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REAL-TIME IMAGE PATTERN SENSOR FOR WELD POOL PENETRATION THROUGH REFLECTION IN GTAW

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REAL-TIME IMAGE PATTERN SENSOR FOR WELD POOL PENETRATION THROUGH REFLECTION IN GTAW

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Electrical Engineering in the College of Engineering
at the University of Kentucky

By
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Lexington, Kentucky
Director: Dr. YuMing Zhang, Professor of Electrical and Computer Engineering,
Lexington, Kentucky
2018

ABSTRACT OF THESIS

REAL-TIME IMAGE PATTERN SENSOR FOR WELD POOL PENETRATION THROUGH REFLECTION IN GTAW

In gas tungsten arc welding (GTAW), weld pool surface contains crucial information for welding development. In this research, simulate skilled welders to control the welding process and determine the penetration stages based on the weld pool reaction.

This study focuses on solving the uncertainty of the liquid weld pool in joint bases. The weld pool penetration process is highly depending on how the weld pool surface shape. To observe the weld pool, reflect the weld pool surface by the laser and image on the shield glass. The experiments show that the penetration can't be determine by the reflecting grayness due to the variability of base metal. To control the joint bases diversity, fed a tip of the wire after the arc is established. Crate the new pattern of the weld pool penetration. Experiments verified the feasibility of this method.

KEYWORDS: GTAW, Weld pool, Joint bases, Reflection

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REAL-TIME IMAGE PATTERN SENSOR FOR WELD POOL PENETRATION THROUGH REFLECTION IN GTAW

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background

Gas tungsten arc welding (GTAW) is the primary process used by human welders for critical applications. In this process as shown in Figure 1. An arc is established between the non-consumable tungsten electrode and base metal. Different from the other welding techniques like Shielded Metal Arc Welding (SMAW) and Gas Metal Arc Welding (GMAW) both use consumable electrode. The base metal is melted by the arc forming a liquid weld pool that joins the two pieces of base metal together after coagulation. An optional filler metal (not show in figure) can be added if necessary but it is melted by the arc column, rather than directly by an arc spot as in gas metal arc welding (GMAW) where the anode can much more efficiently melt a continuously-fed wire than the arc column to increase the melting productivity. However, the detachment and impact of the associated droplets on the weld pool compromise the controllability of the process and limit its use in precision applications. [1]

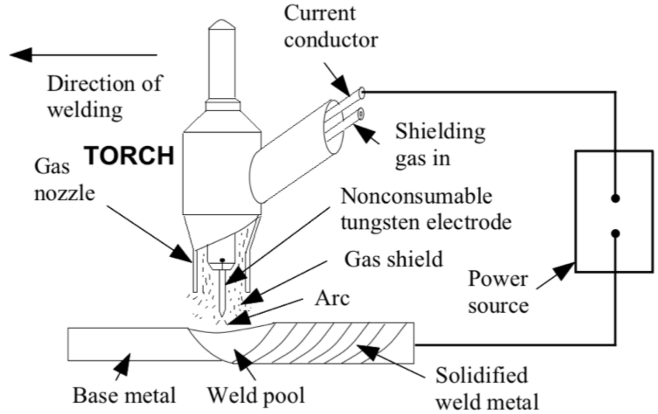


Figure 1.1 Illustration of GTAW Process and Weld Penetration

It requires many elements to produce a high-quality weld produces, such as, the isotropic homogenous workpiece, the filler metal's quality, an adequate welding current, the distance from torch to the workpiece and the penetration stage, etc. Human welder experience and skills are critical in manufacturing quality welds. However, it is hard to duplicate the welder's significant welding experience. Therefore, if we could observe the welding process and developed the system, it will reduce the human welder training expense.

1.2 Objectives and Approach

As revealed in the last section, many of the elements are required to a quality weld produce. The full penetration stage is the welding desired, which human welder needs years education and training to master. The objective of this research is to develop an automatic system which could successfully and proficiently determine the full penetration without human welder intervene. In previous research works, we associate the penetration stages with the weld pool's oscillation. The study of the weld pool behavior could assist the automatic system identify when the welding reach full penetration.

There are countless research works could detect the full penetration by using various techniques, such as infrared-based sensing, ultrasonic-based sensing, voltage variation-based sensing and vision-based sensing. Using ideal welding environment to characteristic the weld pool behavior. However, this study focuses on the joint bases welding. This work utilizes direct current to decrease the oscillation that beneficial to the accuracy of images.

Established on the weld pool dynamic process, we build the model that indicate different penetration stage's correlation with the image's altitude. Furthermore, tipping the wire after the arc is established and forming a droplet on top to the joint bases weld pool. With the information, if the altitude still high means the droplet hasn't dissolve into the weld pool. It implies that the weld pool still in partial penetration. After the altitude drop significant of the amount, the current is cut off.

1.3 Organization

In this dissertation, a technique is introduced that overcome the uncertainties and detect the full penetration of the weld pool in GTAW. The main research steps and results are discussed in the following chapters.

