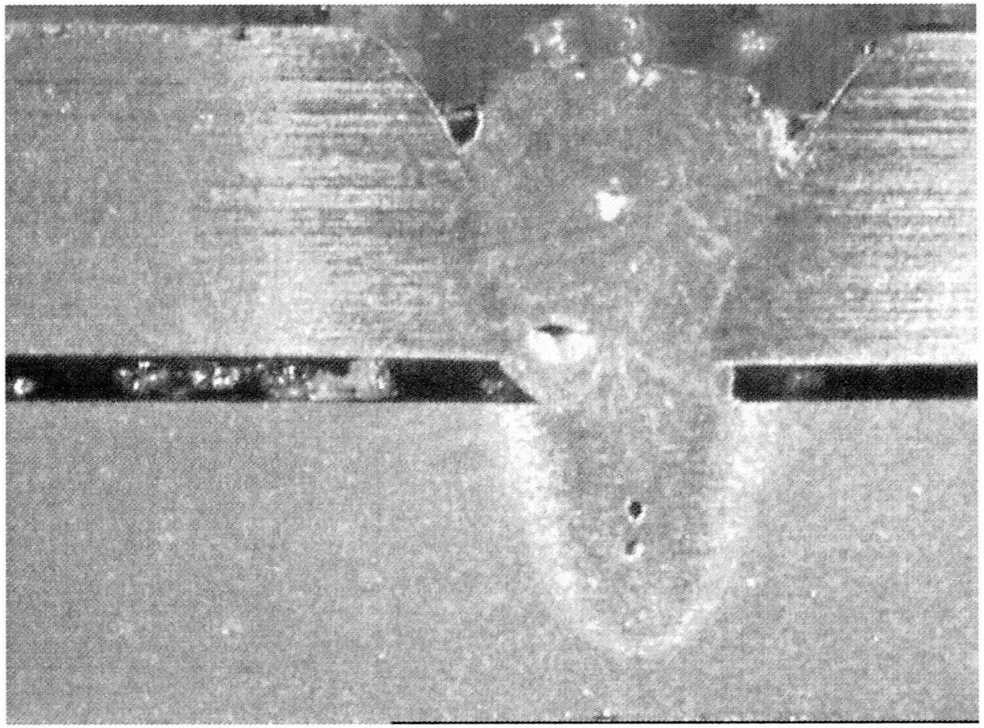

Figure 17. PALW Undercut Example. Weld performed on 80Y90T using PALW (2500W, 75A, 2000mm/min., +1 focal position, 8.6% gap).

