# Effects of part-to-part gap and the variation of weld seam on the laser welding quality

Amit Kumar Sinha

Engineering and Systems Design Program

Graduate School of UNIST

# Effects of part-to-part gap and the variation of weld seam on the laser welding quality

A thesis
Submitted to the graduate School of UNIST
In partial fulfillment of the
Requirements for the degree of
Master of Science

Amit Kumar Sinha

02.10.2014
Approved by

Major advisor
Duck-Young Kim

# Effects of part-to-part gap and the variation of weld seam on the laser welding quality

Amit Kumar Sinha

This certifies that the thesis of Amit Kumar Sinha is approved.

02.10.2014

Signature

Thesis supervisor: Duck-Young Kim

Signature

Nam-Hum Kim

Signature

Seungchul Lee

## Abstract

Laser welding is an emerging joining technique for automotive industry. Due to the complex process, the control of laser welding quality problem such as spatter, porosity, and undercut is not easy. Traditional mechanical testing of weld is time consuming, costly, and inefficient for on-line monitoring of laser welding quality. In this regards, this thesis aims to estimate the laser welding quality in a non-destructive way by using the geometry of top weld seam of weldment.

The most challenging task which is covered in this thesis is the estimation of the tensile shear strength in a non-destructive way. Experimental analysis reveals that the existence of two types of correlation in the variation of weld seam and tensile shear strength in the laser welding of galvanized steel: (1) positive correlation exists between the log-transformed average width of the top weld seam and maximum tensile shear strength, and (2) negative correlation exists between the variation of the width of top weld seam and maximum tensile shear strength. These correlations exist only when top weld seam having non uniform seam boundary. However, weld seam having uniform seam boundary do not have sufficient evidence of the correlation between the variation of weld seam and tensile shear strength. The reason for this is due to the high value of standard deviation of the average width of the top weld seam. Width of weld seam is more responsible for tensile strength rather than variation of weld seam.

# Contents

# List of Figures

# List of Tables

# 1. Introduction

## 1.1 Background

Light amplification by stimulated emission of radiation (Laser) is a coherent, convergent and monochromatic beam of electromagnetic radiation (Steen and Mazumder 2010). The wavelength of laser comes under the zone from ultra-violet to infrared.

**Development of Laser welding**

In 1960 first laser beam was created with the help of ruby crystal laser. In the same year, Hughes Aircraft Company (Mainar) developed the first ruby laser and Bell telephone laboratories (Ali Javan) developed the first gas laser with the help of neon and helium. After 6 years later, General Motor Corporation (Dayton Ohio) started the first automotive production application of lasers welding using 1.25 kW $CO_2$ laser for welding valve assembly of the car (Steen and Mazumder 2010). After that, application of laser can be judged from the data which reveals that laser based industry including laser cutting, laser welding, laser cleaning, and laser bending growing at nearly 10% per year (Steen 2003).

**Advantages of Laser welding**

The advantages of the laser welding (LW) over conventional joining process include high beam quality, high power fiber-delivery laser, higher precision of the welding process, long focal optics, less mechanical movement, better accessibility of the beam to the work piece, fast processing speed, non-contact welding and capability of joining material by one-side access (Ribolla *et al.* 2005, Zhang 2008). In general, the basic needs of laser welding are as follows:

- High productivity: Welding speed up-to several meters/min is possible.
- Low distortion: Minimum distortion is possible only by laser welding.
- Deep narrow weld: According to the rule of thumb 1 kW laser is appropriate for welding to a depth of 1.5 mm steel sheet at 1 m/min welding speed (Dawes 1992). Therefore, 10 kW laser can easily weld up-to 15 mm steel sheet.
- Low volume manufacture
- Low vibration
- Higher hardness of the weld seam: Due to high cooling rate, the hardness of laser welds is high as compare to either Plasma or Tungsten Inert gas (TIG) welding (Sun *et al.* 2002). In general, experimental results reveal that the hardness of the weld seam is 2.5 times higher than the base metal (Anand *et al.* 2006).

- Non-contact process/large welding distance: Welding up to 500 mm distance and also to inaccessible parts (inside a glass envelope) is possible[1].
- High power density (up to 1 $MW/cm^2$)
- Small heat-affected zone: Very little heat is generated at the weld point, welding can be performed just only 0.05mm (0.002 inches) away from the complicated parts without damaging heat sensitive materials[2]. It produces 1.5 times, and 4 times lower heat affected zone (HAZ) as compare to electron beam and mash seam welding, respectively (Lee *et al.* 1996).
- It produces higher heating as well as cooling rates.
- Generation of 0.2 mm to 13 mm spot size (of the laser beam) is possible.
- Laser beam can be transmitted through air no requirement of vacuum.
- Greater material utilization.

**<u>Disadvantages of laser welding</u>**

- Easy formation of welding defects: appearance of porosity in the weld fusion zone (Katayama *et al.* 2010)
- High cost of laser welding setup
- Difficult to weld high reflective or high thermal conductive materials
- In general, laser welding is 50 to 200 times costly than a conventional industrial arc welding (Dawes 1992)

**<u>Laser welding of galvanized steel</u>**

Laser welding of galvanized steel is important because galvanized steel plays a major role for automotive industry. Although, depending upon the laser process parameters (welding speed, focal position, and laser power) the mechanical and physical properties (including part-to-part gap) of the work-piece, a good quality of weld can be achieved (Sahin *et al.* 2010) but part-to-part gap is still critical issues for this work. Insufficient part-to-part gap creates weld defects like porosity, formation of intermetallic brittle phase, and spatter (Akhter & Steen 1990). The basic reason behind the formation of such types of welding defects is the lower boiling point of Zn (906 $^0$C) as compared to the melting point of Fe (1538 $^0$C) (Mei *et al.* 2009). For quality welding, the mechanical properties (tensile strength, hardness, endurance fatigue limit, and ductility), metallurgical properties (distributions of the grain and graphite flank, no evidence of porosity, spatter, and undercut), and geometrical features (width of weld seam, depth of penetration, aspect ratio) of the resulting laser welding of galvanized steel are required to match the desired level of

[1] Quarda art of laser, http://www.quada-office.com/advantages-and-disadvantages-of-laser-welding.html

[2] Laser star Technology, https://www.laserstar.net/welding-products/manual-weld.cfm

specification. In the LW system, response variables (strength, hardness, and laser welding defects) are highly sensitive towards the micro disturbance/fluctuations of process variables (Zhang 2008).

**Variation of weld seam**

Literature survey reveals that geometry of weld seam/weld pool or weld bead is directly affected by welding process parameters. In general, geometry of weld seam includes depth of penetration, width of weld seam, and aspect ratio. Chen *et al.* (2011) suggested a mathematical model which shows a relationship between the geometry of weld seam and tensile strength. However, their model was based on destructive testing. Duley (1999) also suggested that there is some correlation between weld seam and welding quality, but it still needs further investigation. However, little attention has been paid to analysis of the correlation between the geometry of weld seam and tensile strength. Therefore, variation of the width of weld seam can be considered as a statistical measurement for assessing the quality of the weld. Figure 1.1 shows the variation of the weld can be used as an estimator for tensile strength.

**Why monitoring of LW is necessary?**

For improving the efficiency of the LW systems, a quality measurement system should be incorporated in the production system itself because traditional off-line inspection of welds not only reduce productivity, but also required mechanical equipment and a large amount of work force. Therefore, the development of an automated on-line monitoring system is inevitable. In the future trend of laser welding, it became inevitable to install automated computer numerical control (CNC) equipment and robots with laser welding process. It is important to note that this installation should be noise free from the optical energy. However, the interaction of the laser with the work-piece is still an open loop process. In other words, the process parameters and response variables in laser welding system does not any correlation with each other. It means that the response variables cannot be directly controlled. Therefore, we are getting unacceptable quality of the weld. This type of problems can be overcomed only through the close loop feedback control system of the laser welding process.

**Monitoring of LW through signals**

Sensory feedback signals from the LW process is the only solution for creating such types of close loop laser welding monitoring system (Weerasinghe *et al.* 1990). A real time quality monitoring system is only possible by appropriate selection of sensors which measures the quality of the weld. In general, laser material processing is unusually free from various forms of signal's noise; therefore, laser welding requires an in-process sensing system (Steen and Weerasinghe 1987b). Although several solutions have been proposed by several researchers, it is still a challenging task for academicians and practitioners.

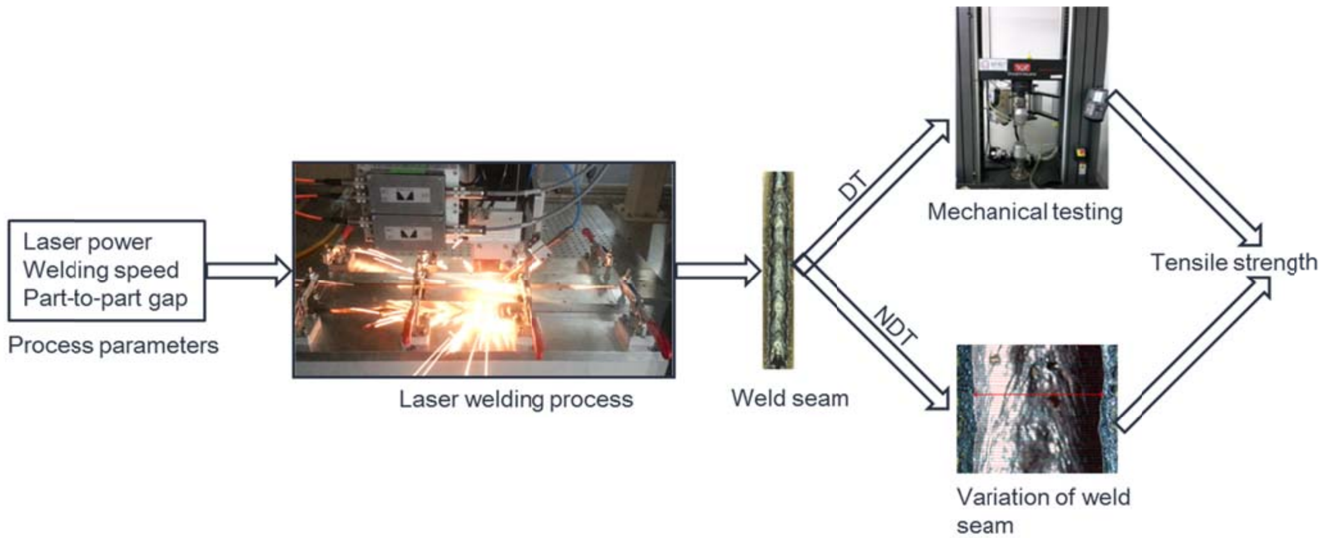



Figure 1.1: Schematic diagram of laser welding system for estimating tensile strength of the weld seam (DT: Destructive testing; NDT: Non-destructive testing)

## 1.2 Motivation

- The work in this thesis is based on the research project of Korea Institute for Advancement in Technology and the European Commission that aims at improving industrial laser welding systems through better understanding of the causes of welding defects and its corresponding fluctuations in the monitoring signals.
- Motivation for this thesis comes from the existence of traditional post-process procedures for evaluating the weld quality for example: ultrasonic testing, radiography, radiography, mechanical testing, or visual testing inspection (Farson *et al.* 1990). In these procedures, only after completion of the process we can identify the defective welds. In industry, defective welds need to be repaired which includes both wasting of material as well as processing time. Traditional mechanical testing of weld is time consuming, costly and inefficient. Therefore, evaluation of the quality of the weld seam based on non-destructive way during laser welding process would be a promising technique for automatic controlling of laser weld.
- We need to inquire whether there is any relationship in between variation in the width of the top weld seam and shear tensile strength[3].
- How to measure the width without conducting destructive test.

[3] Hereafter called tensile strength in short

- With nondestructive testing, evaluation of the quality of the laser weld seam is a challenging task. Miniaturization trends in electronics and sensors as well as advances in new sensing methods provide new technical edge for an online quality control of a laser weld seam. Therefore, we propose a new method to estimate the tensile shear strength of the laser weld seam with variance of the weld seam width.

## 1.3 Objectives

- The objective of the thesis is to investigate the correlation analysis of the variation of to the width of top weld seam and tensile strength in laser welding of galvanized steel.

**Experimental studies**

For this investigation (which is discussed in objectives/1.3 section), at first a continuous magnified panorama of top weld seam have been created. After that, with the help of CATIA V5 we extract left and right boundary curves of the top weld seam and measure the variation in the width of top weld seam with the help of deviation analysis between the two extracted curves. The experiment shows a negative correlation between the variance of the width of the top weld seam and maximum shear tensile strength. For more information about this work please refer Sinha *et al.* (2013).

## 1.4 Outline of the Thesis

The thesis includes five chapters. Chapters 2 deals with the basic literature survey related to laser welding and monitoring of laser welding. Chapter 3 deals with experiment based on variation of weld seam (Sinha *et al.* 2013). Chapter 4 deals with conclusions and Chapter 5 provides an open platform of the discussion for future works related to laser welding of galvanized steel.

This Page Intentionally Left Blank

# 2. Literature survey

## 2.1 Laser welding

### 2.1.1 Laser

Table 2.1 illustrates the different laser welding systems which are frequently available in industry.

Table 2.1: Comparative study of different types of laser welding systems

| Laser types / Properties | Fiber | $CO_2$ | Nd:YAG | Disk | Diode | References |
|---|---|---|---|---|---|---|
| Wavelength | 1.03micro-meter | 10.6 micro-meter | 1.06 micro-meter | 1.03 micro-meter | 0.8-1.0 micro-meter | |
| Beam quality | High | Medium-High | Low | High | Very low | |
| Wall Plug efficiency | <=20 % | 5-15 % | | <=20 % | 30 % | |
| Beam delivery | Fiber | Mirror | Mirror or fiber | Fiber | Mirror or fiber | |
| Typical industrial power availability | | 12kW | 4.5 kW | 4 kW | 6 kW | |
| Energy density | High | High | Medium | High | Low | |
| Melting rate ($cm^3/s$) | 0.195 | 0.261 | 0.205 | 0.248 | | (Ream 2004) |
| Cost per hour | $21.31 | $24.27 | $38.33 | $35.43 | | (Ream 2004) |
| Cost per cm3 (cents) | 3.04 | 2.58 | 5.19 | 3.97 | | (Ream 2004) |
| Technology | Very limited industrial experience | Proven and accepted | Proven and accepted | Very limited industrial experience | Limited industrial application | |

**Wall plug efficiency/Radiant efficiency**[4]

Wall plug efficiency = Radiant flux (Total optical output power)/Input electrical power

TWI (UK based welding Institute) demonstrated the use of 9kW laser power to weld 12mm thickness steel sheet at 1.0 m/min (Yapp and Blackman 2004).

[4] Wall plug efficiency = Radiant flux (Total optical output power)/Input electrical power

### 2.1.2 Laser welding defects

In this section, I will discuss laser welding defects which frequently appears during laser welding of galvanized steel. On the basis of literature survey and my welding experience, we can easily identify two types of welding defects. First one is surface defects and second one is internal defects (See Figure 2.1). Table 2.2 demonstrates the causes and remedies of laser welding defects.

