2008. 02

Master's Thesis

A Study on the Mechanical Characteristics of Galvanized Steel by Using Hybrid Welding(Pulsed Nd:YAG Laser+TIG)

Graduate School of Chosun University

Department of Naval Architecture and Ocean Engineering

Kim Yeon-Ho

A Study on the Mechanical Characteristics of Galvanized Steel by Using Hybrid Welding(Pulsed Nd:YAG Laser+TIG)

하이브리드(Pulsed Nd:YAG Laser+TIG) 용접을 이용한
갈바륨 강판의 역학적 특성에 관한 연구

February 2008

Graduate School of Chosun University

Department of Naval Architecture and
Ocean Engineering

Kim Yeon-Ho

A Study on the Mechanical Characteristics of Galvanized Steel by Using Hybrid Welding(Pulsed Nd:YAG Laser+TIG)

Advisor : Professor Han-Sur Bang

A Thesis submitted for the degree of

Master of Engineering

October 2007

Graduate School of Chosun University

Department of Naval Architecture and

Ocean Engineering

Kim Yeon-Ho

CONTENTS

ABSTRACT

A Study on the Mechanical characteristics of Galvanized steel by using Hybrid Welding(Pulsed Nd:YAG Laser+TIG)

Kim Yeon-Ho
Advisor : Prof. Bang Han-Sur Ph.D.
Department of Naval Architecture & Ocean Engineering,
Graduate School of Chosun University

Hybrid welding process has been taken a technical attraction due to its superiorities such as deep penetration, gap bridging ability, high speed, automation compared with other conventional methods. Galvanized steel is a promising material for long service life and superior corrosion resistance capability, namely, at least 3~6 times than that of Zn-coated steel. Therefore, this study has tried to prepared the hybrid welded (pulsed Nd:YAG laser+TIG)Joints of Galvanized steel as a new substitute process for conventional welding of lightweight parts. For clarifying the mechanical phenomena of thermal elasto-plastic behavior on the hybrid welded joints, we carried out two-dimensional thermal elasto-plastic analysis on them. Firstly, a two-dimensional heat conduction and thermal elasto-plastic programs were developed by an iso-parametric finite element method. Secondly, from the results analyzed by the developed programs, thermal,

mechanical characteristics and their production mechanism on hybrid welded joints were clarified. Moreover, effects of the parameters of hybrid welding condition(gap between laser beam and arc, height of electrode, welding current, welding speed, etc.) on the temperature distribution, welding residual stresses and plastic strain of hybrid welded joints were evaluated. These results suggested sound hybrid welded joints of Galvanized steel would be obtained by optimizing the welding conditions, indicating that the penetration of 70~80% was reasonable compared to full penetration.

List of Figure

List of Table

CHAPTER 1. Introduction

1.1 Introduction

Corrosion of automotive components by road salt has become a widely recognised problem The parts under the car body and the interior surface of body panels easily suffer corrosive attacks by sodium chloride solution deposited on roads for melting snow. In general, galvanic coupling to zinc, as either an anode or a coating, is an effective means for combating steel corrosion Zinc-coatings which have sufficient negative potential to cathodically protect steel have therefore been employed extensively by automobile manufacturers to improve the corrosive resistance of car bodies

Of the numerous laser available today, two still dominate the materials processing area: the CO2 and the Nd:YAG laser. Previously, because of their better beam quality and high output power, CO2 laser, usually operated in continuous wave(CW)mode, went unchallenged for many years in applications of cutting and welding of unusually thick materials. However, at the present time, the Nd:YAG laser with its capability of operating in both high power CW and pulsed-modes and its flexible beam delivery through fibre optics, poses a threat to the CO2 laser, As for the pulsed mode Nd:YAG laser, its inherently complicated pulsed laser parameters permits a wide range of experimental conditions to be applied. The laser also has the ability of pulse shaping at pulse repetition rates of up to several kilohertz and with a duration varying from 0.5 to 20ms. This flexibility gives control of the thermal input whit a precision not previously available

While constructing an automobile body using the pulsed mode Nd:YAG laser welding technique, zinc coatings on the fusion zone and the heat-affected zone of the mild steel sheet are damaged to a certain extent due to vapourisation. This will certainly impair to some extent the local corrosion resistance of the heat-treated zone of the zinc-coated sheet steel

Laser welding process has some advantages compared with Arc welding due to the characteristics of non-contactable process and higher speed, etc.; however, it is difficult to say which the best method is because of its different concept to join the materials.