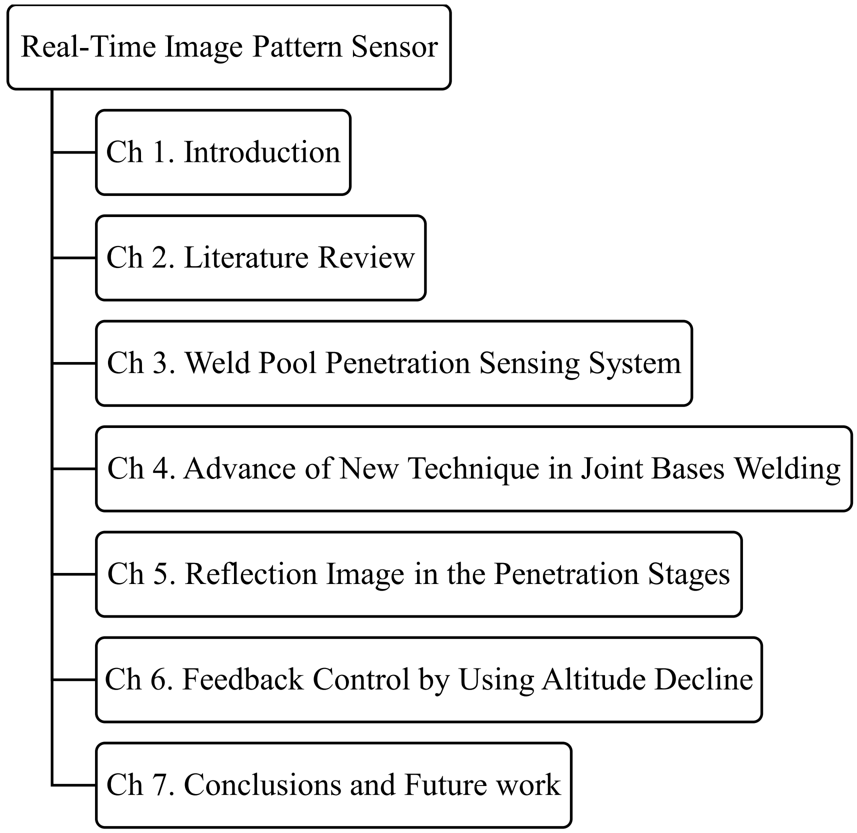


Figure 1.2 Organization of the Dissertation

Chapter 1: Introduction

The background knowledge about GTAW technique of this dissertation is demonstrated and follow by the outline of objectives and approaches.

Chapter 2: Literature Review

In this section, introduce the sensing techniques of the welding process. Furthermore, discuss the weld pool oscillation's relationship with welding penetration stats.

Chapter 3: Weld Pool Penetration Sensing System

An innovative weld pool sensing feedback control system is proposed, which consists of the GTAW system, the image capturing system, and the welding current control system. In this system, GTAW system operate the welding process; the imaging system captures the reflected images which is shined by laser line lights on the weld pool; the feedback control system controls the welding process by judging the image's curative change.

Chapter 4: Advance of New Technique in Joint Bases Welding

The advantage of the new method over the existing methods are demonstrated. Experiments are designed to execute the welding progress in joint bases. Explain the difficulty of the environment change would reduce the reliability of existing methods. Discuss the new method development process.

Chapter 5: Reflection Image in the Penetration Stages

The images captured in the entire welding process are processed to obtain the altitude change that reflect the stage of the weld pool penetration.

Chapter 6: Feedback Control by Using Altitude Decline

A simple control is constructed, which is used as the feedback control to determine the full penetration. Experiment results show that the imagine process is effective in automating GTAW.

Chapter 7: Conclusion and Future Work

Conclusions are drawn base on this study and the future work is outlined and briefly discuses.

CHAPTER 2. LITERATURE REVIEW

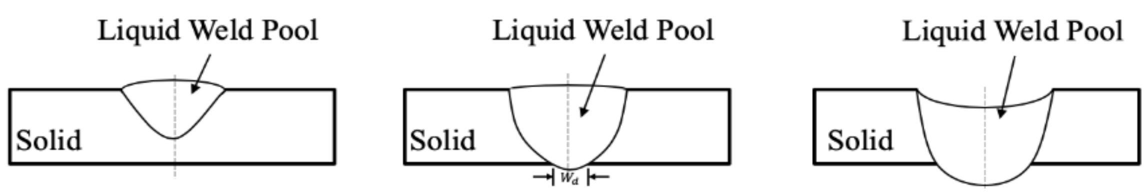
2.1 Overview

In the manufacturing industries the welding process has been widely applied. The welding technique is improved over the years. Nowadays, produce a fast, reliable and cost-effectively weld is still the major challenge.

GTAW was developed in the 1940s. As it mentions in chapter 1, GTAW was not economical because it requires inert gas which was expensive at the time. As technology advances, GTAW has seen improvement in cost-effectively because the inert gas cost is lower. Even thought, the GTAW produces higher quality welds, the complex factors in GTAW welding are limited its usage.

In manufactory, the penetration is the most important aspect and we could basically sort as three different stages in Figure 2.1. The full penetration is mostly looked-for its quality in microstructure

As shown in Figure 2.1, there are three stages of weld pool penetration. Generally full penetration is desired since the weld produces has high qualities in terms of mechanical properties, appearance, structure and strength. Nevertheless, the full penetration is hard to create. Human welder must have experience and skill to execute the process. On the other hand, partial penetration is fairly easy to manufacture. It can be used in weld produces with less critical requirements. Previous stages both could be applied in certain welding condition except the over penetration should definitely be avoided. It has damaged the material properties. In precious studies, the penetration stages are relating to weld pool oscillation. Hence, to study the weld pool and identify the characteristics is important. In this chapter will introduce some sensing techniques, for example, the vision-based sensing, voltage variation-based sensing, infrared-based sensing and ultrasonic-based sensing.