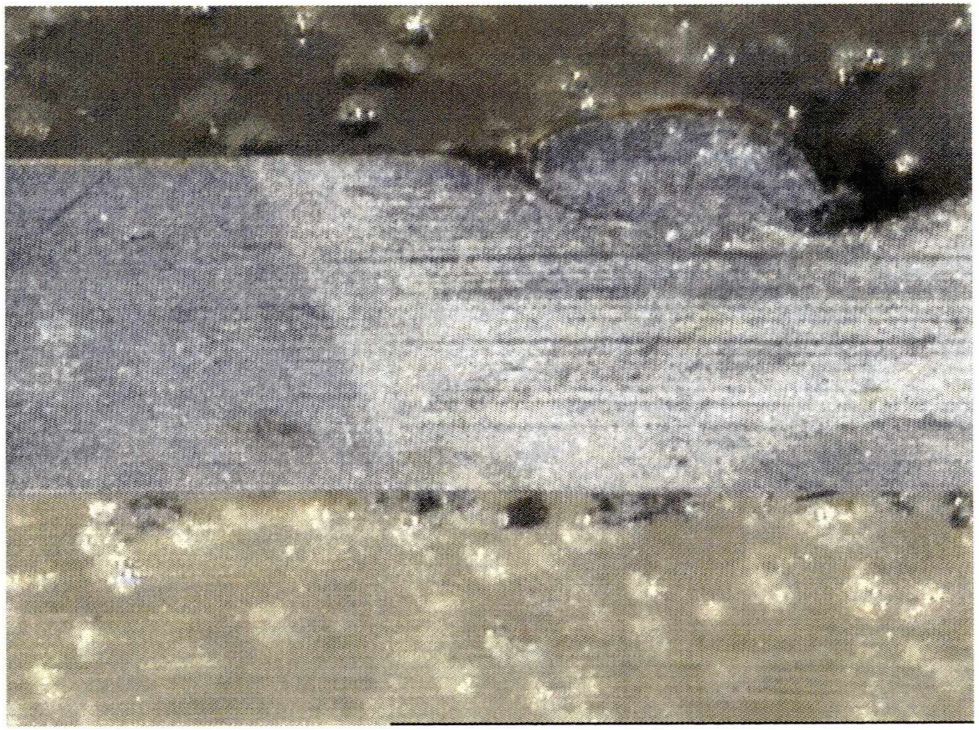

Figure 18. Plasma Torch Only Undercut Example. Track performed on 80Y90T using only the plasma torch (75A, 1000mm/min.).

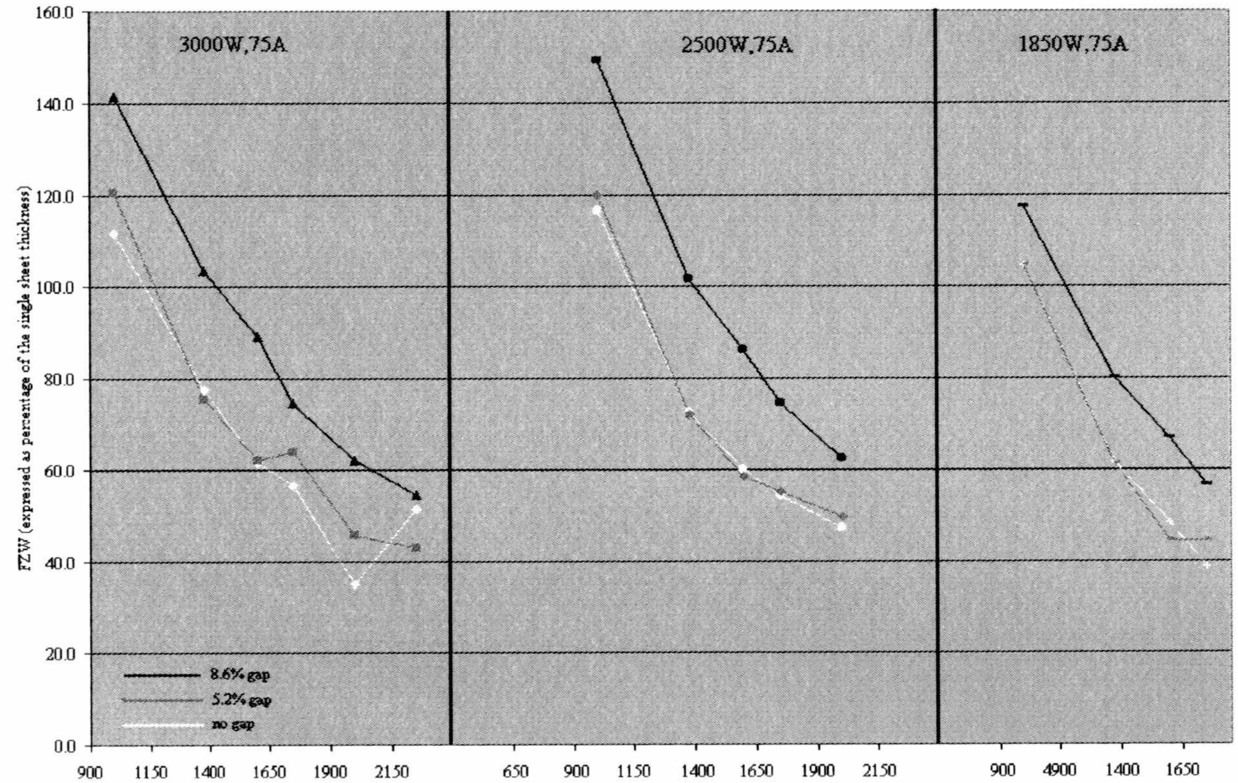

Figure 19. FZW vs. Processing Speed, for PALW.