The purpose of this study is to develop and apply alternative fusion welding process for Galvanized steel; therefore, study is limited to fusion welding process. The advantage of laser welding over the conventional welding processes is the lower overall heat input and hence lower thermal distortion, smaller HAZ (heat affected zone), deep-weld effectand higher welding speed. Especially smaller HAZ is giving improved joint mechanical properties However, laser welding is required tight joint fit up tolerances and this restricts application of laser welding sometimes. In initial capital investment in the equipment is higher than other welding process but this can be overcome by productivity and weld quality improvements. Another disadvantage is that operating efficiency is low. Conventional lamp pumped Pulsed Nd:YAG laser has typically between 1 and 3% energy efficiency

On the other hand, conventional welding processes, MIG and TIG, have their inherent advantages which are low capital investment in equipment, good gap bridging ability and improvement of metallurgical and mechanical properties by added filler wire, etc

Therefore, new attempt was tried to combine welding processes of different type, that is, to adopt the advantages of each welding process by merging of laser and arc welding process in the same process zone. First trial is conducted by M. Eboo, et al. in 1978. They had obtained the results of increased penetration depth and welding speed in the combined process over the results of each welding method by using 2 kW CW CO_2 laser system and TIG.

In general, we are calling it the name of "hybrid welding process"and this meaning is that different welding heat sources are merging in the same process zone to get the synergy effect of each welding process. But, further development did not follow after their first reports for a long time. Setting in mid of 1990's, researcher's attention was returning to this topic again. Remarkable development of laser technology, increased power of laser and beam delivery technology using optical fibre, etc., was accomplished during this gap. The importance of laser welding was highlighted in many industrial fields.

Laser+TIG hybrid welding is a completely innovative technology that offers synergies for wide fields of application in automotive, shipbuilding, aerospace etc. compared to single process. This technology specializes in that advantages of each welding process can be maximized in concurrence with complementing the disadvantages.

Due to these merits, many industrial companies in developed countries has been investigating and applying the hybrid welding process.

TIG welding can weld large joints and control the chemical composition of weldment using welding rod. Welding deformation, however, can be occurred by slow welding speed and high heat input producing a wide and shallow weld.

Laser welding focuses the beam in high density and joins the materials. Very deep penetration and narrow heat affected zone (HAZ) can be obtained. Welding deformation can be also minimized due to concentrated high heat input density. But the critical problem of laser welding is that gap bridging capability is much less than TIG welding. Because diameter of laser beam is too small, an exact joint preparation and clamping are needed. Also metal composition cannot be controlled by filler wire.

Along with conquest of faults in two welding process, laser+TIG hybrid welding can be realized by good points of laser and TIG welding process in one welding zone, like a good bridging ability, high travel speed, deep penetration and improved process stability etc.
Finally laser+TIG hybrid welding can improve the Galvanized steel welding and reduce the welding deformation.

Many welding process phenomena and mechanical experiments of hybrid welding have been studied for a long time. On the other hands, researches on characteristics of hybrid welding heat source have been investigated but it leaves much to be desired. So in this study, characteristics of heat source in laser+TIG hybrid welding were inquired by numerical analysis and compared to experimental results.