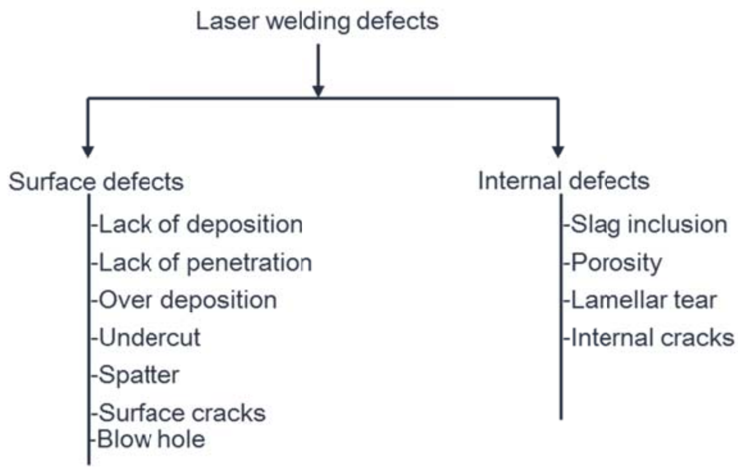
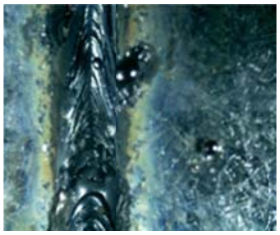
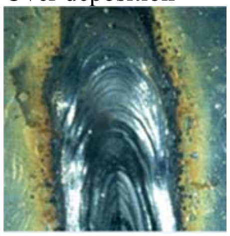



Figure 2.1: Common laser welding defects during laser welding of galvanized steel

Table 2.2: Study of welding defects during laser welding of galvanized steel

| Laser welding defect related to galvanized steel | Description | Causes | Remedies | References |
|---|---|---|---|---|
| Spatter  | -Droplets of weld metal expelled from weld pool<br>-Generally, spatter help to the formation of underfilled weld beads | -Presence of zinc layer on the specimen<br>-Insufficient part-to-part gap (no passage for escaping of zinc oxide) | -Facilitate channel for escaping zinc oxide gas (please see the part-to-part section for more information)<br>-Proper selection of laser power and welding speed<br>-Proper selection of inclination of laser beam | (Olson 1993) |
| Lack of fusion /Inadequate or incomplete penetration  | -Inadequately rising the temperature of based metal results in the form of lack of fusion | -Less amount of heat input due to<br>-High welding speed<br>-Low power<br>-Large part-to-part gap<br>-High reflectivity of work piece | -Proper selection of process variables (laser power, welding speed, part-to-part gap) | |
| Porosity  | -When the spherical gases/bubbles are entrapped in the solidifying weld metal | -Gases/bubbles are generated due to<br>-Zinc layer<br>-Contaminated shielding gas<br>-Absorption of moisture<br>-Bubbles created at keyhole due to low welding speed<br>-Bubbles created at the keyhole due to high laser power<br>-Low welding speed<br>-Presence of rust, dust, oil, and grease on the surface of specimen | -Provide excess (slightly more than actual requirement) heat input<br>-High welding speed<br>-Pre cleaning of work piece<br>-Pre removal of zinc layer<br>-Proper selection of laser power and welding speed | (Katayama *et al.* 2010) |

Tables 2.2 Continued

| **Laser welding defect related to galvanized steel** | **Description** | **Causes** | **Remedies** | **References** |
|---|---|---|---|---|
| Undercut  | -Formation of notch either in one side or both the sides of the weld seam which prone towards stress concentration and finally result in the early failure of the weld seam | -Not enough material in upper weld zone<br>-High welding speed<br>-High part-to-part gap | -Appropriate selection of welding sped, laser power and part-to-part gap | (Norman *et al.* 2009a) |
| Over deposition  | -Decomposition of excess metal | -Low welding speed | -Appropriate selection of laser process parameters | |
| Blow hole/Underfill  | -A depression on the top weld surface extending below the surface of the adjacent base metal | -Low welding speed<br>-High part-to-part gap | -Appropriate welding speed and part-to-part gap | (Olson 1993) |

### 2.1.3 Tensile strength

In general, the tensile shear test of laser welded lap joint configuration reveals that mainly fractures occurs at three distinct places: (1) at the base metal, (2) at the weld metal, and (3) at the adjacent to the weld joint (Miyazaki and Furusako 2007). But some of the scholars and practitioners argue that in most of the cases the fracture is not occurring at the weld metal. On the basis of the performance of tensile test Dechao (2007) observed that in 90 % of the cases, fracture occurs at the interface between HAZ (adjacent to the weld joint) and base metal of the work-piece. They also observed that this interface shows lowest hardness. In other words, fracture follows the path of lowest hardness zone.

Nakayama (2010) experimentally observed a correlation between infrared light signal integrated with respect to time and weld strength for lap joint laser welding configuration (material was SUS 304). From their experiment it is clear that the strength of weld seam increases as the integrated infrared light signal increases and vice versa.

Acherjee *et al.* (2009) proposed an optimized model based on response surface method to predict the quality of weld in terms of tensile strength of laser welding. On the basis of the proposed model, by selecting appropriate combination of laser process parameters, we can determine the threshold value of the energy where we get maximum tensile strength.

The level of spatter or porosity can be judged from the weight loss (gm/mm) of the work-piece. High weight loss of the work-piece conforms the higher amount of spatter or porosity and vice versa. A report published from NIPPON Steel shows the correlation between weight loss and tensile shear strength of the laser welding of galvanized steel (Report 2010). Kim *et al.* (2008) also suggested a strong relationship between weight losses and surface area of porosity. Experimental results also confirmed that appropriate combination of laser power and welding speed provides an upper limit of part-to-part gap where the tensile strength of the weld seam can shows maximum value.

### 2.1.4 Part-to-part gap

Part-to-part gap is an important parameter for laser welding of galvanized steel. In general, the threshold value of part-to-part gap should be within ten percent of the thickness of upper part (Havrilla 2012). A lots of techniques have been developed to realize the required gap control during laser welding of galvanized steel in lap joint configuration, such as shim insertion (Rito *et al.* 1988), pre-stamped projections (Petrick 1990), synchronous rolling during welding (Ozaki *et al.* 2006), dual beam techniques (Wu *et al.* 2008), dimpling (Colombo *et al.* 2013), pre-drilling vent hole (Pennington 1987), and Vertical positioning of metal parts (Delle Piane *et al.* 1987). Table 2.3 discusses the different industrial solutions for creating/eliminating part-to-part gap.

**<u>Laser dimpling techniques</u>**

Laser dimpling technique is an alternative method to produce part-to-part gap (Colombo *et al.* 2013). In general, humping effect facilitates to generate dimples in one of the galvanized steel in a lap joint configuration of laser welding. The salient feature of dimpling process is that there is no need of extra laser system.

**<u>Fill the part-to-part gap with a porous powder metal</u>**

Part-to-part gap is created with the help of porous power metal through which facilitates for escaping the zinc vapour. But, it is not feasible way to create part-to-part gap in real life production system.

**<u>Pre-drilling vent hole techniques</u>**

Another technique to eliminate a part-to-part gap is a pre drilling vent hole techniques. The vent hole is directed towards the welding line and this hole provides a room to escape zinc vapors (Pennington 1987). Requirement of preprocessing is major disadvantage of this technique.

**<u>Prior zinc removal techniques</u>**

Before staring of laser welding process, removal of zinc coating from the weld area is also a feasible solution for preventing part-to-part gap (Graham *et al.* 1996). After welding, the welded area can be coated with nickel to provide corrosion protection. Removal of zinc coating and addition of nickel coatings are very expensive techniques. Therefore, prior zinc removal technique is not a suitable way to eliminate part-to-part gap in mass production.

**<u>Lower power pulsed laser welding</u>**

In the lap joint configuration with 2.5 KW pulse $CO_2$ laser welding of galvanized steel produces good quality of weld without part-to-part gap is first claimed by Heyden *et al.* (1989). Kennedy *et al.* (1989) also conform good quality of laser welding can be achieved with the use of pulsed Nd:YAG laser in galvanized steel without part-to-part gap. Although, their mechanism for getting good quality of weld are not satisfactory explained. Tzeng *et al.* (1999) also experimentally observed that spatter free laser welding of galvanized steel can be achieved with the help of 400 W pulsed Nd:YAG laser. But, major drawback of the lower power pulsed laser welding is that welding speed cannot be more than 2.4 mm/s, which is not possible in mass production for any industry.

**Vertical positioning of metal parts**

At first in 1987, General Motors proposed a vertical positing of metal parts for doing continuous wave $CO_2$ laser welding of galvanized steel with the help of continuous wave (Delle Piane *et al.* 1987) and in this technique there is no need to maintain part-to-part gap. The salient feature of this technique is that the base metal aligns in the vertical position during welding process and moves vertically by maintaining static position of laser beam which applied horizontally. In real life situation, it is difficult to maintain vertical position of base metal that's why it is not a suitable process for commercial production.

**Alter joint geometry techniques**

Alter joint geometry is a special technique which provide a channels for escaping zinc vapour during laser welding of galvanized steel (Milberg and Trautmann 2009). In this process we intentionally created either convex or concave geometrical shape on the upper part of the metal sheet or this geometrical shape acts like a channel which facilities for escaping the zinc vapour during laser welding. Although, this technique is most acceptable if the metal sheets has waviness structure but it is not an acceptable techniques for industrial production because we need extra work to create alter joint geometry.

**Dual beam hybrid technique**

Dual beam/bi-focal hybrid laser systems is at first provides preheating effects for vaporizing the zinc and after that second beam is utilised as actual laser welding (Wu *et al.* 2008). But, this technique needs extra setup of laser welding system which enhances the cost as well as deteriorates the efficiency of the laser welding system.

**Addition of oxygen as a shielding gas to argon**

Mixing of two to five percentage of oxygen with shielding gas (argon) is another technique to eliminate the part-to-part gap. Actually, reaction mechanism of provided oxygen with zinc decreases the formation of spatter (Hanicke and Strandberg 1993). But, major problem is to optimize the flow of shielding gas otherwise; oxides porosity will be deposited on the weld surface.

Table 2.3: Part-to-part gap control techniques in laser welding of galvanized steel (adopted from (Sinha *et al.* 2013)

| Industrial solutions | Description | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Shim insertion | Insert shims in between sheets | Intuitive and easy to control the required clearance | Needs additional work and tool for shim insertion | (Rito *et al.* 1988) |
| Pre-stamped projection | A preprocessing creates V-shaped tabs in the lower part to facilitate escaping of zinc vapor | Useful for hem joints (special case of lap joint configuration) | Needs preprocessing | (Petrick 1990) |
| Laser dimpling techniques | In this techniques a preprocessing is carried out in which the laser beam generates dimple to maintain a part-to-part gap | Dimples can be produced with the same laser system used for the laser welding | Needs two-step process: (i) pre-processing by which dimples will generate and (ii) actual welding | (Colombo *et al.* 2013) |
| Fill the part-to-part gap with a porous powder metal | The porous power metal allow zinc vapour to escape without distributing molten metal | No need to remove the porous power metal after welding | Difficult to implement in a real production environment | (Pennington 1987) |
| Pre-drilling vent hole techniques | Pre-drilling hole along the line allow zinc vapour to escape without formation of spatter | No need to provide part-to-part gap | Time consuming and expensive process | (Pennington 1987) |
| Prion zinc removal techniques | Removal zinc coating from welding zone and then coat the treated zone with nickel in order to provide corrosion protection | Nickel coating not only provides good corrosion resistance but also do not form spatter | Preprocessing is necessary | (Graham *et al.* 1996) |
| Lower power pulsed laser welding | By careful control of pulse energy, pulse duration, peak power density, mean power, and welding speed, the formation of zinc gas reduces in the pulse mode | Literature survey reveals that both CO2 and Nd:YAG pulsed laser provide porosity/spatter free welds | The limitation of low laser power causes slow welding speed of less than 2.4 mm/s, which is hard to maintain in an industrial environment | (Bilge *et al.* 1993) |
| Alternate joint geometry techniques | Altered joint geometry offers channels between the metal parts to exhaust zinc vapour | This technique is very useful when the dimensional variation in between part-to-part gap is high | Intentionally we need to create altered joint geometry in the form of either convex or concave shape on the upper part | (Milberg and Trautmann 2009) |

Table 2.3: Continued

| Industrial solutions | Description | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Dual beam hybrid technique | The first beam creates a slot which act as a preheating process and the second beam implements as a welding process | The first beam facilitates vaporization of the zinc that will prevent weld defects | Needs additional complex equipment | (Gualini 2001, Wu *et al.* 2008) |
| Addition of oxygen as a shielding gas to argon | Mixing of two to five percent oxygen with shielding gas; reaction mechanism of additional oxygen with zinc reduces the chance of the formation of spatter | No need to provide part-to-part gap | Optimize flow of shielding gas is necessary, otherwise oxides porosity will be formed | (Hanicke and Strandberg 1993) |
| Vertical positioning of metal parts | Metal parts align vertically and moves in vertical position by keeping static positioning of laser beam in horizontal direction | Due to gravity, zinc vapour escapes very easily during laser welding | Hard to maintain the positions of metal parts as well as laser beam | (Delle Piane *et al.* 1987) |
| Synchronous rolling techniques | Roller creates pressure on the part-to-part gap which provided favorable condition for escaping the zinc vapour during laser welding | Reduces the chances of the formation of zinc oxide | Needs additional roller during welding | (Ozaki *et al.* 2006) |

### 2.1.5 Laser power and welding speed

For a give specification of the work-piece, there are certain combinations of laser power, welding speed, focus point and part-to-part gap which can produce optimal depth of penetration during the laser welding of galvanized steel (Balasubramanian *et al.* 2008).

**Weld seam**

In one hand, laser power is proportional to the width of weld seam (Acherjee *et al.* 2009). Acherjee *et al.* (2009) experimentally observed that the width of weld seam is increases as we the laser power up to a certain limit. In one side, welding speed is inversely proportional to the width of weld seam as well as heat affected zone (HAZ) (Benyounis *et al.* 2005). Cao and Jahazi (2009) experimentally observed that the width of heat-affected zone is ranging from 0.2 to 0.5mm (very narrow) and decreases with increasing welding speed.

**Tensile strength**

Welding speed has a negative effect on tensile strength but laser power has a positive effect on the tensile strength (Anawa 2008). As compare to the base material, the laser weld joints shows similar or slightly higher joint strength but significant lower ductility (Cao and Jahazi 2009). The reason for low ductility is the presence of micro-porosity.

**Hardness**

In general, it was found that the hardness of the weld seam was about 2.5 times higher than the base metal (Anand *et al.* 2006). The hardness of the fusion zone of the laser weld seam increases with welding speed up to a threshold limit (Cao and Jahazi 2009).

### 2.1.6 Shielding gas

In general, shielding gas performs two tasks in laser welding (Hügel and Graf 2009, Zaeh et al. 2010). The first task is to protect the work piece from oxidation. Actually, shielding gas displaces the oxygen which is presented in the environment and provides a safe environment for laser welding. Theoretically, an inert shielding gas, higher density, provides a better protection from the oxygen. The second task is to remove metal vapor and particles from the laser beam path. Some researchers (Miller and DebRoy 1990, Beck et al. 1995) argue that the removal of metal vapor and particles from the laser beam is necessary for avoiding defocusing in the plasma (Greses et al. 2002), and absorption of the laser beam by the plume (Michalowski et al. 2007) (more often in the case of solid-state laser). Commonly, useful factors of the shielding gas which affect the quality of laser weld can be characterized as follows (Davim 2008):

- Physical properties
- Chemical composition
- Flow rate
- Distribution of a shielding gas

With reference to physical properties of shielding gases, particularly, thermal conductivity and density of the shielding gas is more important factors for laser welding (Seto *et al.* 2000).