had little or no effect on the FZW results, compared to the no gap case. It is also readily seen that the FZW is largest for the 8.6% gap case. Comparing this figure to figures 20 through 22, it is apparent that the introduction of gap has more effect on the laser only welds. The reason that the variation in the FZW results for the laser only welds is not seen for PALW, is the amount of metal melted in the PALW process. Because of the larger amount of metal melted by PALW, the variation in data caused by the introduced gaps accounts for a much smaller percentage of the dimensions and therefore does not appear as readily. Therefore, with respect to FZW, the PALW process is more tolerant to the presence of material gap.

5.4 Plasma Torch Effects on the Laser Beam

If the processing parameter are the same, one can add the area of metal melted by the laser alone to the area of metal melted by the laser alone and see that this total area is less than the total area melted by the PALW process. This shows that Biffin is correct, and that the plasma torch does serve to increase the effective absorption of the metal and cause more laser power to be absorbed. Accordingly, it can be said that the area of metal melted by PALW can be expressed as:

$$A_L + A_P + \Delta = A_{PALW}.$$

Where the A_L is the area of metal melted by the laser alone, A_P is the area melted by the plasma torch alone, A_{PALW} is the area melted by PALW, and Δ represents the area melted by the effects of the plasma torch on the laser beam.

As an example of this, at 75A of current and a processing speed of 1000mm/min. cross sections, of a plasma torch only track, show that an area of metal was melted equal