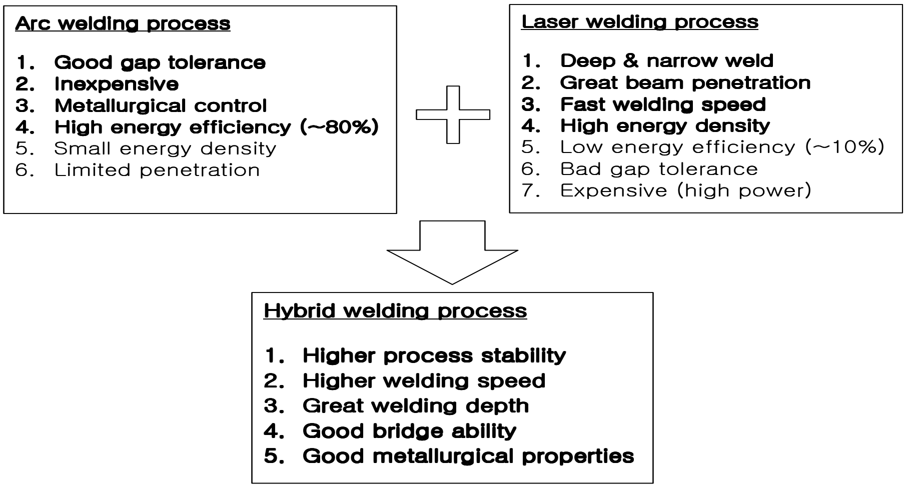


Fig. 1.1 Synergy effects of Laser+Arc hybrid welding process

1.2 Materials Used

Galvanized steel, widely used in the industry, are selected in this study for their high strength to weight and ratio combined excellent corrosion resistance and general good durability, low cost. For the reasons, Galvanized steel is an ideal material for a multitude of building applications and the industry

Table 1.1 Mechanical Properties of Galvanized steel

TS(MPa)	YP(MPa)	EL(%)
400	235	21

Table 1.2 Chemical compositions of Galvanized steel(%)

C	Si	Mn	P	S	Ni	Cr	Mo
0.06	0.0244	0.225	0.0128	0.0167	0.0056	0.0192	0.0071

1.3 Scope of the current research

As increasing the use of Galvanized steel it is obviously certain that an improvement of Galvanized steel welding is needed. And for meeting this demand, it has come out that hybrid welding could be applied in the manufacturing fields of Galvanized steel and many researches in this field has been carried out. But a study in regard to heat sources of hybrid welding has not yet been investigated.

Therefore, in this study, fundamental information about heat source of hybrid welding used for its numerical simulation and various experiments on hybrid welding have been performed.

For analyzing the heat source of Pulsed Nd:YAG laser+TIG hybrid welding, basic theory of heat transfer was formulated using finite element method(FEM). A previously developed heat source model of Pulsed Nd:YAG laser+TIG hybrid welding has been used to carry out the heat transfer analysis and determine the thermal history. Also residual stress distribution was analyzed and compared with measured residual stress values.

Galvanized steel were jointed by Pulsed Nd:YAG laser+TIG hybrid welding and the weldments were observed. Finally experimental results of Pulsed Nd:YAG laser+TIG hybrid welding were compared with results of numerical simulation.

CHAPTER 2. Numerical Simulation of Hybrid welding

There are many practical engineering problems that require the analysis of heat transfer and residual stress. A finite element codes for the heat transfer and residual stress analysis is developed. In many cases a significant percentage of the time spent on FEM analysis is devoted to pre-and post processing stage. This is the case for numerous FEM codes used in specialized researches. In the present work an interface is built using the high level language PCL (PATRAN Command Language) that can be compiled directly from PATRAN desktop so that PATRAN can be used as pre- and post processor for the developed codes.

2.1 Theoretical Basis for Analysis

2.1.1 Heat Transfer Theory

Fourier's law is an empirical law based on observation. It states that the rate of heat flow, dQ/dt, through a homogeneous solid is directly proportional to the area, A, of the section at right angles to the direction of heat flow, and to the temperature difference along the path of heat flow, dT/dx i.e.

$$q = -\lambda_x \frac{dT}{dx} \tag{2.1}$$

So for 2D-case the rate of heat transfer is

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) \tag{2.2}$$

The thermal analysis was conducted using temperature dependent thermal material properties. From conservation of energy the governing equation of heat conduction in weldment is obtained as (considering the medium to be isotropic)

$$\rho c\frac{\partial T}{\partial t}=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\dot{Q} \tag{2.3}$$

where

T : Temperature (℃)

ρ : Density (g/cm^3)

$\dot{Q}$: Rate of temperature change due to heat generation per volume (cal/cm^3· sec)

t : Time (sec)

λ : Thermal conductivity of isotropic material (cal/cm^3· sec· ℃)

c : Specific heat (cal/g· ℃).