Although, most researchers have focused on efficiently and economically use of shielding gas to suppress plasma initiation for getting higher welding efficiency but still it is a challenging issues (Grupp 2003). In steel welding with the help of optimize laser process parameters, we can reduce operating cost by replacing expensive helium by argon (argon is about 3 times cheaper than helium). Seidel *et al.* (1994) experimentally explain that in the case of aluminum welding the weld quality can be improved by applying the mixture of argon and helium with high argon portion. The results shown by (Wu *et al.* 2008) illustrate that the depth of penetration acquired by adopting argon (Ar) as protective gas is better than that of one acquired by adopting nitrogen ($N_2$) during the experiment of $CO_2$ laser welding of automotive parts. With the use of Ar as a side-blow protective gas during the laser welding of galvanized steel, we can find reasonably good mechanical properties of the joint, thin crystal grain in heat affected zone, and visually sound welding seam (Mei *et al.* 2009).

### 2.1.7 Laser beam quality

Low value of beam parameters reflects high laser beam quality which means the beam can be easily focused into a small diameter optical delivery fiber (Verhaeghe and Hilton 2005). At a fixed spot size the high beam quality produces a high brightness[5]. Laser beam diameter, and propagation factor provides an important information about the laser beam quality. Spatial beam quality determines how tightly the beam can be focused or how well the beam propagates over long distance without significant spreading. The beam propagation factor ($M^2$) help for accurate calculation of the properties of laser beam which depart from the theoretically perfect $TEM_{00}$ beam. $M^2$ is the ration of a beam's actual divergence to the divergence of an ideal, Gaussian $TEM_{00}$ beam having the same waist size and location.

[5] Brightness is defined as the ratio of the power density in the beam waist and the solid angle formed by the focusing beam cone

## 2.2 Monitoring system of laser welding process

Several scholars and practitioners have conducted experimental studies to investigate the quality of laser welding process. Quality monitoring of laser welding system has been carried out by Kim *et al.* (2003). On the basis of experiment, they observed that a depth of the penetration can be evaluated with the fluctuation of the frequency of the plume signals.

The LW systems rely on the analysis of different signals which are emitted during the laser welding process. In real-time monitoring of LW, various sensors like acoustic emission (Hamann *et al.* 1989, Li and Steen 1992), audible sound, infrared detectors, ultraviolet detectors, electromagnetic acoustic transducers, and polyvinylidene fluoride are frequently used for detecting weld states (Sun *et al.* 1999). Airborne audible acoustic emissions, weld pool infrared emissions, structure-borne infrared emissions, bottom-side infrared emissions, transmitted laser emissions, bottom-side plasma optical emissions, and ultraviolet emissions play a major role during monitoring of laser welding system (Zhang 2008). Shao and Yan (2005) presented the applications of visual, acoustic, thermal, ultrasonic, and optical techniques for monitoring of laser welding system. In-process control of laser welding can also improve the reliability. However, it is not so simple because failure may occur before the signal is obtained. In nutshell, it needs very reliable mechanism without the false alarm in in-process control or monitoting.

On the other hand, Steen and Weerasinghe (1987a) pointed out that laser material processing is free from signal noise. Luo *et al.* (2005) concluded that as compare to time domain, frequency domain distributions are a better way to identify weld defect from acoustic emission from the laser induced plasma signal which generates during laser welding. They experimentally observed that if any welding defect occurred during laser welding then the intensity of low frequency (<781 Hz) components of the acoustic signals decreased rapidly.

During the laser welding, the laser-material interactions emit energy in the form of acoustic, thermal, optical (plasma), ultrasonic, ultrasound, audible sound and visual emission etc., each of emission indicates certain properties of the weld quality in terms of porosity, spatter, depth of penetration, and hardness (Sun 2001, Shao and Yan 2005).

A fuzzy logic based penetration control system for the laser welding of aluminum alloy AA5182 and zinc coated steel DX54D-Z has been developed by (Aalderink 2007). They already tested their laser welding monitoring control system for Tailor Welded Blanks (TWB) production. Kaierle *et al.* (1998) developed a multivariable online control system for controlling the depth of penetration in laser welding. Experimentally, they illustrated the monitor of the depth of penetration during laser welding by evaluating the CCD camera images.

The most challenging task in the robustness of fault detection in LW is to identify the in variation between different fault effects or between the effects of faults and of unknown inputs (process parameters) of LW. There are several different ways to approach this goal (Patton *et al.* 1989)

- The detection filter approach (Beard 1971, Bokor and Balas 2004)
- The parity space approach (Chow and Willsky 1984, Kim and Lee 2005)
- The eigen structure assignment approach (White and Speyer 1987)
- The unknown input observer approach (Watanabe and Himmelblau 1982)

**Acoustic emissions**

Colombo *et al.* (2013) experimentally observed that during laser welding some internal changes occurs in the material and these changes are responsible for acoustic emission and this acoustic emission produces the sound wave. Shao and Yan (2005) already clearly explain that such type of sound wave has potential for monitoring stress wave. They also experimentally observed that the changes in the internal structure of specimen, emission of the back reflection and emission of metal vapour on the surface of specimen are responsible for creating stress wave. In other words, we can say that from acoustic emission or from the stress wave signal we can monitor the mechanical properties of the laser welded seam. Hamann *et al.* (1989) demonstrate the monitoring of weld depth with the help of acoustic emission.

The major drawback of laser welding is the easy formations of welding defects say for example porosity in the deeply penetrated weld fusion zone. Therefore, it is necessary to understand the mechanism of laser weld penetration and the correlation between quality of laser weld and the emissions generated during laser welding.

**Limit Checking methodology for fault detection**

A variety of researchers have been performed limit checking methodology whether the signal exceeds a threshold for identification of weld defect. This technique is well known for researchers and practitioners. This technique is based on the empirical values which we are getting from the signals and the monitoring system has to be trained for each welding defect (spatter, porosity, crack etc.). Generally, welding defect produced unexpected signal response, which can be analyses through various algorithms. Eriksson and Kaplan (2009) experimentally observed that on the basis of empirical value humping is easy to detect from the signal but spatter is hard to detect from signals (temp, back reflection and plasma) for the case of laser welding of galvanized steel. Norman *et al.* (2009b) argue that some of the laser welding defect such as blowhole, undercut and root sagging is hard to detect from the sensor signal by using limit checking methodology. They also experimentally argue that if there is only root sagging laser welding defect (generally, undercut and root sagging laser weld defect occurs together) then it is hard to detect by on line monitoring system.

### 2.2.1 Plasma

During the laser welding process plasma (plume) is produced when the interaction occurs between laser beam and work piece (Sibillano *et al.* 2005). The ionization of shielding gas and metallic vapour are responsible for formation of plasma. The high temperature and characteristic emission of the keyhole plasma is responsible for creating the majority of the radiant energy in the visible and ultraviolet range during LW process. With the help of covariance mapping technique, (Sibillano *et al.* 2007a) observed a strong relationship between the welding defects and the plasma plume. On the basis of correlation coefficient plots, Sibillano *et al.* (2007a) suggested a range of the welding speed and within a range the quality of the weld is acceptable. (Sibillano *et al.* 2007b) proposed a real-time monitoring technique to identify the mode (keyhole/conduction) during laser welding of AA5083 aluminum-magnesium alloy. We cannot decide the internal defect of laser weld with the help of plasma electron temperature (Sebestova *et al.* 2012). (Mirapeix *et al.* 2007) utilized PCA (principal component analysis) as pre-processing for plasma signal and after that they estimate weld defect with the help of artificial neural network (ANN). Here, PCA is utilized for dimensional reduction and redundancy elimination for plasma signal.

Sabbaghzadeh *et al.* (2007) tried to make a comparison in between laser welding quality features (depth of penetration, and seam weld width) and the thermal characteristics of the plasma plume.

### 2.2.2 Back reflection

The strength of the back reflection from the weld zone is mainly depend on the surface geometry of the melt pool rather than the temperature of the melt pool or the vapour cloud during LW process (Olsson *et al.* 2011). Zhang (2008b) identified that the strength of the back reflection's signal is a function of the distance of the work piece from the focal position and part-to-part gap. Back reflection mainly depends upon the reflectivity of the material, reflective surface with little roughness show higher back reflection and, vice versa. High noise level and high strength of the back reflection's signal is a key characteristic of the absence of keyhole. Therefore, back reflection gives us clear cut indication of the formation of keyhole. Colombo *et al.* (2012) confirmed that a strong correlation exists in between the back reflection of the laser light and part-to-part gap in laser welding monitoring system.

### 2.2.3 Temperature

Temperature gives indirect measurement of heat input per unit volume because both are strongly correlated. Therefore, with the help of temperature field, we can monitor the quality of the weld like weld pool geometry (top weld bead, bottom weld bead, depth of penetration, aspect ratio).

Bardin *et al.* (2005) explain the real-time temperature measurement system for assessing the quality (depth of penetration) of the resulting weld seam. They experimentally observed that maximum depth of penetration is obtained when the surface temperature is just below the vaporization point of the work-piece. Although, almost similar depth of penetration can be obtained above the vaporization point but the resulting weld seam also shows the presence of porosity. Therefore, for getting optimal depth of penetration without porosity, it is necessary to maintain the surface temperature just below the vaporization temperature.

### 2.2.4 Depth of penetration

The monitoring of laser welding thought the acoustic emission is reported by Jon (1985). Jon (1985) clearly mention that acoustic emission could be used for detecting the quality of laser weld which are arises due to laser misfocusing, loss of laser power and part-to-part gap. The detection of the laser weld quality through acoustic emission is also confirmed by (Li *et al.* 1992). Further, the use of acoustic emission for monitoring of depth of penetration in galvanized steel has been investigated by Gu and Duley (1996). The digital signal of the acoustic emission (AE) was processed with fast Fourier transformation (FFT) at different welding condition and with the help of linear discrimination algorithm they have identified three separate welding classes: overheated, fully penetrated and partially penetrated with 67-83% reliability. On the basis of acoustic emission, Farson *et al.* (1990) suggested Neuro-fuzzy feedback control system for monitoring of the depth of penetration for laser welding. Sebestova *et al.* (2012) observed that depth of penetration can be conformed to the help of optical emission spectrum of plasma. When they performed discrete wavelet transformation on the plasma signal then they were in a position to divide each signal segment into seven frequency bands starting from 200 Hz to 30 kHz and they also observed that a distinctive frequency distribution forms under different welding conditions. Plasma electron temperature can be a promising technique for estimation of the depth of penetration (Sebestova *et al.* 2012, Sibillano *et al.* 2012). They found a quantitative relationship between the plasma electron temperature and the depth of penetration.

The lack of spatial resolution is a major disadvantage of the photodiode but camera provides a facility of spatial resolution (Norman *et al.* 2009b). The correlation between signals and laser welding defects can become clearer when we apply both photodiode sensor and camera (Norman *et al.* 2008).

### 2.2.5 Part-to-part gap

Fleming *et al.* (2008) experimentally investigated that downward force in stir welding is highly sensitive parameters for identifying the welding defect which occurs due to part-to-part gap. At first they converted the downward force data signal into the frequency domain and after that they applied principal component analysis (PCA) technique and linear discriminant analysis, for identifying category of fault. But, they can identify welding fault only if the data were nearly linearly separable (assumption) (Fleming *et al.* 2008). Yang *et al.* (2008) also proposed a methodology for automatic gap detection in friction stir welding in butt joint configuration.

### 2.2.6 Keyhole or conduction mode

In general, there are two laser welding mechanism: conduction mode and keyhole (deep penetration) mode. Insufficient laser intensity ($<10^6$ W/cm$^2$) is responsible for formation of conduction mode. Although in conduction mode optical emission from the plasma plume is somehow weak but due to the small vaporization the laser welding process is more stable. The small vaporization of material is responsible for yielding low aspect ratio (depth of penetration/width of weld seam), shallow weld width. Sufficiently large laser power density ($>10^6$ W/cm$^2$) creates keyhole formation. Although large amount of vaporization provides unstable laser welding process but it forms high aspect ratio, narrow heat affected zone. Detection of the transition from conduction mode to keyhole mode provides sufficient information of the quality of the weld in terms of width of the weld seam, depth of penetration. Figure 2.2 illustrates the basic principal for the formation of conduction and keyhole welding mode. Mao *et al.* (1993) experimentally investigated that there is a significant difference in acoustic emission when laser welding of conduction mode is converting into keyhole mode. With the help of fast Fourier transformation they experimentally observed that the amplitude of acoustic emission in keyhole mode is roughly 20 times higher than that of conduction mode. In order to detect the threshold condition between conduction and keyhole mode of welding, Sibillano *et al.* (2007b) advocate covariance mapping technique (CMT) to the plasma signal.

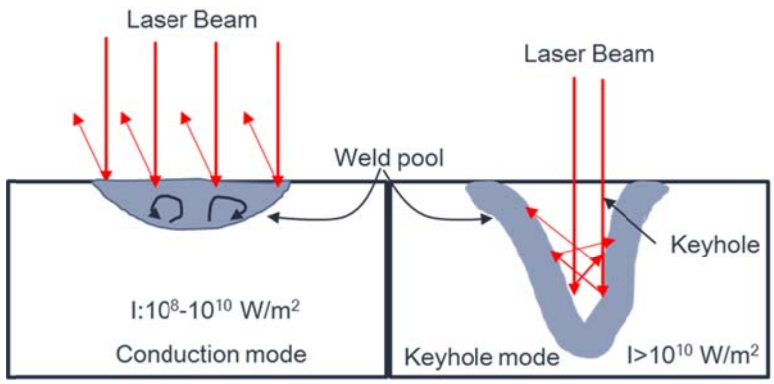



Figure 2.2: Laser material interaction phenomena of conduction and keyhole welding mode

### 2.2.7 Undercut, blowhole, and root sagging

It is a challenging task to identify certain defects like undercut, blowouts and root sagging with the help of signal (Norman *et al.* 2009b). But on the basis of exhaustive experiment and their signal analysis, we can identify undercut, blowhole and root sagging.

### 2.2.8 Why we need multi sensor fusion techniques?

**Multi sensors**

In the literature, several studies have been made in monitoring the quality of the weld by using a variety of emissions, including acoustic, thermal, optical (plasma), ultrasonic, ultrasound, audible sound, electromagnetic radiation, free charge and visual emission. Although, some researchers and practitioners suggests very high reliability for different monitoring techniques of laser welding, even some of the techniques are utilized in industry but still there is a need of the utilization of multiple sensors. One reason for this is a lack of robustness because these techniques (based on single sensor) are very sensitive to small changes in process parameters which have practically no effect on the weld quality but it significantly changes the emissions (Farson 1996).

Farson *et al.* (1999) utilized linear discrimination analysis (LDA) technique on average frequency spectra of sensor signals (optical, acoustic, and plasma) and they observed that the combined signals identify better separation between full penetration and half penetration with 88-89 % reliability.

On the basis of previous work related to on-line process monitoring of laser welding indicates that no single emission/signal/sensor can accurately detect the full spectrum of quality of the weld (Sun *et al.* 1999, Kaftandjian *et al.* 2003). Say for example, a temperature sensor value indicates that there is no fault, but for the same specimen, plasma signal reveals that there is fault (Sinha and Kim 2013). In other words, we can say that for the same specimen, we can get conflicting estimation on the basis of different sensors. Therefore, in order to evaluate the weld quality more accurately, the use of multiple sensor fusion is necessary for integrating the features of individual sensors.

## 2.3 Classification techniques for fault detection in laser welding

In general, classification is a technique to discover a mathematical model for assigning the data into different classes with satisfying constraints. In other words, classification is a process of data mapping into different cases. The design of pattern classification techniques involves five main phases: (1) data collection, (2) feature selection, (3) model formulation, (4) training, and (5) evaluation (Duda *et al.* 2012). There are several kinds of classification algorithms are being utilized by practitioners and scholars, say for example: k-nearest neighbor (KNN) classifier, Naive Bayes, Support Vector Machine (SVM), Neural Network (NN) and AdaBoost. It is not often clear which classifier methodology is better for a particular sets of problem. It depends upon so many factors.

The basic fundamental principal behind the supervised learning classification technique is to create human expertise for categorizing the object into a class/group with the acquisition from training data sets. These training data sets teach classification techniques to classify objects.