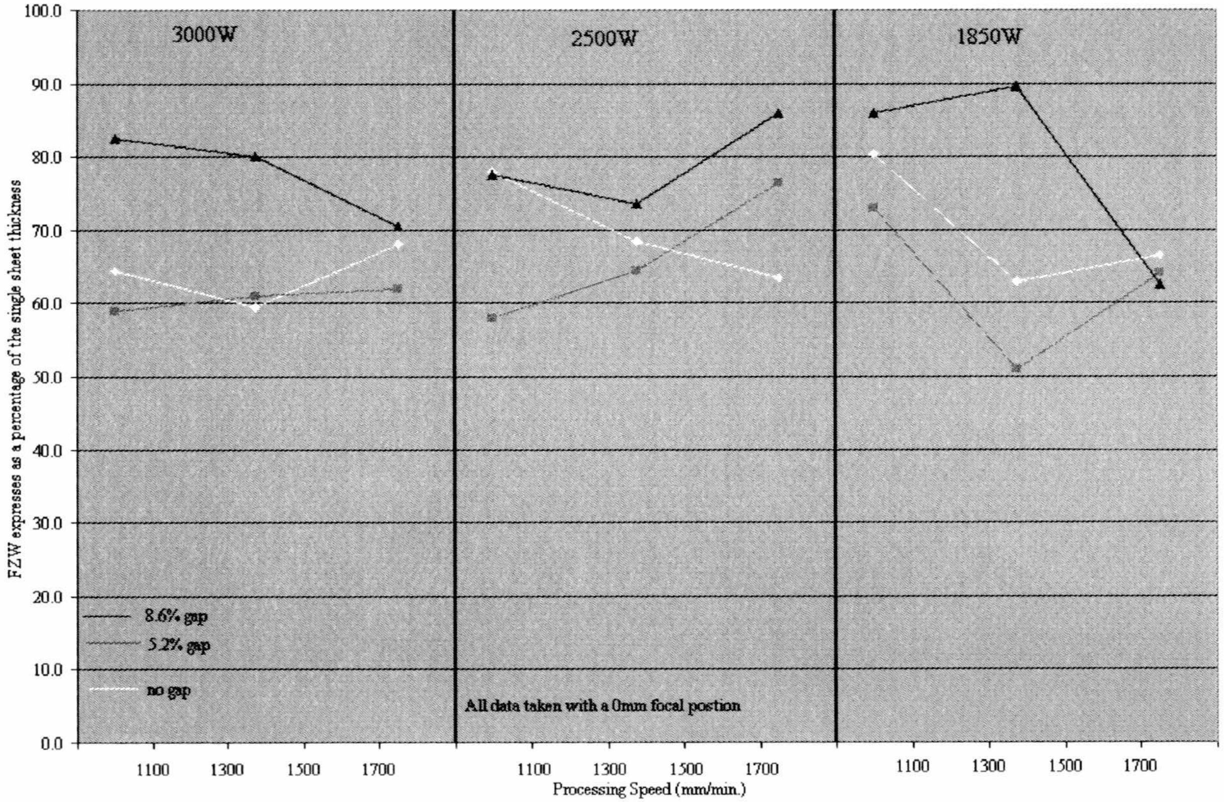

Figure 20. FZW vs. Processing Speed, for Laser Only, 0mm Focal Position. Helium gas was used.

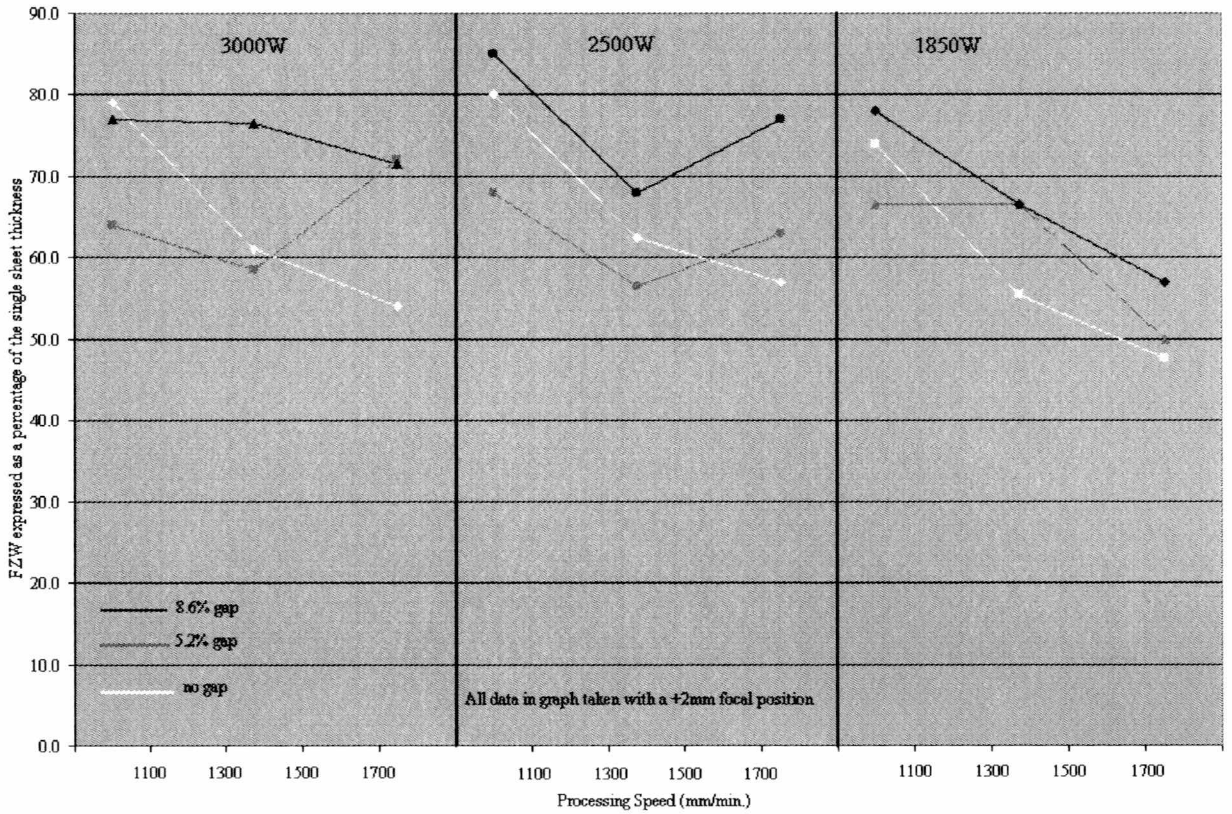

Figure 21. FZW vs. Processing Speed, for Laser Only, +1mm Focal Position. Helium gas was used.