(a) Partial Penetration (b) Full Penetration (c) Over Penetration

Figure 2.1 Different Penetration Statues in Welding Process

Weld pool play a fundamental role in determine resultant weld. In many recent studies [2-8], welding phenomena has been studied subject. The oscillation is the main study target around the world [9-29]. Kotechki et al. [9] is the first who observed the phenomena of weld pool oscillation in 1972. He studied the full penetration weld pool behavior using high-speed motion pictures which brought attention to correlate the natural frequency and the weld pool diameter. The weld pool full penetration theoretical model was proposed based on this theory.

Xiao et al. [19-21] studied the weld pool oscillation under stationary and low speed welding condition. They proposed two weld pool oscillation modes which are partial penetration and full penetration modes. They discovered that the oscillation frequency is higher while the it is in partial penetration stage. Furthermore, the oscillation has a sudden change between the partial and full penetration. This research help to distinguish between partial and full penetration.

2.2 Sensing Techniques of Welding

Study the weld pool behaviors and built the pool models is the core of the sensing system. In order to identify the stage of full penetration, human welder depend on the surface appearance and change of the weld pool. Thus, a lot of research has developed an effective method which can automatedly detect full penetration welds. It requires sensing techniques to identify the different stages. Unlike human welding could only use vision as the key observation, many researches cultivate different sensing foundation.

2.2.1 Infrared Sensing

Infrared sensing is based on the difference in temperature of various penetration status. Welding is basically a thermal processing method. Chin et al. [30] use infrared thermal imaging to capture the thermal profile variations to study weld pool penetration. Figure 2.2 [30] is the experiment system. They use thermal cameras to detect the infrared radiation which could characterize the temperature disseminations of the weld pool. Thermal sensing is convenient in practical use. However, the temperature profiles require meticulous calibration due to it's not directly connected with pool surface. The accuracy of the thermal sensing is reduced by the arc light. The pool oscillation can't be classified by two-dimensional temperature profile.

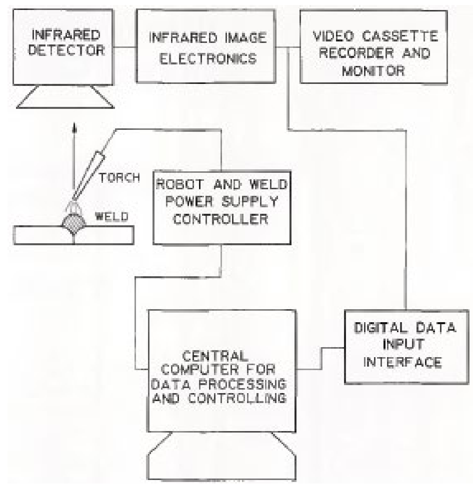


Figure 2.2 Schematic for Online Weld Monitoring Using Infrared Sensing

2.2.2 Ultrasonic Sensing

Ultrasonic sensing is another area of study, using ultrasonic waves to measure the depth of the penetration. Ume et al. [31] studied the ultrasonic sensing techniques to measure weld pool penetration, shown as Figure 2.3 [31]. They used Electro-Magnetic Acoustic Transducer to receive the ultrasound. The flight duration of the ultrasound is related to the pool penetration depth information. However, there are some restrictions of using ultrasonic. Such as, the workpiece must be simple and homogeneous to guarantee the coupling with transducer; minimize the vibration and sudden movement.

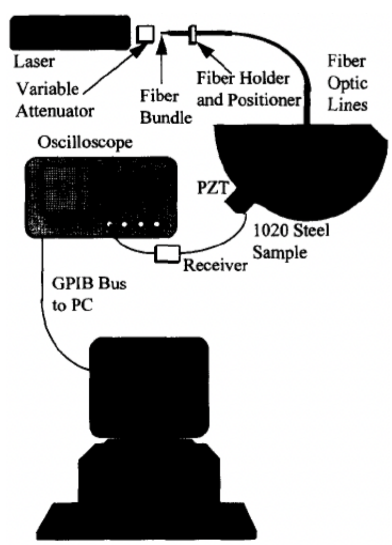


Figure 2.3 Schematic for Penetration Depth Measurement Using Ultrasonic Sensing

2.2.3 Voltage Variation Sensing

Xiao et. al. [21], shown in Figure 2.4, developed the voltage variation-based sensing technique in their study of weld pool oscillation. They discovered the arc voltage variation is correlated with oscillation by applying pulsed current on the torch. Furthermore, the pool oscillates different frequency in partial and full penetration. As the result, detect the arc voltage variation could lead to categorize penetration stage.

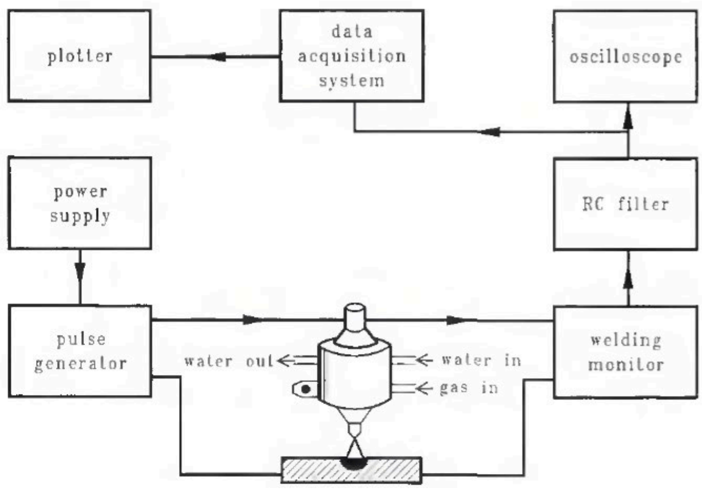


Figure 2.4 Schematic for Weld Pool Oscillation Monitoring Using Voltage Variation

2.2.4 Vision Sensing

Vision-based sensing is an instinct technique that imitate automatic welding as human welder's determine penetration skill. Vison sensing need to acquire and process the image of weld pool surface as an input. The system could compare and make decision based on the image. Usually, the vision sensor can be categorized into two categories: two-dimensional (2-D) and three-dimensional (3-D). 2-D weld pool has been used by many methods. Using camera captures the weld pool profile including length, width and area. By reconstructing 2-D images, we could have 3-D sensing.