If the classification problem contains only two or three features then it is easy to classify otherwise it is difficult to classify. It is not difficult to understand classification of two features because two features can make very simple scatter-plot and graphically we can divide the plane into homogeneous regions. The classification of many features not only creates difficulties for high-dimensional space visualization but also needs exhaustive search for different combination of features space. Theoretically, almost all of the classification methods work on the heuristic approach.

### 2.3.1 Support vector machine

In 1998, SVM was introduced by Prof. V N Vapnik (Vapnik 1998) and proven very effective mathematical tool for regression, classification and general pattern recognition (Cristianini and Shawe-Taylor 2000). The development of SVMs and the development of NNs are completely opposite to each other. In one hand, the evolution of SVMs is based on the ground of sound theory

"In one hand, the evolution of SVMs is based on the sound theory to the implementation and experiments and on the other hand, NNs followed more heuristic path, from applications and extensive experimentations to the theory (Wang 2005)". SVM guarantees for providing global minimum and its geometrical interpretation can be easily understood (Burges 1998).

Recently, SVM has been proven promising classification techniques without prior function (separation) hypothesis (Stecking and Schebesch 2003). Application of SVM for monitoring of RL system is briefly discussed in Table 2.4.

Zhang *et al.* (2007) identified the classification of fault and no fault of laser welding on the basis of the quality of weld seam. They used support vector machine for such classification. The input of the support vector machine was signals value obtained during laser welding. From the literature it is not conform that which type of signal they used.

Zhou *et al.* (2009a) proposed a monitoring system for measuring the quality of laser weld by using support vector machine. They used the signal of sound sensor as an input for support vector machine and the formation of small hole within the weld seam as an output. They also used SVM to obtain laser process variables like welding speed and laser power for getting higher quality of weld seam.

Shao and Yan (2007) utilized optical sensor (for getting signal that generated during laser welding) for monitoring the quality of laser welding. Their optical sensor is sensitive to a spectrum ranging from visible to infrared region. With the help of SVM they classified two bad category of weld seam namely misalignment, and not enough burn (partial penetration). In this experiment they used variance, first peak, last peak and mean value of the signal as a feature for SVM.

In the laser welding of aluminum sheet, the presence of antioxidant coating deteriorates the quality of the weld seam. Actually, the formation of antioxidant coating indicates the presence of high level of impurity in the aluminum sheet. The presence of antioxidant coating creates similar problems like laser welding of galvanized steel. (Anabitarte et al. 2010, Anabitarte et al. 2012) used SVM to classify the weld quality on the basis of the presence of antioxidant coating residues on the weld seam.

Wang and Gao (2013) proposed a mathematical model to predict the width of the molten pool. Their prediction was based on the SVM as well as NN. Lastly, their experimental results shows that SVM is more reliable for predicting the width of the molten pool as compare to the NN for high power disk laser welding.

SVM can be utilized as a promising tool for evaluating the quality of laser weld seam by using image processing techniques. Timm *et al.* (2009) introduce a novel feature set known as secularity features (SPECs) which includes almost all the complex properties of specular reflection. They used these features as an input for SVM and experimentally they reached in the position to say either weld seam has fault or not on the basis of the shape and geometry of the weld seam. I think their main contribution is the extraction of SPECs from image processing techniques.

Xue-wu *et al.* (2011) used size, shape and texture measurement as a characteristics of the binary image obtained from the laser weld seam for an input into a support vector machine to identify seven types (Burr, Loophole, Oil strain, Peeling, perforation, Pit and Scratch) of fault in the weld seam.

Table 2.4: Application of SVM for monitoring of LW system

| Contributors | Inputs | Outputs | Remarks |
|---|---|---|---|
| Zhou *et al.* (2009a) | Sound sensor | Formation of small hole within the weld seam | Classification |
| Shao and Yan (2007) | Optical sensor | Misalignment and partial penetration | Classification |
| Wang and Gao (2013) | Optical sensor | Width of the weld seam | Classification |
| Timm *et al.* (2009) | Reflection | Fault or no fault on the basis of the geometry of weld seam | Classification |
| Xue-wu *et al.* (2011) | Binary image | Seven types of fault namely Burr, Loophole, Oil strain, Peeling, perforation, Pit and Scratch | Classification |

### 2.3.2 Neural Network

The history of neural networks is based on the work of trying to model the neuron. The first try in the domain of the modeling of neuron was carried out by physiologists, McCulloch and Pitts (1943). Their model considered only two inputs and one output. After a long period of time, the field of NN has been a remarkable renaissance for scholars and practitioners in the latter half of the 1980's. Over the past few decades, numerous theoretical and experimental investigations have proven that NN can be promising techniques in a broad range of applications (e.g., classification, regression and modeling for various sectors) (Rumelhart *et al.* 1986). Therefore, in this thesis, a study into the feasibility of using a NN as a laser welding monitoring process is described. Application of SVM for monitoring of RL system is briefly discussed in Table 2.5.

The preliminary results shown by Farson *et al.* (1990) explain that a significant amount of the quality of the laser weld seam can be estimated with the application of NN in the acoustic emission generated from the laser welding process. With the help of NN, Cook *et al.* (1995) estimated the top as well as bottom width of the weld seam for plasma arc welding. They used forward current, reversed current, torch standoff and welding speed as an input parameters for NN modeling.

With the help of NN, Sathiya *et al.* (2012) tried to develop a relationship between the laser welding process parameters (beam power, welding speed, and focal positions) and the three response variables namely depth of penetration, width of the weld seam, and tensile strength of the weld.

In the inert gas welding process, Pal *et al.* (2008) established a regression model with the help of NN. In this model, their model predicted the ultimate tensile strength as a quality of the weld.

Ismail *et al.* (2013) suggested a NN based model for prediction of the geometry of weld seam (weld width, and depth of penetration). They used laser power, welding speed and spot diameter as a process variables for prediction of the geometry of weld seam. Campbell *et al.* (2011) applied an NN model to predict the depth of penetration, effective throat thickness, and leg length for specified process parameters (laser power, shielding gas configuration, and welding speed). Chokkalingham (2012) suggested a NN based model for prediction of depth of penetration and width of weld seam from the infrared thermal images of the weld seam.

Lastly, Table 2.6 explains the basic fundamental concept of different types of classification techniques.

Table 2.5: Application of NN for monitoring of LW system

| **Contributors** | **Inputs** | **Outputs** | **Remarks** |
|---|---|---|---|
| Farson *et al.* (1990) | Acoustic emission | Full or partial penetration | Classification |
| Cook *et al.* (1995) | Forward current, reversed current, torch standoff and welding speed | Width of top weld seam, and width of bottom weld seam | Modeling |
| Ismail *et al.* (2013) | Laser power, Welding speed, Spot diameter | Depth of penetration, and width of weld seam | Modeling |
| Campbell *et al.* (2011 | Laser power, Welding speed, shielding gas configuration | depth of penetration, leg length, and effective throat thickness | Modeling |
| Chokkalingham (2012) | Infrared thermal images of the weld seam | Depth of penetration, and width of weld seam | Modeling |

Table 2.6: Comparative study of classification techniques for LW systems

| Classification techniques | Descriptions | Advantages | Disadvantages |
|---|---|---|---|
| **Neural networks (NN)** | -It is a parametric model<br>-NN follows a heuristic path→ applications→ experimentation →preceding theory | -It can handle large number of input features/parameters. Even in the case of N-dimensional feature space it performs well.<br>-Just doing manipulation in features we can get better results with same computational effort. Say for example, We can create an area feature from the length and width and that area features can give better results with same computational efforts. | -Needs huge computational time for both the training as well as testing phase<br>-It is a black box. In other words, it is hard to find how the net is performing<br>-It is hard to find which features are important and which are worthless for classification<br>-Selection of the optimum network architecture is a challenging task<br>-It often converges on local minimum rather than global minima<br>-In the case of long training sets, it shows over fitting problem therefore, noise can also be considered as a part of the pattern<br>-As compare to SVM, it suffer from multiple local minimum<br>-Computational complexity is dependent on the dimensionality of features |
| **K Nearest-Neighbor (KNN) Classifier** | -The closest (neighbor) object from the training set treated as in the same class<br>-The class of a new testing sample is decided on the basis of the majority class of its k closest neighbors by considering euclidean distance | -Easy to implement<br>-By optimizing weighting function on features, it performs well | -Process is quite slow in the case of large dimensional data sets<br>-It is very sensitive towards the presence of irrelevant features. Addition of a single features that has a random value for all objects completely misguided the results |
| **Decision tree** | -It works on the principal of heuristics | -It performs better in the case of both discrete as well as continuous features<br>-It is comprehensible.<br>-It is easy to understand the basic principal behind the classification | -At each internal nodes, it works on the basis of single feature<br>-It is hard to utilizing in the case of classification problem where diagonal partitioning is needed<br>-Generally, it creates rectangle hyper-plane because the division of the space is perpendicular to one features and parallel to other features |

Table 2.6: Continued

| Classification techniques | Descriptions | Advantages | Disadvantages |
|---|---|---|---|
| **Support vector machine (SVM)** | -SVM is based on learning algorithm<br>-It formulate a linear discriminant function with the help of training data sets of each class and try to maximize the separation between these two classes<br>-For non-linear case, techniques of Kernel performs well<br>-By default, sigmoid function is utilized for calculating the probability of the output from the SVM<br>-It is a non-parametric model<br>-SVM follows sound theory→ implementation → experiments<br>-Creation of fewer hyper parameters<br>-It needs comparatively (as compare to NN) less grid-searching to get a reasonably accurate model | -Its interpretation is based on simple geometrical understanding<br>-Global and unique minima as compare to NN<br>-SVM are less prone( as compare to NN) to over fitting<br>-Needs less memory (compare to NN) to store the predictive model<br>-Guarantee of global optimal due to quadratic programming<br>-Strong founding theory<br>-Have less prone (compare to NN) to over fitting<br>-Yield more readable results and a geometrical interpretation | -Although there are kernel SVM for nonlinear hyper plane but its performance is not good for nonlinear classification |

# 3. Variation of weld seam

## 3.1 Correlation analysis of the variation of weld seam verses tensile strength

**Motivations**

- Literature survey suggests that the width of weld seam is correlated with the welding quality.
- For getting information about tensile strength of laser welding, traditionally, mechanical tensile testing is necessary which is costly as well as time consuming. Therefore, some mathematical modeling based on non-destructive techniques is necessary for improving the production in a laser welding industry.
- How to measure the width of weld seam without destructing the weld seam will be discussed.

**Objectives**

To investigate the correlation analysis of the variation of the width of top weld seam and tensile strength in laser welding of galvanized steel

**Experiment procedures**

The material used for laser welding experiment of lap joint configuration was two different galvanized steels: SGARC440 (upper part) and SGAFC590DP (lower part). The dimensions (Length×Width×Thickness) of upper and lower parts are 130 mm×30 mm×1.4 mm and 130 mm×30 mm×1.8 mm respectively. The lower parts contain 45.5 g/m$^2$ of zinc coating and upper parts 45.4 g/m$^2$, respectively. Chemical composition and mechanical properties of the experimental materials are listed in Table 3.1 and 3.2, respectively.

Table 3.1: Chemical composition (weight %) of the experimental materials

| **Experimental materials** | **C (%)** | **Si (%)** | **Mn (%)** | **P (%)** | **S (%)** |
|---|---|---|---|---|---|
| SGARC440 (1.8 mm thickness) | 0.12 | 0.5 | 1.01 | 0.021 | 0.004 |
| SGAFC590DP (1.4 mm thickness) | 0.09 | 0.26 | 1.79 | 0.03 | 0.003 |

Table 3.2: Mechanical properties of the experimental materials

| **Experimental materials** | **Tensile test** | | |
|---|---|---|---|
| | **Yield strength (N/m$^2$)** | **Max-tensile strength (N/m$^2$)** | **Elongation (%)** |
| SGARC440 (1.8 mm thickness) | 327.5 | 451.1 | 38 |
| SGAFC590DP (1.4 mm thickness) | 413.8 | 625.7 | 28 |

The laser welding system (see Figure 3.1) used for the experiment is a 2.5 axis gantry robot automated welding system. It delivers a laser beam from YLS-2000-CT fiber source with a maximum power of 2kw in the $TEM_{01}$ mode. For all the experiments, a parabolic mirror with a focal length of 165 mm and the diameter of the laser beam with 35 mm are used. The laser technical parameters used in the experiments are listed in Table 3.3. The wall plug efficiency is more than 28% and diode life is more than 100,000 hours.

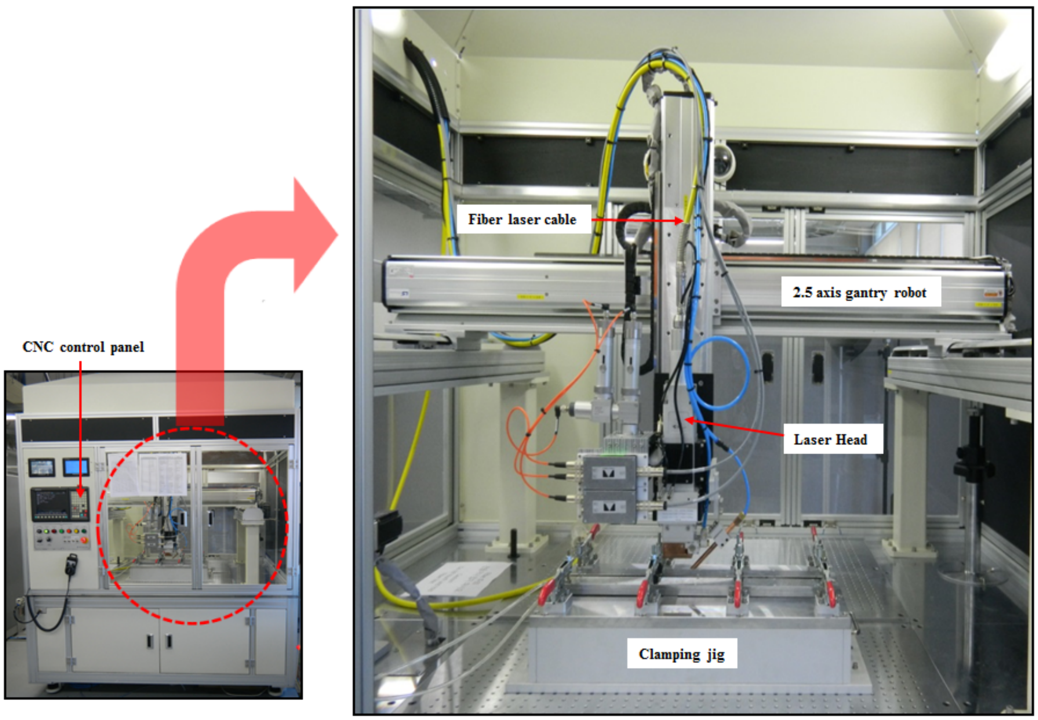



Figure 3.1: The laser welding system (2.5 axis gantry robot, maximum power of 2kW)

Table 3.3: Laser technical parameters

| Parameters | Value |
|---|---|
| Maximum laser power | 2 kW |
| Laser mode | $TEM_{01}$ |
| Focus length | 165 mm |
| Operation mode | CW |
| Switching ON/OFF time | 80 ms |
| Emission wavelength | 1070 nm |
| Output power instability | 2.0% |
| BPP* ($1/e^2$) at the output of fiber | 2.0 mm*mrad |

For investigating the correlation analysis of the variation to the width of top weld seam and tensile strength in laser welding of galvanized steel in lap joint configuration, we used three process variables: laser power, welding speed and part-to-part gap. The coded and actual values of the welding process parameters are listed in Table 3.4.