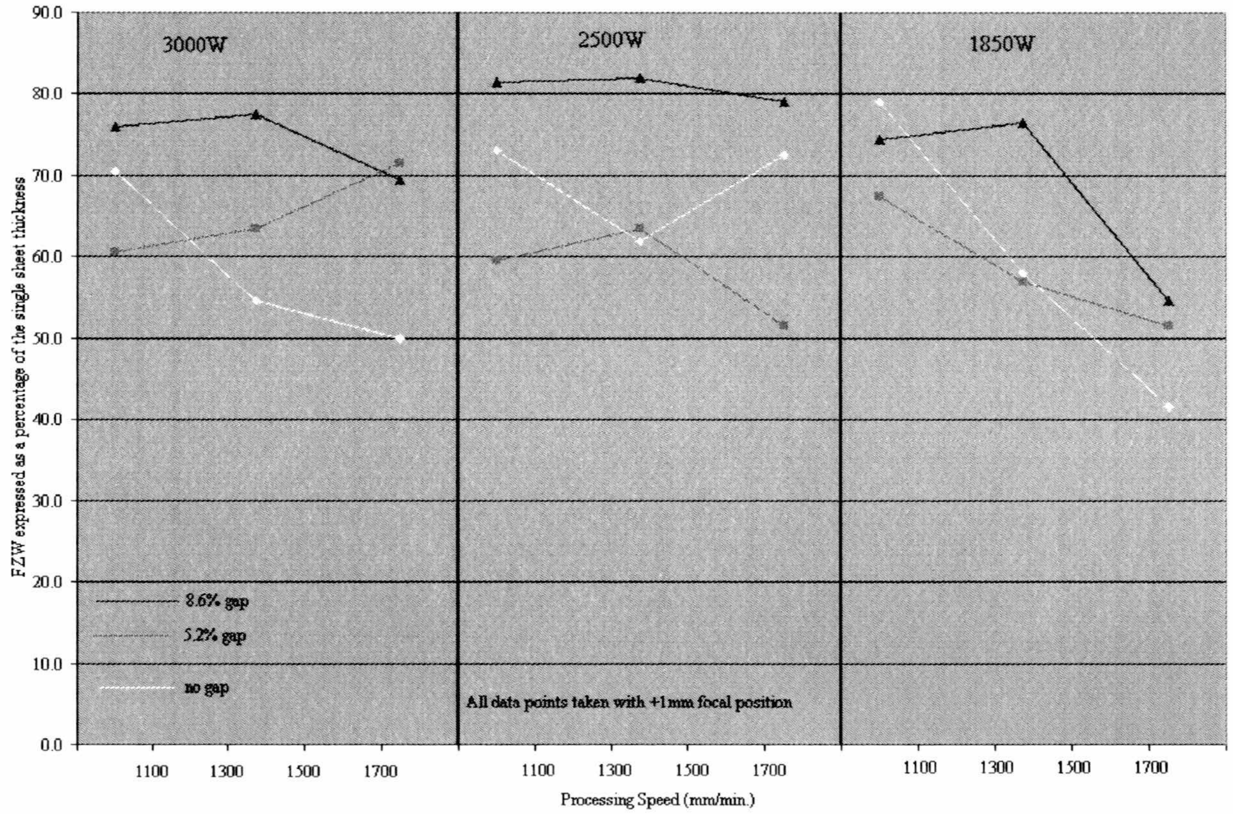

Figure 22. FZW vs. Processing Speed, for Laser Only, +2mm Focal Position. Helium gas was used.