Figure 2.5 [32, 33] depicts the three-dimensional sensing system developed at University of Kentucky. In this research, the experiment setup as the laser continuously shines dots matrix light on the weld pool surface. The refraction would project on the screen and capture by the high-speed camera, shown at the second picture in the Figure 2.2. The pool surface has the characteristic like mirror could reflect the laser dots and base on the natural oscillation it won't be the same shape as the dot matrix. Figure 2.6 shows the laser movement. The 1st laser which irradiate on the lower right pool is reflected on the screen 's top; the 2nd laser which irradiate on the top of the pool is reflected on the screen's middle; the 3rd laser which hit on the lower left pool is reflected on the screen's bottom. The spatial information between each laser dot could reconstructed the 3-D image of the weld pool, shown as the third picture in Figure 2.5. 3-D image sensing has much complete information of the weld pool, but the reconstruction process is ineffectively in real-time control. In this research, they keep current constant to minimize the disturbance of oscillation for the clear laser-dot. Vision-based sensing have to avoid high torch current else the weld flash would be too bright which effect the low resolution of image.

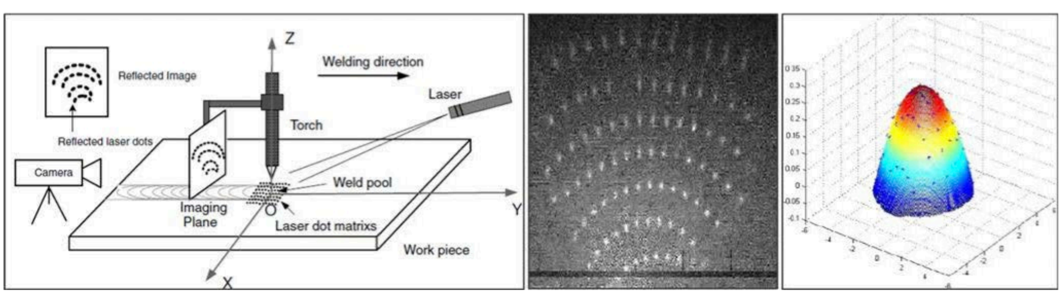


Figure 2.5 3D Sensing System, Captured Image and the Reconstructed 3-D Weld Pool

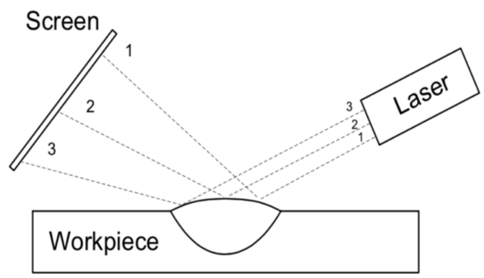


Figure 2.6 Schematic of the light rays' reflection on the weld pool

CHAPTER 3. WELD POOL PENERATION SENSING SYSTEM

As it mentions earlier, there are different sensing systems to detect the weld pool's penetration stages. In this study, we try a novel vision-based sensing technique in Figure 3.1.

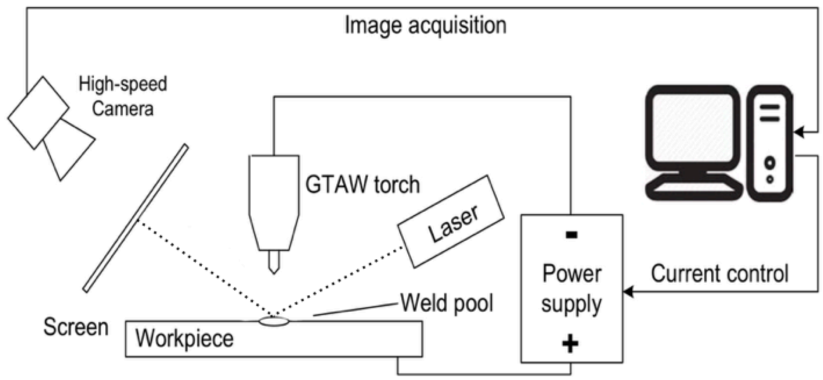


Figure 3.1 Schematic of the Proposed Weld Pool Penetration Sensing System

3.1 The Imaging System

The imaging system is composed of a laser, a camera and a screen. The laser used is a 20mW StockerYale's Lasiris SNF laser. The different of the optical heads could provide different laser patterns such as dot matrix and line both used in this research shown in Figure 3.2. In order to observe the weld pool, the laser is needed in this research. It generates highly concentrated monochromatic light source. The laser could pass the filter which segregate the weld flash. It is aligned 30° with the workpiece, 50 mm away from the torch.