Table 3.4: Full factorial design with three welding process parameters each at three-levels

| Code unit | Experimental factor | | |
|---|---|---|---|
| | Laser power (W) | Welding speed (mm/min) | Gap (mm) |
| -1 | 1600 | 1200 | 0.1 |
| 0 | 1800 | 1500 | 0.2 |
| 1 | 2000 | 1800 | 0.3 |

**Procedure to estimate the variation of weld seam**

At first a series of magnified pictures of top weld seam are taken. After that, with the help of CATIA V5 we extract two boundary curves of the top weld seam and measure the variation in the width of top weld seam with the help of deviation analysis between the two extracted curves (as illustrated in Figure 3.2).

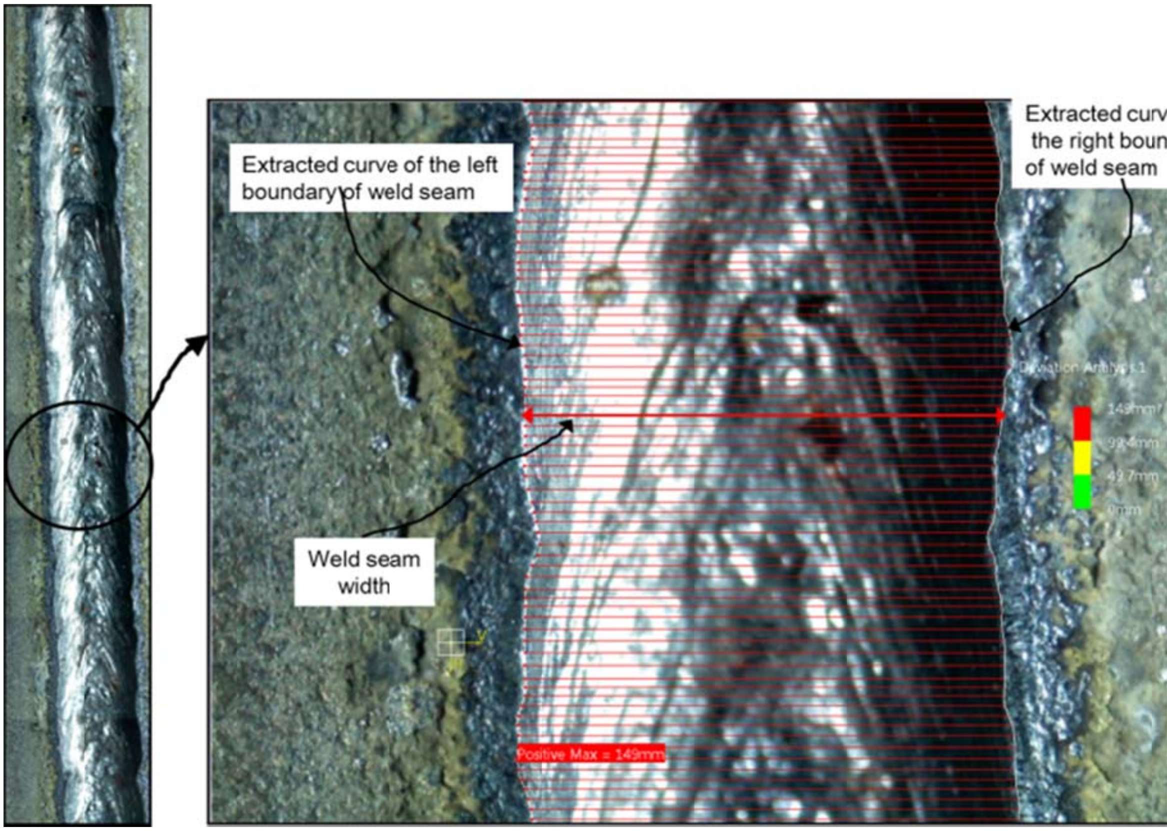



Figure 3.2: Definition of the width of the top weld seam by using the two extracted boundary curves (adopted from Sinha *et al.* 2013)

Figure 3.3 shows the variance of top weld seam of all the 27 specimens. Laser power, welding speed, and part-to-part gap with corresponding width of weld seam and their variances are illustrated in Figure 3.3.

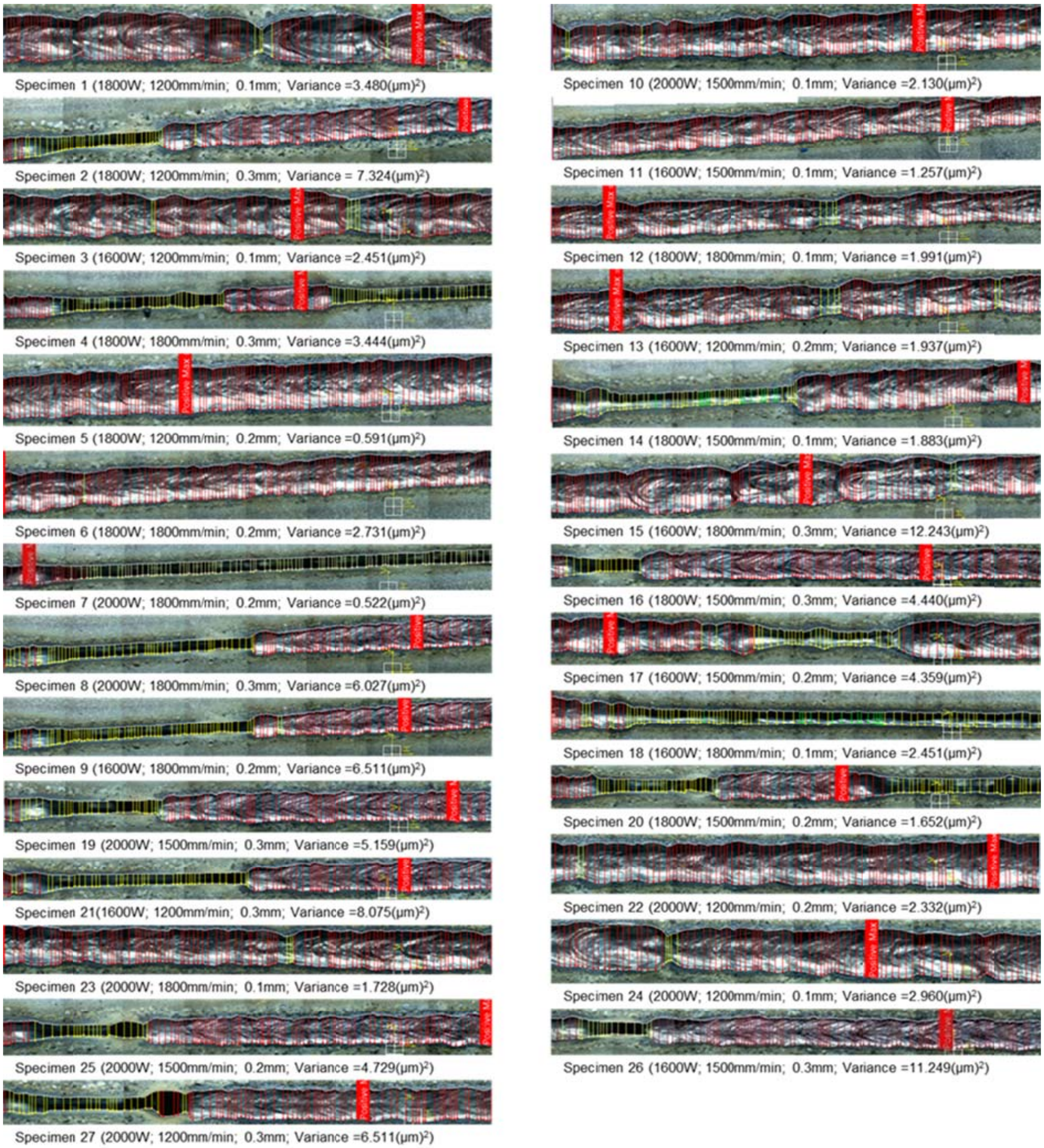



Figure 3.3: Variation of top weld seams

The results (tensile strength, width of top weld seam, variation in the top weld seam) of laser welding experiments are summarized in Table 3.5.

Table 3.5: Laser welding experiment data for analysis of the variation of non-uniform weld seam and tensile strength (adopted from Sinha *et al*. 2013)

| Speci men No | Run order | Laser power (Watts) | Welding speed (mm/min) | Part-to-part gap (mm) | Maximum tensile strength (MPa) | Top weld seam width (µm) | |
|---|---|---|---|---|---|---|---|
| | | | | | | mean | variation |
| 1 | 3 | 1800 | 1200 | 0.1 | 161.30 | 1528.00 | 3.48 |
| 2 | 11 | 1800 | 1200 | 0.3 | 101.77 | 930.64 | 7.324 |
| 3 | 6 | 1600 | 1200 | 0.1 | 161.50 | 1550.80 | 2.451 |
| 4 | 5 | 1800 | 1800 | 0.3 | 124.00 | 934.14 | 3.444 |
| 5 | 13 | 1800 | 1200 | 0.2 | 156.30 | 1721.40 | 0.591 |
| 6 | 17 | 1800 | 1800 | 0.2 | 148.00 | 1358.39 | 2.731 |
| 7 | 12 | 2000 | 1800 | 0.2 | 162.00 | 1480.17 | 0.522 |
| 8 | 7 | 2000 | 1800 | 0.3 | 114.70 | 762.57 | 6.027 |
| 9 | 1 | 1600 | 1800 | 0.2 | 123.33 | 731.93 | 6.511 |
| 10 | 23 | 2000 | 1500 | 0.1 | 165.69 | 1438.16 | 2.13 |
| 11 | 18 | 1600 | 1500 | 0.1 | 134.51 | 1339.16 | 1.257 |
| 12 | 20 | 1800 | 1800 | 0.1 | 141.24 | 1355.35 | 1.991 |
| 13 | 22 | 1600 | 1200 | 0.2 | 140.60 | 1352.12 | 1.937 |
| 14 | 4 | 1800 | 1500 | 0.1 | 141.73 | 1335.01 | 1.883 |
| 15 | 27 | 1600 | 1800 | 0.3 | 34.43 | 555.48 | 12.243 |
| 16 | 25 | 1800 | 1500 | 0.3 | 137.90 | 1047.93 | 4.44 |
| 17 | 15 | 1600 | 1500 | 0.2 | 145.40 | 1051.72 | 4.359 |
| 18 | 9 | 1600 | 1800 | 0.1 | 134.48 | 1319.14 | 2.451 |
| 19 | 2 | 2000 | 1500 | 0.3 | 159.95 | 931.07 | 5.159 |
| 20 | 24 | 1800 | 1500 | 0.2 | 156.19 | 1702.29 | 1.652 |
| 21 | 26 | 1600 | 1200 | 0.3 | 90.90 | 817.32 | 8.075 |
| 22 | 21 | 2000 | 1200 | 0.2 | 181.00 | 1641.91 | 2.332 |
| 23 | 16 | 2000 | 1800 | 0.1 | 153.02 | 1338.06 | 1.728 |
| 24 | 19 | 2000 | 1200 | 0.1 | 170.10 | 1625.75 | 2.96 |
| 25 | 8 | 2000 | 1500 | 0.2 | 158.90 | 951.07 | 4.729 |
| 26 | 14 | 1600 | 1500 | 0.3 | 57.52 | 649.90 | 11.249 |
| 27 | 10 | 2000 | 1200 | 0.3 | 163.00 | 950.38 | 6.511 |

The regression model illustrates the relationship between average width of top weld seam '*w*' and maximum tensile strength 'T' (see Figure 3.4):

$$T = 86.248\ln(w) - 469.56, \qquad R^2 = 0.6472$$

The coefficient of determination $R^2$ shows that 64.72% of the variation of maximum tensile strength is occurring due to ln(*w*). The computed P-value (4.2478E-7) of the above regression model explain an existence of a positive correlation between *T* and ln(*w*) is statistically acceptable at the 0.05 level of significance.

The mathematical regression model between the variance of the top weld seam width ‘$v$’ and maximum tensile strength ‘$T$’ can be explain as follows (see Figure 3.5):

$$T = -0.8087 \times v^2 + 158.63, \qquad R^2 = 0.7867$$

The coefficient of determination $R^2$ explains that a strong negative correlation is existing between ‘$v$’ and ‘$T$’. The small P-value (7.2109E-10) also statistically (0.05 level of significance) conform the existence of negative correlation.

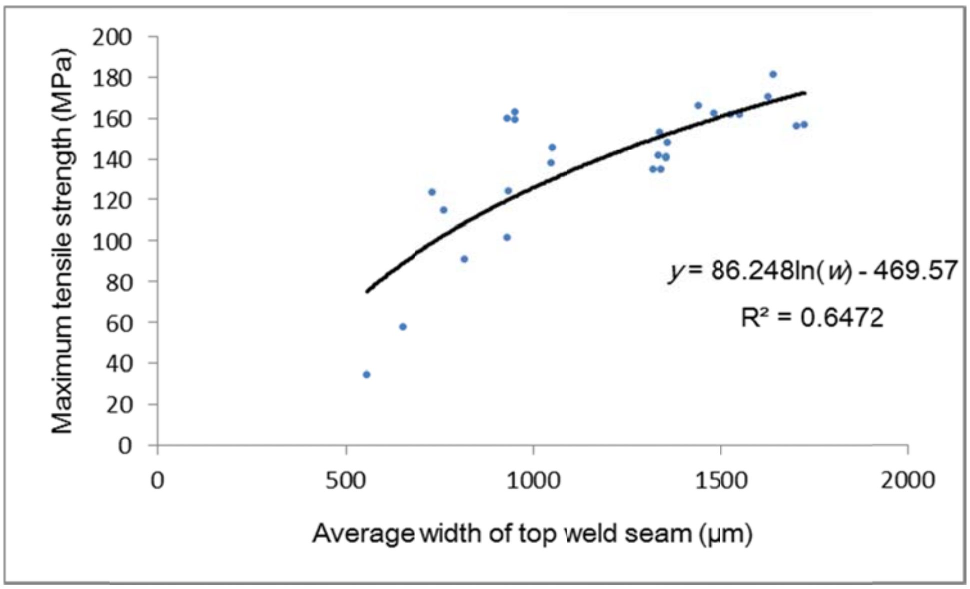



Figure 3.4: A positive correlation between the log-transformed average width of the top weld seam and maximum tensile strength (adopted from Sinha *et al*. 2013)

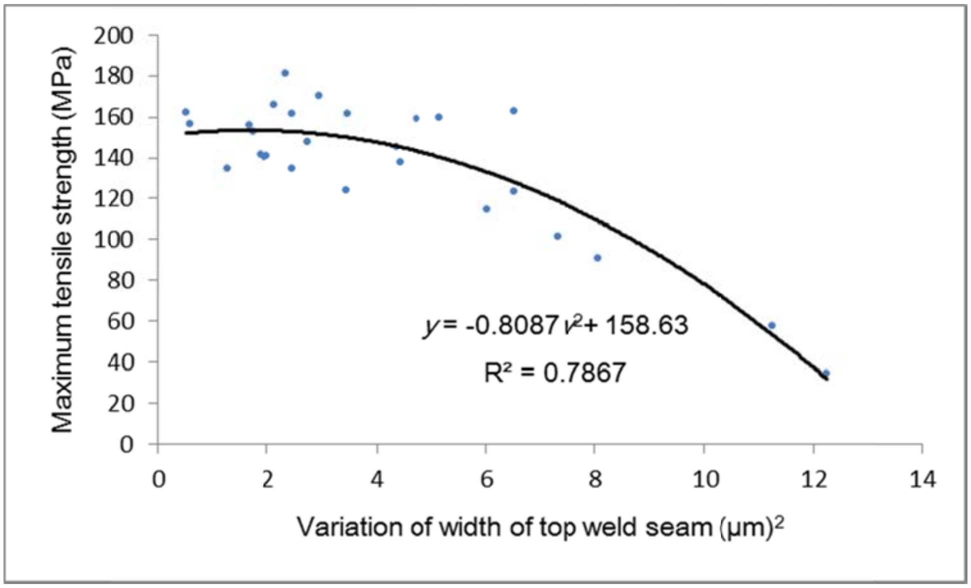



Figure 3.5: A negative correlation between the width of the top weld seam and maximum tensile strength (adopted from Sinha *et al*. 2013)

**Conclusions**

- There is a positive correlation between the log-transformed average width of top weld seam and maximum tensile strength.
- There is a negative correlation between the variance of the width of top weld seam and maximum tensile strength.