to .59mm^2. At the same processing speed, the measured amount of metal melted by the laser, using 1850W and argon gas, was 2.66mm^2. PALW, combining the two previous cases and using 75A torch current and 1850W was able to melt 5.25mm^2. Applying the previous equation, Δ is then equal to 2.00mm^2. This additional melting shows that the effective reflectivity of the metal is being reduced and that the metal is absorbing more power. This increased power absorption accounts for the increased FZW found with PALW, compared to the laser only case. Table 5 shows the data for the area of metal melted by the laser only using argon and helium, the plasma torch alone, and PALW. The Δ, and an efficiency factor have also been calculated and are shown in table 5. When looking at table 5 the increase in Δ and the efficiency factor for the 3000W case is very apparent. This is a result of the case mentioned in the laser only welding with argon gas, where plasma formation prevented a keyhole being produced. Because of this the area of metal melted by the laser alone is much smaller than the lower powers. This is also a good example of the effects of the plasma arc. Without the plasma arc assist very little metal is melted by the laser however, once the torch is added a keyhole was formed. While less metal was melted by PALW for this case, compared to the lower power cases, the addition of the plasma arc did bring the area of metal melted up close to the other cases.

Figure 23 shows a plot of the area melted by the laser with argon, laser with helium and PALW versus the laser power used. This plot shows that the area of metal melted was lowest for the laser only using argon. The greatest area of metal was melted by the PALW technique, for the laser power input. The laser only case using helium was able to melt more metal than the argon case but falls below the PALW case.

Table 5. Area Melted Results.

							Efficiency Factor
Current(A)	Power(W)	Speed(mm/min.)	A_L(mm2)	A_P(mm2)	A_{PALW}(mm2)	D(mm^2)= $[A_{PALW} - (A_L + A_P)]$	$A_{PALW}/(A_L+A_P)$
75	1850	1000	2.66	0.59	5.25	2	1.62
75	2500	1000	3.07	0.59	5.42	1.76	1.48
75	3000	1000	0.39	0.59	5.09	4.11	5.19