Figure 3.2 The StockerYale's Lasiris SNF laser

The second component of the imaging system is the high-speed camera. Figure 3.3 Gazelle’s high frame rates and high-resolution camera is used is this research to capture insignificant change in the weld pool. The camera speed is 1000 frames per second. The band pass filter centered at 685 mm and with 20 nm bandwidth is installed on the camera.

Figure 3.3 Gazelle’s GZL-CL-22C5M-C high speed camera

Last but not least, the screen is made of white grid paper attached onto a glass substrate. The screen is placed 50 mm away from the torch to receive the laser reelection.

3.2 The GTAW System

The torch, power supply, workpiece and inert gas supply combine are the GTAW welding system. The gas pipe is inside the torch in place with the power cable shown as Figure 1.1. In this research, we use the gas cover the entire pool surface through the torch and under the workpiece to protect the metal won’t be oxidized. Figure 3.4 shows most of the welding system. The joint bases workpiece is placed on the welding workbench. The Miller PM200 DC power supply, which could provide a maximum 200 A current output, is connected to the torch through the cable.

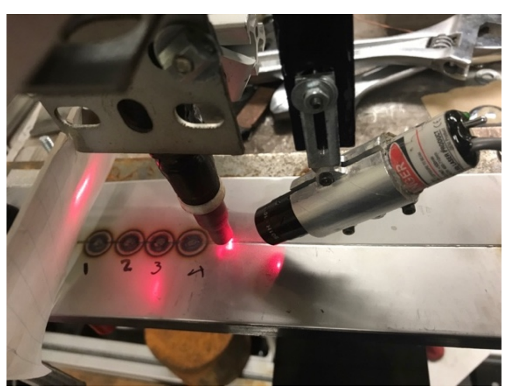


Figure 3.4 The GTAW Welding System

3.3 The Control System

For the Control system, we use the NI PCI-6229 data acquisition device. The computer collaborates with the image system collecting images in real-time. We use C++ programing to process the image and base on the result to determine the welding whether reach the desire penetration stage or not. The computer could control the torch current through the NI DAQ. The image processing condition could change along with each experiment' setup.

CHAPTER 4. ADVANCE OF NEW TECHNIQUE IN JOINT BASES WELDING

There is a connection between the weld pool penetration and the pool's oscillation. While the welding just started, the oscillation frequency is high and has small amplitude because of the pool is small. The pool oscillation frequency decreases and the amplitude escalate when the weld pool builds up to full penetration stage. There are many researches base on this oscillation and penetration relationship in single workpiece welding experiment. However, in joint bases welding the oscillation is less reliable on vision base sensing for two main reasons. As show in Figure 4.1, the clearance and surface difference cause the oscillation unpredictable.

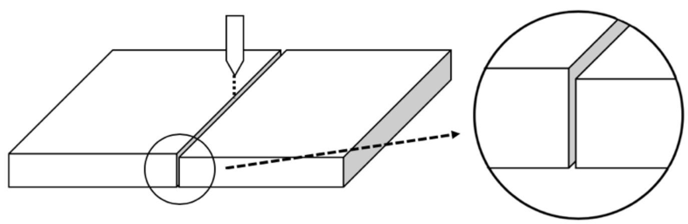


Figure 4.1 Butt Joint Bases Workpiece

4.1 Vision-Based Sensing Method

The new method introduce in this research is admirable in few important circumstances.

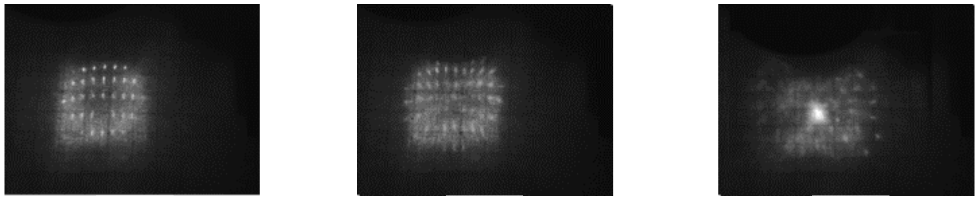
Vision-based sensing method is a two-dimensional technique which most other methods are based on one-dimensional. Such as the voltage variation sensing mention in Chapter 2. It is based on the relationship between voltage and pool oscillation. As the voltage is the only quantity it considers one-dimensional. In two-dimensional method, it detects the weld pool surface's information through each penetration stage.

In order to observe the weld pool oscillation, we attach the extra equipment or experiment procedure. Those could still be an interruption in welding process. For example, the voltage detection method uses the pulsed current to correlate with oscillation frequency. The addition pulsed current, nevertheless, obstructs the welding process. Unlike the vision sensing in this research rely upon the laser and camera. The image process won't interfere the welding progress.

The welding environmental variations could disturb the experiment data. In the infrared sensing, thermal property is the primary parameter to determine the penetration stage. The temperature field gradient isn't highly related to pool oscillation; thus, it can't precisely reconstruct the pool's status especially the liquid-solid junction. On the other hand, the vision-based method focuses on the weld pool surface development. The camera constantly captures the weld pool image through the welding flash. The welding process could even be observed by a haphazard glance.

4.2 New Vision-Based Sensing Method for Joint Bases Welding

The new method is based on the previous vision-based method discussed in Chapter 2. The goal for this method is to solve the joint based welding vision sensing difficulty. The oscillation of the weld pool is disturbed by the difference of clearance and surface at each welding point. In single workpiece welding, we could easy tell by the image transformation of each penetration stage, show as Figure 4.2. The oscillation hasn't been disturbed before critical penetration. After the weld pool reach the critical penetration, the image shows gloomy and blurred. The reason is that the pool root has been penetrated. The additional freedom resulting in strong and irregular oscillation such as Figure 4.2 (c).