## Criticism of the experiments

In this experiment in one way we considered those specimens whose average width is very high (1721.40 µm) and in other way we also considered whose average width is very low (930.64 µm) (see Figure 3.6).

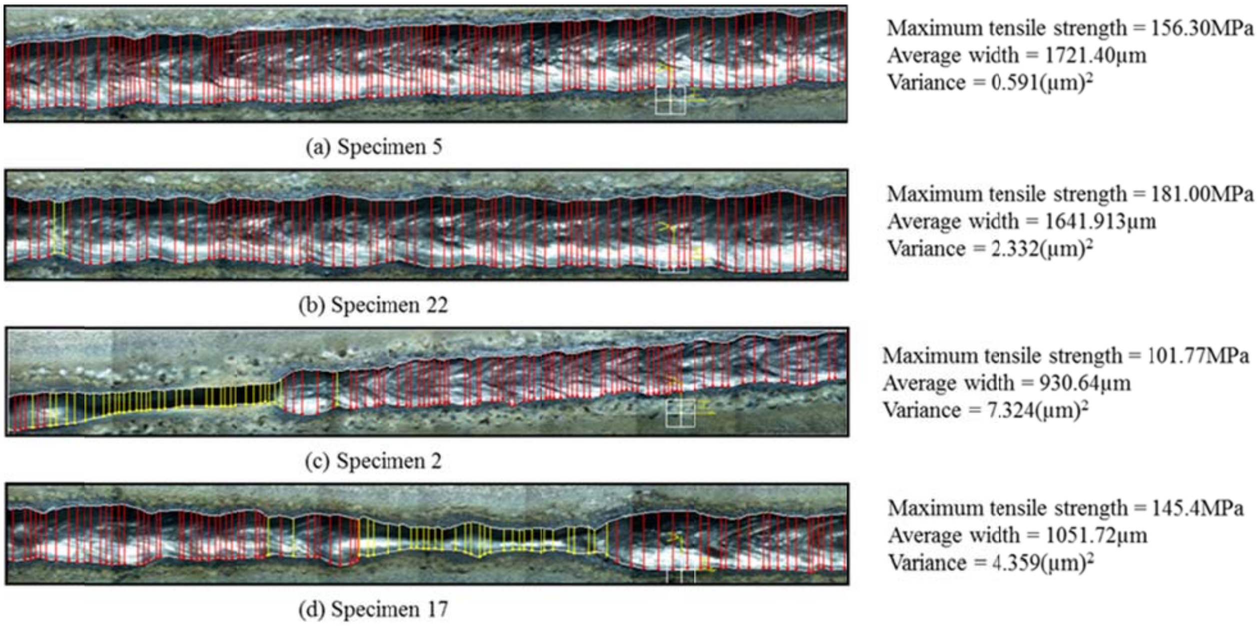



Figure 3.6: Top weld seams: (a) and (b) have higher average width with higher maximum tensile strength, while (c) and (d) have higher average width with lower maximum tensile strength

Some researchers and practitioners criticize that the higher value of average width is responsible for maximum tensile strength rather than lower variations in top weld width. In other words, we should discard those specimens which show lower value of average width say for example specimen numbers 2, 4, 8, 9, 15, 17, 19, 21, 25, 26, and 27. Therefore to overcome this criticism, I did another experiment to realize the reality.

## 3.2 Correlation analysis of the variation and average weld seam verses tensile strength

**Motivation**

The criticism of the previous experimental results is the major motivation for this experiment.

**Objective**

To investigate the correlation of the variation of weld seam and tensile strength during uniform width of top weld seam in laser welding of galvanized steel

**Experiment procedures**

By keeping in mind for getting uniform top weld seam, I performed 40 laser welding experiments with constant laser process parameters. For all the 40 experiments, I used 2000W laser power, 2100 mm/min welding speed, 0.1 mm part-to-part gap, and 160 mm focal length. On the basis of a microscopic inspection only 20 specimens was considered for further analysis. Out of 40, 20 (half of the total) specimens become rejected because they contains either spatter or non-uniform weld seam. The same procedure which is explained in the previous experiment has performed to investigate the average width and variance of top weld seam. The result of the laser welding experiments is summarized in Table 3.6.

Table 3.6: Laser welding experiment data for analysis of the variation of uniform weld seam and tensile strength

| Specimen No | Laser power (Watts) | Welding speed (mm/min) | Part-to-part gap (mm) | Maximum tensile strength (MPa) | Top weld seam width (μm) | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | | | mean | variation | |
| 03 | 2000 | 2100 | 0.1 | 158.682 | 1787.68 | 2.220 | |
| 04 | 2000 | 2100 | 0.1 | X | 1849.67 | 3.027 | R |
| 05 | 2000 | 2100 | 0.1 | 157.013 | 1764.80 | 2.992 | |
| 08 | 2000 | 2100 | 0.1 | X | 1707.11 | 3.648 | R |
| 09 | 2000 | 2100 | 0.1 | X | 1943.46 | 4.622 | R |
| 10 | 2000 | 2100 | 0.1 | 159.182 | 1809.50 | 4.040 | |
| 11 | 2000 | 2100 | 0.1 | 168.479 | 1757.47 | 5.198 | |
| 12 | 2000 | 2100 | 0.1 | 162.391 | 1733.94 | 4.752 | |
| 13 | 2000 | 2100 | 0.1 | 161.604 | 1743.21 | 8.179 | |
| 16 | 2000 | 2100 | 0.1 | 166.459 | 1794.82 | 3.097 | |
| 17 | 2000 | 2100 | 0.1 | 171.728 | 1741.45 | 2.856 | |
| 18 | 2000 | 2100 | 0.1 | 163.703 | 1795.62 | 3.204 | |
| 19 | 2000 | 2100 | 0.1 | 174.312 | 1727.47 | 5.712 | |
| 20 | 2000 | 2100 | 0.1 | 152.165 | 1734.16 | 4.161 | |
| 22 | 2000 | 2100 | 0.1 | 166.925 | 1726.69 | 4.536 | |
| 24 | 2000 | 2100 | 0.1 | X | 1659.90 | 6.553 | R |
| 25 | 2000 | 2100 | 0.1 | 174.735 | 1761.41 | 4.120 | |
| 27 | 2000 | 2100 | 0.1 | X | 1682.52 | 4.622 | R |
| 30 | 2000 | 2100 | 0.1 | 156.428 | 1715.47 | 5.017 | |
| 31 | 2000 | 2100 | 0.1 | 170.141 | 1778.68 | 6.708 | |

R: Reject

Average value of average width = 1760.752μm

Standard deviation of average width (σ) = 60.294μm

Acceptance range of average width =

$Average\ width + \sigma$ To $Average\ width - \sigma$ = 1821.046μm To 1700.457μm

In one hand specimen numbers 8, 24, and 27 are rejected because their width is less than 1700.457μm and on other hand specimen numbers 4, and 9 are rejected because their width is more than 1821.046μm. Now, for our further analysis we will discard these rejected specimens.

Figure 3.7 shows the variance of top weld seam of all the 15 specimens. Laser power, welding speed, and part-to-part gap with corresponding width of weld seam and their variances are illustrated in Figure 3.7.

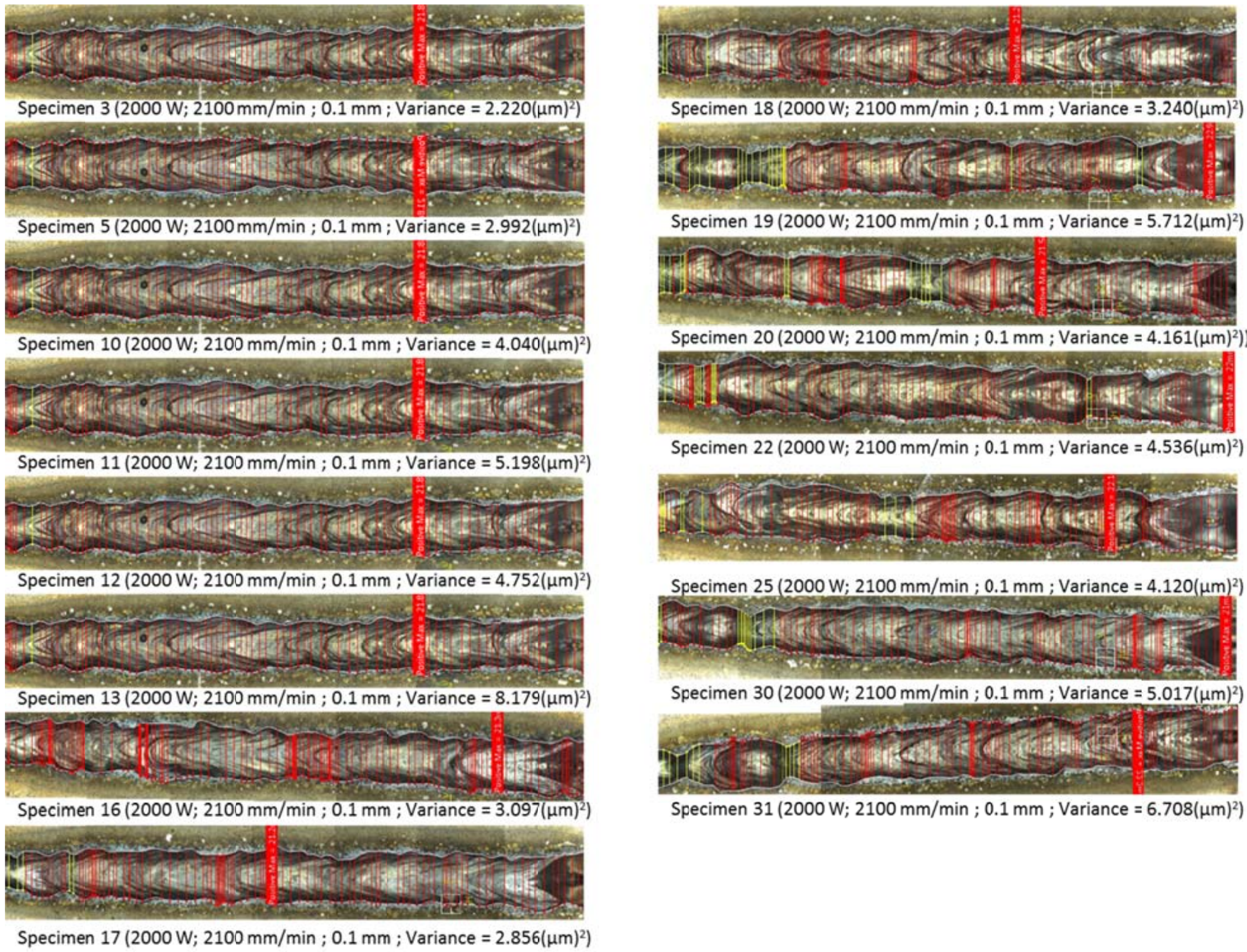



Figure 3.7: Variation of top weld seams

From the statistical analysis, the coefficient of determination $R^2$ shows that 0.05% of the variation of maximum tensile strength is occurred due to log-transformed average width of the top weld seam (see Figure 3.8).

In the same way, the coefficient of determination $R^2$ shows that 5.11% of the variation of maximum tensile strength is occurred due to the variance of the width of the top weld seam (see Figure 3.9).

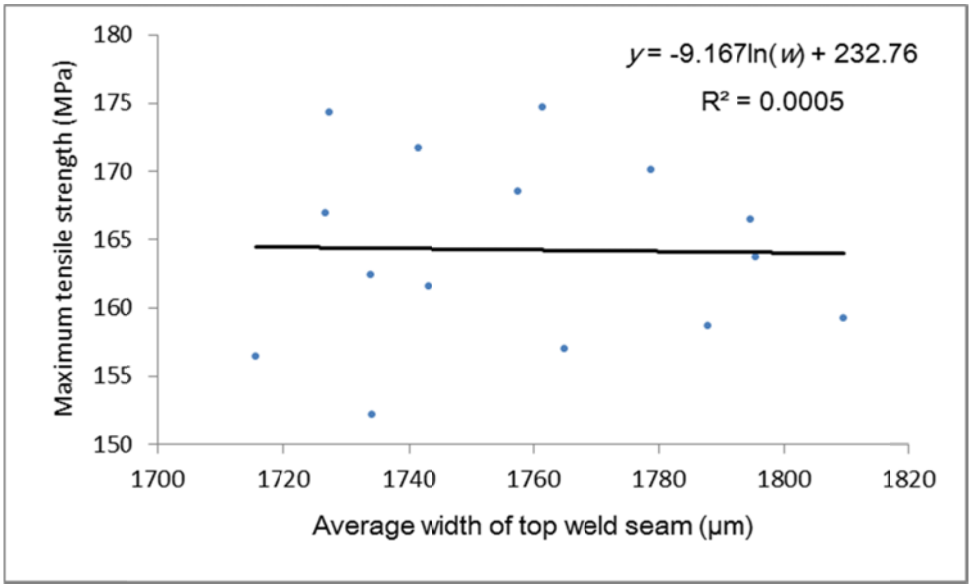



Figure 3.8: Correlation between log-transformed average width of the top weld seam and maximum tensile strength

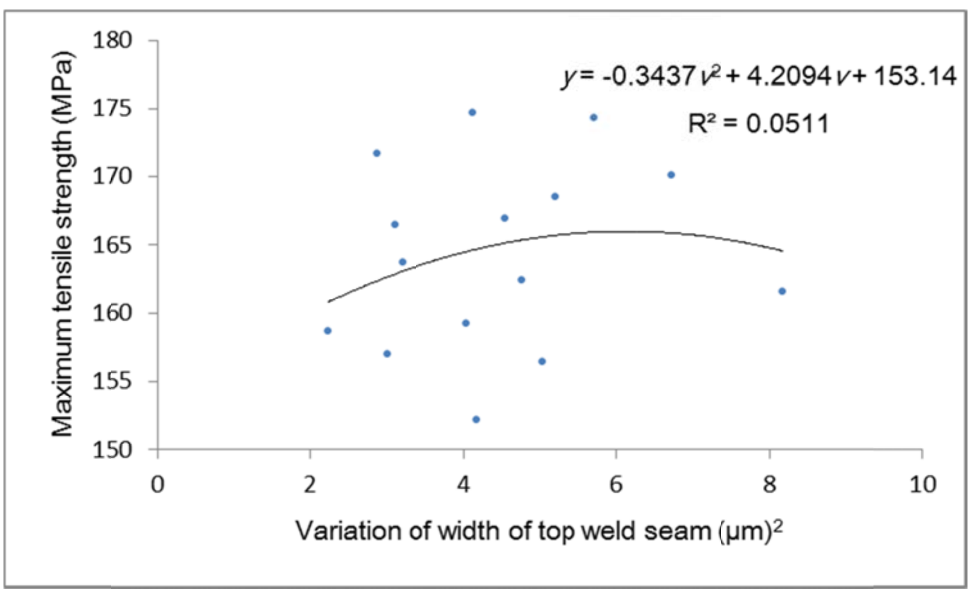



Figure 3.9: Correlation between the variance of the width of the top weld seam and maximum tensile strength

## Conclusions

The regression model which is shown in Figure 3.8 shows that there is no correlation between average width of top weld seam and maximum tensile strength. In the same way, the regression model which is shown in Figure 3.9 shows that there is no correlation between variance of the top weld seam and maximum tensile strength.