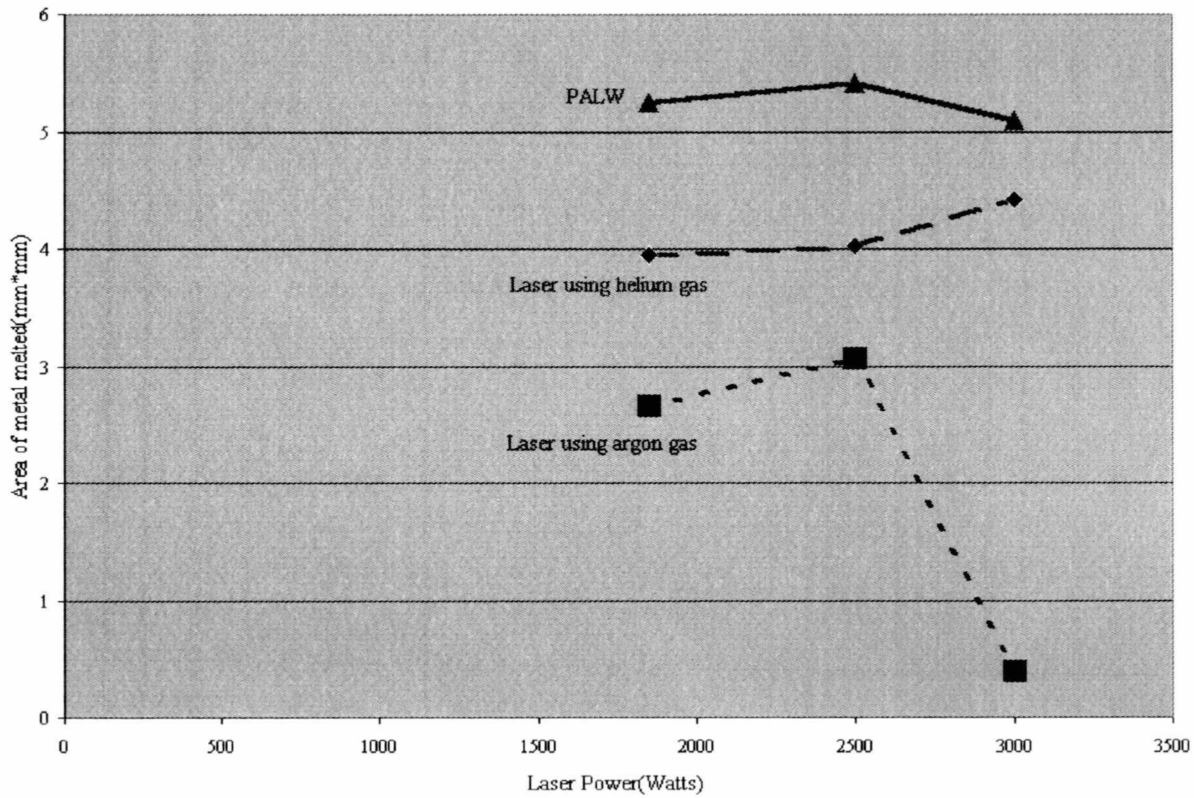

Figure 23. Area Melted vs. Laser Power. All data gathered with a +1mm focal position and the 80Y90T material was used.

CHAPTER 6

CONCLUSIONS

The results of the study, recommendations from the study, and options for future work are discussed in this chapter.

6.1 Results

The effects of material gap on laser only welding are the introduction of variation into the FZW, difficulty in achieving proper FZW, and undercutting, at the highest gap level studied here. For PALW, in the presence of material gap, achieving FZW is not a problem, the variations in the FZW are not seen, and undercutting is a concern at all gaps. For both PALW and laser only welding, material gap has little effect on penetration depth, though PALW is capable of achieving a fully penetrated weld at higher speeds.

The use of plasma arc assist can increase FZW even in the presence of material gap. By minimizing the effects of the variations introduced by gaps, PALW shows an increased tolerance to gap compared to laser only welding.

It was also shown here that plasma arc assist can increase the effective absorptivity of the metal being welded, and may also reduce the effective sheet thickness.

6.2 Recommendations

Based on the results of this study, it is recommended here that in an industrial setting every effort be made to restrict material gap to no greater than 5% of the single sheet thickness. This is for both the laser only case and for PALW, in cases where a stringent weld specification is being used. For laser welding applications where it is desired to increase FZW without losing processing speed the use of plasma arc assist is a viable option. Once the undercutting problem with plasma arc assist is solved it could be of great benefit when trying to meet a welding specification, without sacrificing production speed, especially when weld width and depth are of importance.

Gap is best controlled by designing the component to be laser welded from the outset. It is not recommended here to try and overcome severe gaps with fixturing. The part to be welded should be near 5% gap before it is fixtured, because trying to reform a component with fixturing can be difficult or even impossible.

When implementing plasma arc assist the torch can best be taken advantage of it is placed so that it will be premelting the metal, in front of the laser beam. It is not recommended here to try and apply the torch coaxially to the laser beam, as this can create plasma formation difficulties. Placing the torch so that it is incident slightly forward of the laser spot, and at an angle to the laser beam should provide the desired results.

6.3 Future Work

There are a variety of options that might be considered for future work in this area. Several of these involve the improvement of the process studied here. Others could include looking at the use of Nd:YAG laser for PALW, or other uses for plasma torch assistance in the laser materials processing area.

For the application covered here, additional work should determine the proper alignment of the plasma torch and the laser beam. This could produce better results through reduced undercut and increases in speed. Because alignment has such an important impact on the PALW process a great deal could be gained by more complete knowledge of the interaction of the two power sources.