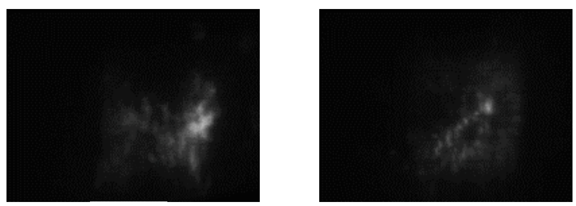


(a) (b) (c)

Figure 4.2 Single Base Penetration Stage

(a)Partial Penetration (b)Critical Penetration (c)Full Penetration

In joint bases welding, we attempt to reconstruct the experiment. However, before the welding process reaches the penetration stage the image Figure 4.3 shows an irregular result that is similar to Figure 4.2 (c). It leads to the algorithm consider the welding process already at the full penetration stage.



(a) (b)

Figure 4.3 Joint Bases Weld Pool Dynamic Behavior

In this research we propose a welding technique to overcome the nonuniform of the joint bases weld pool behavior. After the arc is established, tip the wire like droplet on top of the joint bases weld pool, as show in Firgure 4.4. From this point forward, the refrection on the screen no longer is the irrugular osicalltion from the weld pool than the droplet infiltrate process.

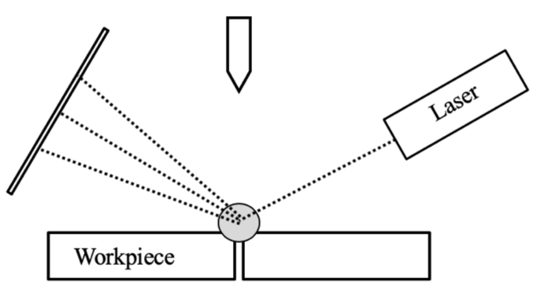
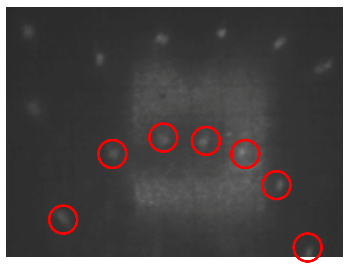
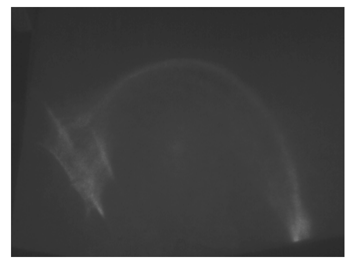


Figure 4.4 Tipping Wire Illustration

Because of the droplet, the refraction image's characteristic from the laser is completely different than previous research. Image sensing system is extremely sensitive about the weld pool surface's variation, furthermore, the droplet size that cover the weld pool. Figure 4.5 (a) demonstrates the weld pool image reflection by 19x19 dots matrix laser after tipping the wire. In previous research, we expect the little dots forming while the welding operate and rely on the grayness of the dots to provide the peneration information. Since the image shows the different pattern, we need the different approch to observe the droplet. Therefore, the laser pattern chagnes from 19x19 dots matrix to a single straight line which could cover the weld pool surface, as shows in Figure 4.5 (b).



(a)



(b)

Figure 4.5 Refraction image from droplet

The image reflection is directly affected by the droplet on the weld pool and it is related to the weld pool penetration. Hence, by measuring the image curvature change, the weld pool penetration can be determined.

CHAPTER 5. REFLECTION IMAGE IN THE PENETRATION STAGES

This chapter focuses on accessing the weld pool penetration behavior. In order to build the model for each welding penetration stage. Acknowledge the information form the weld pool surface would help us duplicate the welding result.

5.1 Experiment Setup

The image sensing system is shown in Figure 5.1. This is the setup without the feedback control system. In earlier research, it usually used the pulsed current to enhance the weld pool oscillation. Also take advantage of the base current to capture the clear image that avoid the strong weld flash. In this research, using direct current through the welding process will give us much integrated welding process which won't need to avoid peak current image while applying pulsed current. However, this will require a better image processing system to reduce noise.

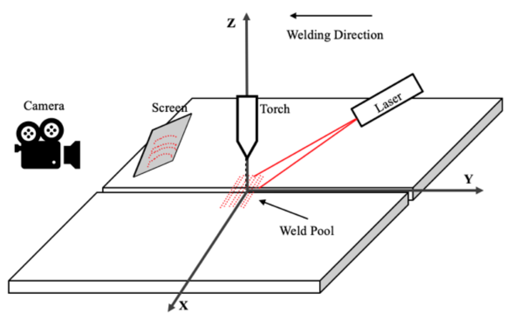


Figure 5.1 Image Sensing System-19x19 dots matrix Laser

Through the experiments, we realize that the joints bases weld pool has an irregular and unpredictable pattern. In order to easily observe the droplet dissolving process, we ameliorate the laser from matrix to single line as shown in Figure 5.2. This step simply reduces the time of image processing. The control system won't have to connecting the dots from the same row before it reflected on the screen.