**Criticism of the conclusions**

Experimental results reveal that there is no correlation between average width of top weld seam and maximum tensile strength during consideration of uniform weld seam. The major reasons behind the conflicting of the results are as follows:

- Slightly fluctuations on the average width of top weld seam cannot accountable for the minor fluctuations in the maximum tensile weld seam. If there are significant changes in the average width of top weld seam then only, we can see its effect in terms of maximum tensile strength. Say for example, the standard deviation of average non-uniform top weld seam is 337.176µm (see Table 3.7) and the standard deviation of average uniform top weld seam is only 28.46µm (see Table 3.7) which is roughly six times lesser than previous one.
- For non-uniform and uniform weld seam the difference between the maximum and minimum average width of the top weld seam are 1165.92µm and 94.03µm, respectively. The huge difference is also responsible for such types of experimental results.
- Literature survey reveals that in general, 15% fluctuations in maximum tensile strength are permissible because a lot of factors are accountable for changes in maximum tensile strength.
- Procedure for estimation of the width of weld seam is manually computed. Therefore, we cannot neglect the human error.
- I hope, if we measure the weld width by cutting the section of the weld seam then it will give more accurate results as compare to the procedure which I used for estimation of the width of weld seam.

Table3.7: Result analysis of the average width of the top weld seam

| | Case1:Non-uniform width of top weld seam (Section 3.1) | Case2:Uniform width of top weld seam (Section 3.2) |
|---|---|---|
| Average width of the top weld seam | 1199.99μm | 1758.15μm |
| Standard deviation of average width of the top weld | 337.178μm | 28.46μm |
| Maximum average width of the top weld seam | 1721.40μm | 1809.50μm |
| Minimum average width of the top weld seam | 555.48μm | 1715.47μm |
| (Maximum-minimum) average width of the top weld seam | 1165.92μm | 94.03μm |

This Page Intentionally Left Blank

# 4. Conclusions

This study introduced an experiment based results for the estimation of the tensile strength in a non-destructive way. In this chapter, the outcomes have been discussed as inferred from chapter 3. The results can be summarized as:

- In the case of non-uniform seam boundary of top weld seam, there is a positive correlation between the log-transformed average width of the top weld seam and maximum tensile strength. However, weld seam having uniform seam boundary do not have sufficient evidence for correlation between average width of the top weld seam and maximum tensile strength.
- In the case of non-uniform seam boundary of top weld seam, there is a negative correlation between the variance of the top weld seam and maximum tensile strength. However, weld seam having uniform seam boundary do not have sufficient evidence for correlation between the variance of the top weld seam and maximum tensile strength. The basic reason for this may be reasoned to significant fluctuations in the width of weld seam. This is a necessary condition for the existence of such type of correlations.
- Width of weld seam is more responsible for tensile strength rather than variation of weld seam.
- By selecting an appropriate combination of laser power and welding speed, it is found that a threshold value of part-to-part gap exists. Where the weld strength reaches the maximum.
- On the basis of the experiments, it is observed that the variation of plasma signal is relatively large as compare to the variation in temperature signals, at the same laser process parameters. Conversely, the variation of back reflection signals is relatively lower as compared to variation in temperature signals.
- Presence of spatters decreases the tensile strength of weld seam.
- During the tensile test, if the weld fractures from the weld seam, then it is safe to conclude that the weld quality is low in terms of tensile strength.

# 5. Future works

This chapter points towards several research questions, open for a thorough investigation in the field of laser welding. Several experiments were conducted in this study, resulting in wide variety of skill development for the same. Hence, based on the know-hows gained while conducting this study, the following questions are opened up for further investigation, for the betterment of industry preferred practices in the field of laser welding:

- Although, we suggested an indirect non-destructive method for estimating the tensile strength of the welded parts but a standardized and automated method for measuring the variation of the width of weld seam is necessary to evaluate the quality of laser weld.
- Alternative experimental methods needs to be developed in order to cross verify finding of this study, i.e. the root cause for the existence of correlation between the variation of top weld seam and tensile strength.
- Further experiments is necessary to verify the correlation results in terms of other welding quality measurements like hardness, toughness, surface roughness, and fatigue with variation of the width of top weld seam.
- A robust signal processing system is necessary to improve the accuracy rate for part-to-part detection in laser welding of galvanized steel.
- The use of multi-sensor fusion is necessary to estimate the tensile strength of the welded parts in an indirect non-destructive way in laser welding of galvanized steel.
- A robust methodology for feature extraction without loss of information from the signals is necessary. Also, identification of optimal number of features extraction from the signal is necessary.

# References


1. Aalderink, B.J. (2007). Sensing, monitoring and control for laser based welding of aluminium sheets; Ph.D Thesis, Eindhoven University of Technology, http://doc.Utwente.Nl/58019/1/thesis_aalderink.Pdf (Retrieved on 10th Jan 2014).
2. Acherjee, B., Misra, D., Bose, D. & Venkadeshwaran, K. (2009). Prediction of weld strength and seam width for laser transmission welding of thermoplastic using response surface methodology. *Optics & Laser Technology*, 41 (8), 956-967.
3. Akhter R. & Steen W. (1990). The gap model for welding zinc-coated steel sheet. *International Conference on Laser System Application in Industry*. Torino, Italy; 219-236.
4. Anabitarte, F., Mirapeix, J., Conde, O.M., Cubillas, A.M., Rodriguez-Cobo, L., Galindez, C. & Cobo, A. (2010). Automatic classification of steel plates based on laser induced breakdown spectroscopy and support vector machinesed. *Proceddings of SPIE*, 765347-1-4.
5. Anabitarte, F., Mirapeix, J., Portilla, O.M.C., Lopez-Higuera, J.M. & Cobo, A. (2012). Sensor for the detection of protective coating traces on boron steel with aluminium-silicon covering by means of laser-induced breakdown spectroscopy and support vector machines. *IEEE Sensors Journal*, 12 (1), 64-70. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-82655183483&partnerID=40&md5=73bf42fdb79dc29bc9a10d0a79b56b56 (Retrieved on 10th Jan 2014)
6. Anand, D., Chen, D., Bhole, S., Andreychuk, P. & Boudreau, G. (2006). Fatigue behavior of tailor (laser)-welded blanks for automotive applications. *Materials Science & Engineering: A*, 420 (1), 199-207.
7. Anawa, E., Olabi, A. (2008). Optimization of tensile strength of ferrite/austenite laser welded component. *Optics and Laser in Engineering*, 46, 571-577.
8. Balasubramanian, K., Siva Shanmugam, N., Buvanashekaran, G. & Sankaranarayanasamy, K. (2008). Numerical and experimental investigation of laser beam welding of AISI 304 stainless steel sheet. *Advance in Production Enggineering & Management Journal*, 3 (2), 93-105.
9. Beard, R.V. (1971). Report based on Failure accommodation in linear systems through self-reorganization. *Massachusetts Institute of Technology*.
10. Beck, M., Berger, P. & Hugel, H. (1995). The effect of plasma formation on beam focusing in deep penetration welding with $CO_2$ lasers. *Journal of Physics D: Applied Physics*, 28 (12), 2430.
11. Benyounis, K., Olabi, A. & Hashmi, M. (2005). Effect of laser welding parameters on the heat input and weld-bead profile. *Journal of Materials Processing Technology*, 164, 978-985.

12. Bilge, U., Jurczyszyn, C.E. & Jenuwine, W.C. (1993). Laser welding method. United States Patent Number: 5,183,992.
13. Bokor, J. & Balas, G. (2004). Detection filter design for LPV systems—a geometric approach. *Automatica*, 40 (3), 511-518.
14. Burges, C.J. (1998). A tutorial on support vector machines for pattern recognition. *Data Mining and Knowledge Discovery*, 2 (2), 121-167.
15. Campbell, S.W., Galloway, A. & Mcpherson, N. (2011). Artificial neural network prediction of weld geometry performed using GMAW with alternating shielding gases. *Welding Journal*, 91(6), 174-181.
16. Cao, X. & Jahazi, M. (2009). Effect of welding speed on butt joint quality of Ti–6Al–4V alloy welded using a high-power Nd: YAG laser. *Optics and Lasers in Engineering*, 47 (11), 1231-1241.
17. Chen L., X., W., Gong, S. (2011). The effect of weld size on joint mechanical properties of 5A90 Al-Li alloy. *Advance Material Research,* 146, 1831-1838.
18. Chow, E. & Willsky, A. (1984). Analytical redundancy and the design of robust failure detection systems., *IEEE Transactions on Automatic Control*, 29 (7), 603-614.
19. Chokkalingham, S., Vasudevan, M., Sudarsan, S., & Chandrasekhar, N. (2012). Predicting weld head width and depth of penetration form infrared thermal image of weld pool using artificial neural network. *Insight-Non-Destructive Testing & Condition Monitoring*, 54(5):272–277.
20. Colombo, D., Colosimo, B.M. & Previtali, B. (2013). Comparison of methods for data analysis in the remote monitoring of remote laser welding. *Optics and Lasers in Engineering*, 51, 34-46.
21. Colombo, D., Colosimo, B.M., Previtali, B., Bassan, D., Lai, M. & Masotti, G. (2012). Through the optical combiner monitoring in remote fiber laser welding of zinc coated steelsed. *SPIE LASER International Society for Optics and Photonics*, 82390F-1-15.
22. Cook, G.E., Barnett, R.J., Andersen, K. & Strauss, A.M. (1995). Weld modeling and control using artificial neural networks., *IEEE Transactions on Industry Applications*, 31 (6), 1484-1491.
23. Cristianini, N. & Shawe-Taylor, J. (2000). An introduction to support vector machines and other kernel-based learning methods. Cambridge University Press.
24. Davim, J.P. (2008). Machining: Fundamentals and recent advances. Springer.
25. Dawes, C. (1992). Laser welding: A practical guide. Woodhead Publishing.
26. Dechao, L.R., Kovacevic; Robert, Ruokolainen; Xiaohong, Gayden. (2007). Report based on Feasibility study of laser welding of advanced lightweight materials. NSF/IUCRC-LAM Industrial Board Meeting.

27. Delle Piane, A., Sartorio, F., Cantello, M. & Ghiringhello, G. (1987). Method of laser welding sheet metal protected by low-vaporizing-temperature materials. United States Patent Number: 4,682,002.
28. Duda, R.O., Hart, P.E. & Stork, D.G. (2012). Pattern classification. John Wiley & Sons.
29. Duley, W.W. (1999). Laser welding: Wiley New York.
30. Eriksson, I. & Kaplan, A.F. (2009). Evaluation of laser weld monitoring–a case studyed. *Proceedings of ICALEO*, 1419-1425.
31. Evgeny, B., Uli, Fechner., Jens, Sadowski., Gisbert, Schneider. (2003). Comparision of support vector machine and artificial neural network systems for drug/nondrug classification. *Journal of Chemical Information and Computer Sciences*, 43, 1882-1889.
32. Farson, D., Ali, A. & Li, X. (1999). Laser weld penetration monitoring with multiple emission signal measurements. *Journal of Laser Applications*, 11, 47-53.
33. Farson, D., Fang, K. & Kern, K. (1990). Classification of laser welds by acoustic signatureed. *Proceedings of the 29th IEEE Conference on Decision and Control*, 1620-1621.
34. Farson, D., Hillsley, K., Sames, J., and Young, R. (1996). Frequency-time characteristics of air-born signals from laser welds. *Journal of Laser Application,* 8, 33-42.
35. Fleming, P., Lammlein, D., Wilkes, D., Fleming, K., Bloodworth, T., Cook, G., Strauss, A., Delapp, D., Lienert, T. & Bement, M. (2008). In-process gap detection in friction stir welding. *Sensor Review*, 28 (1), 62-67.
36. Graham, M.P., Kerr, H.W. & Weckman, D.C. (1996). Laser welding of Zn-coated sheet steelsed. *Photonics West's 96 International Society for Optics and Photonics*, 170-183.
37. Greses, J., Hilton, P., Barlow, C. & Steen, W. (2002). Plume attenuation under high power nd: Yttritium–aluminum–garnet laser weldinged. Paper presented at *ICALEO Conference*, Scottsdale, Arizona, USA, 14 - 17 October 2002, http://www.twi.co.uk/technical-knowledge/published-papers/plume-attenuation-under-high-power-ndyag-laser-welding-october-2002/ (Retrieved on 10th Jan 2014).
38. Grupp, M., Seefeld, T., Vollertsen, F. (2003). Technical Report based on Laser beam welding with scanner. BIAS, Bremen, Germany.
39. Gu, H. & Duley, W. (1996). A statistical approach to acoustic monitoring of laser welding. *Journal of Physics D: Applied Physics*, 29 (3), 556-560.
40. Gualini, M. (2001). Laser welding of zinc coated steel sheets: An old problem with a possible solutioned. *20th International Congress on ICALEO: Applications of Lasers & Electro-Optics*, 492-501.

41. Hamann, C., Rosen, H.-G. & Labiger, B. (1989). Acoustic emission and its application to laser spot weldinged. *International Congress on Optical Science and Engineering (International Society for Optics and Photonics)*, 275-281.
42. Hanicke, L. & Strandberg, O. (1993). Roof laser welding in series production. *SAE Transaction*, 102, 24-24.
43. Havrilla D. (2012). Photonics applied: material processing-sucessful laser welding demands optimized laser joint design. *Laser Focus World*; 48-43-8
44. Heyden J., K. Nilsson, C. Magnusson. (1989). Laser welding of zinc coated steel. *Proc. 6$^{th}$ International Lasers in Manufacturing* 1989; 93-104.
45. Hügel, H. & Graf, T. (2009). Laser in der fertigung: Strahlquellen, systeme, fertigungsverfahren. Springer.
46. Ismail, M.I.S., Okamoto, Y. & Okada, A. (2013). Neural network modeling for prediction of weld bead geometry in laser micro welding. *Advances in Optical Technologies*, 2013, Article ID 415837, 1-7.
47. Jon, M. (1985). Noncontact acoustic emission monitoring of laser beam welding. *Welding Journal*, 64, 43-48.
48. Kaftandjian, V., Dupuis, O., Babot, D. & Min Zhu, Y. (2003). Uncertainty modelling using dempster–shafer theory for improving detection of weld defects. *Pattern Recognition Letters*, 24 (1), 547-564.
49. Kaierle, S., Beersiek, J., Kreutz, E., Poprawe, R., Gunnewig, J. & Rake, H. (1998). Online control of penetration depth in laser beam weldinged. *Industrial Electronics Society, 1998. IECON'98. Proceedings of the 24th Annual Conference of the IEEE*, 1694-1698.
50. Katayama, S., Kawahito, Y. & Mizutani, M. (2010). Elucidation of laser welding phenomena and factors affecting weld penetration and welding defects. *Physics Procedia*, 5, 9-17.
51. Kennedy, S. C., I.M. Norris. (1989). Nd-YAG laser welding of bare and galvanised steels, *International Congress and Exposition. Technical Paper Series 890887*; 1989.
52. Khan, M., Romoli, L., Fiaschi, M., Dini, G. & Sarri, F. (2011). Experimental design approach to the process parameter optimization for laser welding of martensitic stainless steels in a constrained overlap configuration. *Optics & Laser Technology*, 43 (1), 158-172.
53. Kim, C., Choi, W., Kim, J. & Rhee, S. (2008). Relationship between the weldability and the process parameters for laser-TIG hybrid welding of galvanized steel sheets. *Materials Transactions*, 49 (1), 179-186.