After the proper alignment between the torch and laser is found work should be begun to design and integrated welding nozzle, for plasma arc assist. Laser manufacturers and others in the field have begun work on the design of an integrated welding nozzle. This nozzle would be designed to incorporate the use of the plasma torch with the laser. A great deal of work could be done in designing this type of nozzle. Nozzles could be designed to allow for the alignment of the power sources to be varied according to what is desired. Nozzles could also be designed specifically for certain applications, which would fix the alignment in the most desirable position.

Work with the Nd:YAG laser for PALW has been started already by John Biffin. There are problems with the use of YAG lasers on nonferrous materials, because of reflection. The use of plasma arc assist may enable this limitation of the YAG to be overcome. Because of the versatility of the Nd:YAG laser this could be a great advantage to industry.

Using a plasma unit capable of delivering more power to perform a study similar to this one may also be of benefit. If a higher torch current is used, more benefits from plasma arc assist may be seen.

To further study ways of overcoming the effects of material gap on laser welding, one could look at the addition of filler material to the process or other hybrid welding techniques. Through the addition of a filler material it may be possible to limit the amount of undercutting and better fill the material gap. This would however add an additional cost to the laser welding process.

Because of the many possibilities for a plasma assisted laser, in all of the laser materials processing areas, there is justification to study further in this area. Indeed, further study could lead to more efficient use of lasers in applications such as joining and surface modification.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Abbott, D.H. and Albright, C.E., CO2 Shielding Gas Effects in Laser Welding Mild Steel, Journal of Laser Applications, 1994.

2. Abe, N., Agano, Y., Tsukamoto, M., Effect of CO2 Laser Irradiation on Arc Welding, ICALEO 1996, Section D.

3. Belforte, D.A., Laser Welding: There's more to it than you think, Industrial Laser Review, September 1994.

4. Beyer, E., Brenner, B., Poprawe, R., Hybrid Laser Welding Techniques for Enhanced Welding Efficiency, ICALEO 1996, Section D.

5. Biffin, J, Plasma Augmented Lasers Shine Ahead in Auto Body Application, Welding & Metal Fabrication, April 1997.

6. Breuer, P., Nd:YAG Laser Welding Used in Car Body Manufacturing, Industrial Laser Review, July 1994.

7. Darchuk, J.M., and Migliore, L.R., The Basics of Laser Welding, Lasers & Applications, March 1985.

8. Dawes, C., Laser Welding, Abington Publishing, Cambridge, England, 1992.

9. Farson, D., and Duhamel, R., Taking Advantage of Laser Welding, Industrial Laser Review, March 1997.

10. Leong, K.H., Carol, L.A., and Bransch, H.N., Welding with High-power CO2 and Nd:YAG Lasers, Industrial Laser Review, June 1994.

11. Migliore, L.R., Laser Materials Processing, Marcel Dekker, New York, 1996.

12. Powell, J., Nilsson, K., Magnusson, C., CO2 Laser Welding: Mechanism and Techniques, Industrial Laser Review, March 1994.

13. Sun, Z., and Salminen, A.S., Current Status of Laser Welding with Wire Feed, Materials and Manufacturing Processes, Volume 12, Number 5, 1997.

14. Thermal Dynamics Corporation, 1983.

15. Walduck, R.P., and Biffin, J., Plasma Arc Augmented Laser Welding, Welding & Metal Fabrication, April 1994.

16. Webber, T., Laser Welding: Efficient Weld Width Generation, ICALEO, 1993.

VITA

Glendon Tyree was born on 5 September, 1975 in Morehead, Kentucky. He is the oldest of three sons born to Michael and Elaine Tyree, who continue to reside on the family farm in Frenchburg, Kentucky. Glendon graduated from Paintsville Independent High School in 1993. In 1997, he received his Bachelor's degree in Physics and Math from Morehead State University, in eastern Kentucky. Mr. Tyree then pursued a Master of Science degree in Engineering Science at the University of Tennessee Space Institute, which he completed in December of 1998.

After receiving his degree, Glendon began a career as an officer in the United States Military.