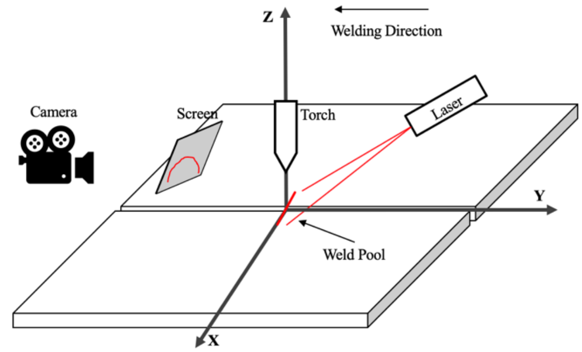


Figure 5.2 Image Sensing System-Single Line Laser

The precise spot of tipping the wire is extreme important for this experiment. Shown as Figure 5.3, the misplace of the droplet would cause the reflection out of the screen, which means the camera won't be able to calculate the welding process.

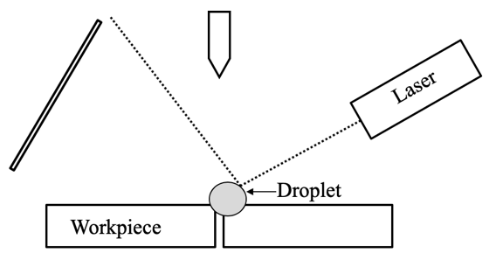


Figure 5.3 Droplet Misplace Illustration

5.2 Experiment Approaches

The experiment goal is to study the droplet dissolving relationship with welding penetration GTAW. The parameters of this study are shown in Table 5.1. The camera was set as 1000 frames per second. The direct current was set at 60 A.

Table 5.1 Welding Parameters

Parameters	Value
Material (Stainless Steel 304L)	2 mm
Distance between Tungsten Tip and Workpiece	5 mm
Direct Current	60 A
Shielding Gas (Ar)	15 CFH
Back Shielding Gas (Ar)	30 CFH

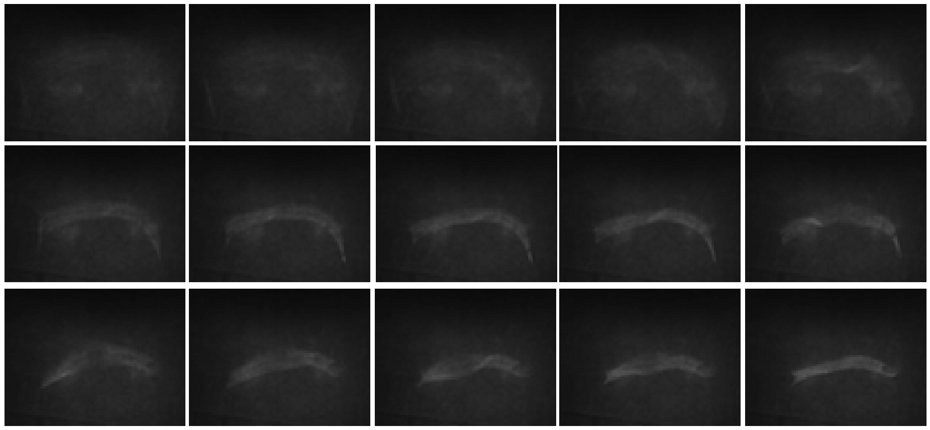


Figure 5.4 Joint Bases Weld Pool Behavior

Figure 5.4 shows that the straight-line laser shine on the weld pool reflect as the curve on the screen. We study the behavior and draw the conclusion as shown in Figure 5.5. When the droplet just covers the weld pool it behaves as convex mirror. With the welding process continue, the droplet assimilates into the weld pool which led to the refraction image change.

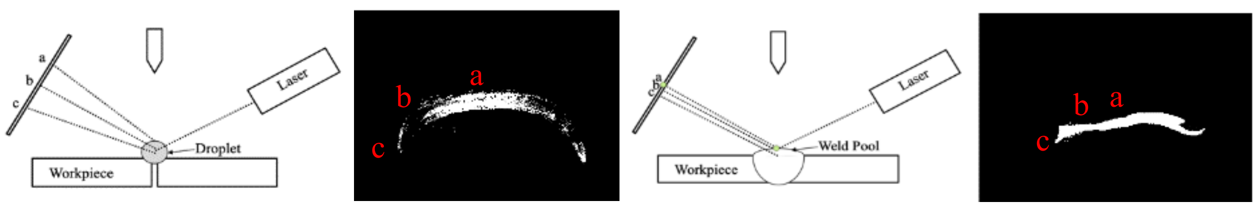


Figure 5.5 Welding Process Illustration

5.3 Summary

The pool behavior has been characterized by the reflection laser line pattern. The droplet malting into weld pool dynamic behavior can be clearly detected and estimated. The reflection from laser shows the droplet overcome the irregular image pattern cause by the difference of clearness and surface. When the altitude less than 70% of the peak altitude, the weld pool changes from partial penetration to full penetration stage.

CHAPTER 6. FEEDBACK CONTROL BY USING IMAGE ALTITUDE DECLINE

As it mentions in chapter 5, the altitude decreases indicate the penetration stage 's change. In order to control the welding produce, a simple feedback system has been deigned to avoid the over penetration stage.

6.1 Simple feedback control system design

We study the Figure. 5.3 that at 70% decreases of the peak height the full penetration is reached. This condition is used in the feedback control system.

For the control unit to gain this information, we need to write an image processing program which calculate 1000 image per second. As the Figure 6.1is the flow chart of the control system. We clear the background of each image and reconstruct the reflected image to the curve so as to measure the height of each image as Figure 6.2. In the program it compares the altitude between each new image to the previous one. If the altitude is higher than before it saves as the new peak value. If not, it will check the altitude drop more than 70%. When it reaches the requirement setting the welding will stop.