54. Kim, H. (2013). Effects of part-to-part gap and the direction of welding on laser welding quality. M.S Thesis, Ulsan National Institute of Science and Technology (UNIST).
55. Kim, J. T., Kim, D. H., Chung, C. M., Baik, S. H., Park, S. K. & Kim, M. S. (2003). Laser welding quality monitoring with an optical fiber system. *Journal of the Optical Society of Korea*, 7 (3), 193-196.
56. Kim, P.S. & Lee, E.H. (2005). A new parity space approach to fault detection for general systems. *Proceedings of The Second International Conference, HPCC (High Performance Computing and Communications), Munich, Germany*. Springer, 535-540.
57. Lee, A.P., Feltham, E. & Van Deventer, J. (1996). Tailor welded blank technology for automotive applications. Sheet Metal Stamping for Automotive Applications, 91-102.
58. Li, L. & Steen, W. (1992). Non-contact acoustic emission monitoring during laser. *Proceddings of the International Congress on Applications of Lasers & Electro-Optics (ICALEO)*, 719-728.
59. Li, L., Steen, W., Shi, K. & Brookfield, D. (1992). Sensor development for in-process quality inspection and optimization of high speed laser can welding process. *Proceeding of LAMP*, 92, 415-420.
60. Luo, H., Zeng, H., Hu, L., Hu, X. & Zhou, Z. (2005). Application of artificial neural network in laser welding defect diagnosis. *Journal of Materials Processing Technology*, 170 (1), 403-411.
61. Mao, Y.L., Kinsman, G. & Duley, W. (1993). Real-time fast fourier transform analysis of acoustic emission during $CO_2$ laser welding of materials. *Journal of Laser Applications*, 5 (2), 17-22.
62. Mei, L., Chen, G., Jin, X., Zhang, Y. & Wu, Q. (2009). Research on laser welding of high-strength galvanized automobile steel sheets. *Optics and Lasers in Engineering*, 47 (11), 1117-1124.
63. Michalowski, A., Hess, A., Russ, A. & Dausinger, F. (2002). Plume attenuation under high power Yb: YAG laser material processinged. *Procedding of the Fourth International WLT-Conference on Lasers in Manufacturing (LIM)*, 357-361.
64. Milberg, J. & Trautmann, A. (2009). Defect-free joining of zinc-coated steels by bifocal hybrid laser welding. *Production Engineering*, 3 (1), 9-15.
65. Miller, R. & Debroy, T. (1990). Energy absorption by metal-vapor-dominated plasma during carbon dioxide laser welding of steels. *Journal of Applied Physics*, 68 (5), 2045-2050.
66. Mirapeix, J., García-Allende, P., Cobo, A., Conde, O. & López-Higuera, J. (2007). Real-time arc-welding defect detection and classification with principal component analysis and artificial neural networks. *NDT & E International*, 40 (4), 315-323.

67. Miyazaki, Y. & Furusako, S. (2007). Tensile shear strength of laser welded lap joints. *Nippon Steel Technical Report*, 95, 28-34.
68. Montgomery, D.C. (1984). Design and analysis of experiments. Wiley, New York.
69. Nakayama, S., Bates, Greg. (2010). Report based on About the laser welding monitor, Miyachi Technical Information., http://www.Miyachi.Com/e/useful/popup/web-laser.html (retrieved on 10th Jan 2014).
70. Norman, P., Engström, H. & Kaplan, A. (2008). Theoretical analysis of photodiode monitoring of laser welding defects by imaging combined with modelling. *Journal of Physics D: Applied Physics*, 41 (19), 195502(1-9).
71. Norman, P., Eriksson, I. & Kaplan, A. (2009a). Monitoring laser beam welding of zinc coated sheet metal to analyze the defects occurringed. *Proceedings of the Nordic Conference in lasr Processing of materials (NOLAMP), Copenhagen, Denmark*.
72. Norman, P., Karlsson, J. & Kaplan, A. (2009b). Monitoring undercut, blowouts and root sagging during laser beam weldinged. *Proceedings of the Fifth International Conference on Lasers in Manufacturing, Munich Germany*, 355-359.
73. Olson, D.L. (1993). ASM Handbook: Welding, brazing, and soldering. ASM Intenational.
74. Olsson, R., Eriksson, I., Powell, J., Langtry, A. & Kaplan, A. (2011). Challenges to the interpretation of the electromagnetic feedback from laser welding. *Optics and Lasers in Engineering*, 49 (2), 188-194.
75. Ozaki, H., Kutsuna, M., Nakagawa, S. & Miyamoto, K. (2006). Laser roll welding of dissimilar metal joint of zinc coated steel and aluminum alloy. *Proceddings of the International Congress on Applications of Lasers & Electro-Optics (ICALEO) 2006*, Arizona USA.
76. Pal, S., Pal, S.K. & Samantaray, A.K. (2008). Artificial neural network modeling of weld joint strength prediction of a pulsed metal inert gas welding process using arc signals. *Journal of Materials Processing Technology*, 202 (1), 464-474.
77. Patton, R.J., Frank, P.M. & Clarke, R.N. (1989). Fault diagnosis in dynamic systems: Theory and application. Prentice-Hall, Inc.
78. Pennington, E.J. (1987). Laser welding of galvanized steel. United States Patent Number: 4,642,446.
79. Petrick, F.D. (1990). Method of making hemmed joints utilizing laser welding. United States Patent Number: 4,916,248.
80. Ramasamy, S. (1997). $CO_2$ and Nd: YAG laser beam welding of 6111-T4 and 5754-O aluminum alloys for automotive applications. Ph.D Thesis, Ohio State University.

81. Ream, S.L. (2004). Laser welding efficiency and cost: $CO_2$, YAG, Fiber, and Disc. *Proceddings of International Congress on Applications of Lasers & Electro-Optics (ICALEO)*.
82. Report. (2010). Weldability of galvanized steel sheets in laser welding; Nippon Steel, Japan, http://www.Nssmc.Com/en/tech/report/nsc/pdf/n9522sl.Pdf (Retireved on 10th Jan 2014)
83. Ribolla, A., Damoulis, G.L. & Batalha, G.F. (2005). The use of Nd: YAG laser weld for large scale volume assembly of automotive body in white. *Journal of Materials Processing Technology*, 164, 1120-1127.
84. Rito, N., Ohta, M., Yamada, T., Gotoh, J. & Kitagawa, T. (1988). Laser welding method. United States Patent Number: 4,745,257.
85. Rumelhart, D.E., Hintont, G.E. & Williams, R.J. (1986). Learning representations by back-propagating errors. *Nature*, 323 (6088), 533-536.
86. Sabbaghzadeh, J., Dadras, S. & Torkamany, M. (2007). Comparison of pulsed Nd: YAG laser welding qualitative features with plasma plume thermal characteristics. *Journal of Physics D: Applied Physics*, 40 (4), 1047-1051.
87. Sahin, A.Z., Ayar, T. & Yilbas, B.S. (2010). Laser welding: The first and second law analysis. *International Journal of Exergy*, 7 (5), 535-546.
88. Sathiya, P., Panneerselvam, K. & Abdul Jaleel, M. (2012). Optimization of laser welding process parameters for super austenitic stainless steel using artificial neural networks and genetic algorithm. *Materials & Design*, 36, 490-498.
89. Sebestova, H., Chmelickova, H., Nozka, L. & Moudry, J. (2012). Non-destructive real time monitoring of the laser welding process. *Journal of Materials Engineering and Performance*, 21 (5), 764-769.
90. Seidel, B., Beersiek, J. & Beyer, E. (1994). Process control in continuous high-power $co_2$ laser beam weldinged. *Proceddings of SPIE*, 290-300.
91. Seto, N., Katayama, S. & Matsunawa, A. (2000). High-speed simultaneous observation of plasma and keyhole behavior during high power $CO_2$ laser welding: Effect of shielding gas on porosity formation. *Journal of Laser Applications*, 12, 245-250.
92. Shao, J. & Yan, Y. (2005). Review of techniques for on-line monitoring and inspection of laser weldinged. *Journal of Physics: Conference Series*, 15, 101-107.
93. Shao, J. & Yan, Y. (2007). An intelligent system for the on-line quality inspection of micro laser spot welding processes. *Journal of Physics: Conference Series*, 76, 1-6. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-

34547687568&partnerID=40&md5=d6763f870006bfb5065da151995372d (Retireved on 10th Jan 2014).

94. Sibillano, T., Ancona, A., Berardi, V. & Lugara, P. (2007a). Real-time monitoring of laser welding by correlation analysis: The case of AA5083. *Optics and Lasers in Engineering*, 45 (10), 1005-1009.
95. Sibillano, T., Ancona, A., Berardi, V. & Lugarà, P. (2005). Correlation analysis in laser welding plasma. *Optics Communications*, 251 (1), 139-148.
96. Sibillano, T., Ancona, A., Berardi, V., Schingaro, E., Basile, G. & Lugarà, P. (2007b). Optical detection of conduction/keyhole mode transition in laser welding. *Journal of Materials Processing Technology*, 191 (1), 364-367.
97. Sibillano, T., Rizzi, D., Mezzapesa, F.P., Lugarà, P.M., Konuk, A.R., Aarts, R., Veld, B.H. & Ancona, A. (2012). Closed loop control of penetration depth during $CO_2$ laser lap welding processes. *Sensors*, 12 (8), 11077-11090.
98. Sinha, A.K. & Kim, D.Y. (2013). Laser welding quality monitoring using plasma, back reflection and temperature signals based on dempster-shafer theoryed. *Proceedings of the Society of CAD/CAM Conference*, 240-242.
99. Sinha, A.K., Kim, D.Y. & Ceglarek, D. (2013). Correlation analysis of the variation of weld seam and tensile strength in laser welding of galvanized steel. *Optics and Lasers in Engineering*, 51, 1143-1152.
100. Stecking, R. & Schebesch, K.B. (2003). Support vector machines for credit scoring: Comparing to and combining with some traditional classification methods. Between data science and applied data analysis. Springer, 604-612.
101. Steen, W. (2003). Review article: Laser material processing-an overview. *Journal of Optics A: Pure and Applied Optics*, 5, 3-7.
102. Steen, W. & Weerasinghe, W. (1987). High-power laser beam diagnostics—Part II. Gas Flow and Chemical Lasers. Springer, 323-329.
103. Steen, W.M. & Mazumder, J. (2010). Laser material processing. Springer.
104. Sun, A., Kannatey-Asibu Jr, E. & Gartner, M. (1999). Sensor systems for real-time monitoring of laser weld quality. *Journal of Laser Applications*, 11, 153-168.
105. Sun, A.S. (2001). Report based on Multiple sensor monitoring of laser welding. University of Michigan.

106. Sun, Z., Pan, D. & Zhang, W. (2002). Correlation between welding parameters and microstructures in tig, plasma and laser welded Ti–6Al–4V alloyed. *6th International Conference: Trends in Welding Research*, 760-767.
107. Timm, F., Klement, S., Martinetz, T. & Barth, E. (2009). Welding inspection using novel specularity features and a one-class svm. *International Conference on Computer Vision Theory & Application, Lisboa, Portugal, VISAPP 2009*, (1), 146-153.
108. Tzeng. Y. (1999). Pulsed Nd: YAG laser seam welding of zinc-coated steel. *Welding Journal*; 78 (7): 238-244.
109. Vapnik, V.N. (1998). Statistical learning theory. Wiley, New York.
110. Velarde, G. & Binroth, C. (2010). Dynamic pattern extraction of parameters in laser welding process. Advances in Data Mining: Applications and Theoretical Aspects. Springer, 350-361.
111. Verhaeghe, G. & Hilton, P. (2005). The effect of spot size and laser beam quality on welding performance when using high-power continuous wave solid-state lasersed. *Proceedings of 24th International Congress on Applications of Lasers and Electro-Optic (ICALEO) 2005*, *Miami, Florida, US*, 264-271.
112. Wang, L. (2005). Support vector machines: Theory and applications. Springer.
113. Wang, T. & Gao, X. (2013). Prediction algorithm of molten pool width based on support vector machine during high-power disk laser welding. Hanjie Xuebao/Transactions of the China Welding Institution, 34 (5), 25-28 Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84879133626&partnerID=40&md5=ee2525b88110eb6307049fba22ac7607 (Retireved on 10th Jan 2014)
114. Watanabe, K. & Himmelblau, D. (1982). Instrument fault detection in systems with uncertainties. *International Journal of Systems Science*, 13 (2), 137-158.
115. Weerasinghe, V., Kamalu, J., Hibberd, R. & Steen, W. (1990). Acoustic signals from laser back reflections. *Optics & Laser Technology*, 22 (6), 381-386.
116. White, J. & Speyer, J. (1987). Detection filter design: Spectral theory and algorithms. *IEEE Transactions on Automatic Control*, 32 (7), 593-603.
117. Wu, Q., Gong, J., Chen, G. & Xu, L. (2008). Research on laser welding of vehicle body. *Optics & Laser Technology*, 40 (2), 420-426.
118. Xue-Wu, Z., Yan-Qiong, D., Yan-Yun, L., Ai-Ye, S. & Rui-Yu, L. (2011). A vision inspection system for the surface defects of strongly reflected metal based on multi-class svm. *Expert Systems with Applications*, 38 (5), 5930-5939.

119. Yang, Y., Kalya, P., Landers, R.G. & Krishnamurthy, K. (2008). Automatic gap detection in friction stir butt welding operations. *International Journal of Machine Tools and Manufacture*, 48 (10), 1161-1169.

120. Yapp, D. & Blackman, S. (2004). Recent developments in high productivity pipeline welding. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 26 (1), 89-97.

121. Zaeh, M., Moesl, J., Musiol, J. & Oefele, F. (2010). Material processing with remote technology revolution or evolution? *Physics Procedia*, 5, 19-33.

122. Zhang, P., Wan, L., Kong, L. & Duan, A. (2007). Quality monitoring of laser welding process by using support vector machine. Huazhong Keji Daxue Xuebao (Ziran Kexue Ban)/*Journal of Huazhong University of Science and Technology (Natural Science Edition)*, 35 (7), 62-63 Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-34547980393&partnerID=40&md5=a9077a495560351191ca8bcda0898c64 (Retireved on 10th Jan 2014).

123. Zhang, Y. (2008). Real-time weld process monitoring. Woodhead Publishing.

124. Zhou, M., Liu, W. & Wan, L. (2009). Multi-information fusion and identification system for laser welding. 986-992.

## Acknowledgment

I would like to express my sincere gratitude to my advisor Prof. Duck-Young Kim for the continuous academic and monitory support of my Master degree. During my graduate study, I learned lots of basic concepts as well as social behavior from him. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my graduate study.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Nam-Hum Kim, and Prof. Seungchul Lee, for their encouragement, insightful comments, and critics.

I thank my fellow labmates: Hyunki-Ki-Kim, Yang-Ji Lee, Su Jung Back, Rocku Oh, and special thanks for Prerna Swati for providing continuous help during my studies. I would like to pay special thanks for all U-CIM lab members. Without the help of UNIST’s library this work was not possible. By heartily, I would like to give my special thanks for all the staffs of UNIST’s library for providing continuous kind hearted support.

I would like to thanks all DHE’s member and staffs for their continuous helping attitude. I would like to thanks all the members and staffs of UNIST.

Talking about my research, I cannot forget to thanks my respected Guru Prof. M. K. Tiwari. He channelized my energy towards this pious profession and guided me to attain the maturity required to pursue a meaningful research.

Lastly, I would like to thank my parents, brother Dr. Vinit Kumar, my sweet sister Pinki Kumari, and Dr. Sanjay Kumar Sinha. Their endless love and support made it possible to complete this study.