Figure 6.3 shows the variation of the altitude with the welding time. The peak altitude is around 120 so as the programing setting the time that welding reaches the full penetration when the altitude drops less than 36(120*30%). Check the front and back of the finished weld shows that the control system replaces the human welder in this experiment.

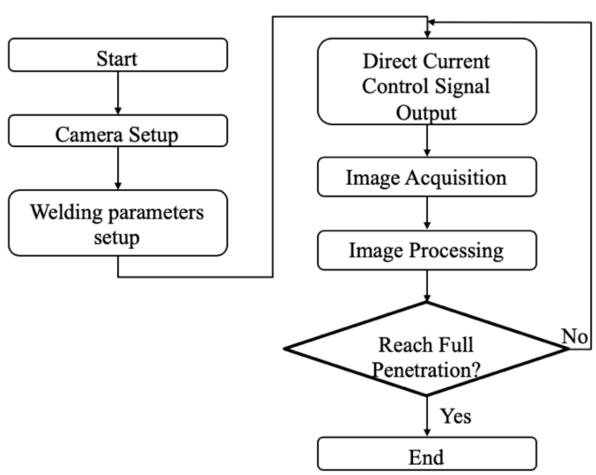


Figure 6.1 Control System Flowchart

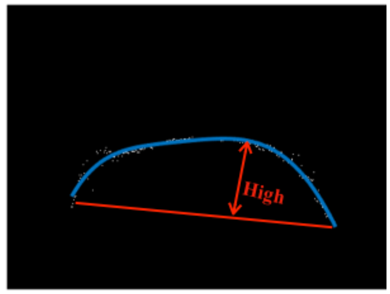


Figure 6.2 Curve Height

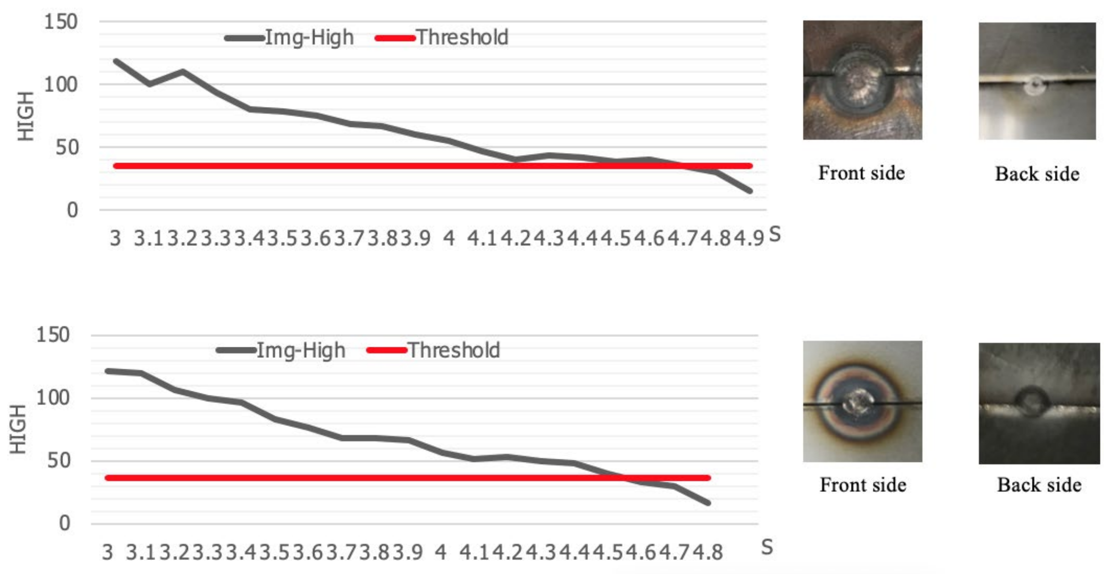


Figure 6.3 Altitude Dropping with Time Using Feedback Control

6.2 Summary

This feedback control system shows the weld pool has been successfully characterized by the reflection laser line in joint bases welding. It is simple and effective; however, this system won't be able to adjust the welding process. This technique could apply on much advance control system such as, the PID Control, Model Predictive Control, Fuzzy Control, etc.

CHAPTER 7. CONCLUSITON AND FUTURE WORK

7.1 Conclusion

A novel method is developed to monitor and control the dynamic development of the weld penetration. Different than previous approaches, this research is not concentrated on reconstructing the weld pool geometry and creating pool's oscillation by pulsed current, yet, observe the image's curvature decreases. This approach in joint bases welding is straightforward and reliable. It is nature phenomenon that melted metal would dissolve into weld pool and follow this concept to track the reflection's curvature reduction.

Using simple feedback control systems to guarantee the weld pool reach the full penetration stage. The system detects the highest curve's altitude and afterwards the altitude decreases by 70% of the peak value, at this point we identify as full penetration stage. This method is effectively observed and control the welding process.

7.2 Future Work

The proposed welding technique is simple and effective. However, there are some aspect could make the system more practical and robotics for GTAW process.

- As it mentions earlier, at the start of each welding we need to tip a wire on top of the weld pool. Human hand could be easily mistaking the amount of the wire and misplace the droplet. Using the robotic arm to feed the wire is much easier to control the amount and precise location of the weld pool.
- This method could extend to the continue welding. In continue welding there is an obvious obstacle for detecting the weld pool oscillation which is the second and following welding point has previous liquid form of weld pool. Even with the period of time to cool-down the weld pool, the pool's oscillation is completely different and irregular. It is similar to the problem in joint bases welding. Tipping the wire at each following point could help the observation.

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