Boundary condition to solve the equation (2.3) is given in the following form using the heat flux q (cal/cm^3· sec· ℃) in normal direction on the boundary of the object.

$$q=-\lambda\frac{\partial T}{\partial n} \tag{2.4}$$

Heat conduction problem for the object of analysis is formulated as the finite element method using Galerkin method. Internal temperature of the element, T, is given by

$$T(x, y, z, t)=[N(x, y, z)]\{\phi(t)\} \tag{2.5}$$

where $[N]$ is a shape function matrix shown the relation between nodal temperature and internal temperature of the element. $\{\phi\}$ is the vector of the nodal temperature of the element at time t.

If Galerkin method is applied in equation (2.3) using $[N]$ as a weighting function at this time, following equation is obtained.

$$\int_{V^e} [N]^T \left\{ \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \dot{Q} - \rho c \frac{\partial T}{\partial t} \right\} dV = 0 \tag{2.4}$$

where superscript, T, shows transformation of matrix and subscript, V^e, shows the domain of element. The term of second order in partial differential equation (2.4) is changed using Green-Gauss theorem, a formula of partial integration, to the following equation.

$$\begin{aligned} &\int_{V^e} \lambda \left(\frac{\partial [N]^T}{\partial x} \frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial y} \frac{\partial [N]}{\partial y} \right) dV \bullet \{\phi(t)\} \\ &+ \int_{V^e} \rho c [N]^T [N] dV \bullet \frac{\partial \{\phi(t)\}}{\partial t} = \int_{V^e} \dot{Q} [N]^T dV - \int_{S^e} q [N]^T dS \end{aligned} \tag{2.5}$$

Simplifying above equation (2.5), un-stationary heat conduction problem can be expressed as following finite element expression for an element.

$$[k]\{\phi\} + [c]\left\{ \frac{\partial \phi}{\partial t} \right\} = \{f\} \tag{2.6}$$

where $[k]$, $[c]$ and $\{f\}$ show the heat conductivity matrix of an element, the heat capacity matrix of an element and the heat flow vector of an element, respectively. They are expressed as follows:

$$[k]=\int_{V^e}\lambda\left(\frac{\partial[N]^T}{\partial x}\frac{\partial[N]}{\partial x}+\frac{\partial[N]^T}{\partial y}\frac{\partial[N]}{\partial y}\right)dV \tag{2.7}$$

$$[c]=\int_{V^e}\rho c[N]^T[N]dV \tag{2.8}$$

$$\{f\}=\int_{V^e}\dot{Q}[N]^TdV-\int_{S^e}q[N]^TdS \tag{2.9}$$

Finite element formula for the whole object analysed is constructed with assembled each matrix of elements and it can be expressed as follows:

$$[K]\{\Phi\}+[C]\left\{\frac{\partial\Phi}{\partial t}\right\}=\{F\} \tag{2.10}$$

where $[\Phi]$, $[K]$, $[C]$ and $\{F\}$ show the vector of the nodal temperature in the whole object, the heat conductivity matrix in the whole object, the heat capacity matrix in the whole object and the heat flow vector in the whole object, respectively.

2.1.2 Thermal elasto-plastic Theory

A. Basic theory for Welding residual stress and strain analysis by finite element method

The increment of strain in the element is given by appropriate differentiation of the internal displacements as shown in bellows.

$$\{d\varepsilon\} = [B]\{dw\} \tag{2.5}$$

The increment of stress in element is obtained by using an appropriate matrix $[D]$, the elasticity matrix $[D^e]$ or the plasticity matrix $[D^p]$, and the increment of strain.

$$\{d\sigma\} = [D]\{d\varepsilon\} \tag{2.6}$$

If the increment of initial strain $\{d\varepsilon_0\}$ exists, increment of stress is expressed as follows.

$$\{d\sigma\} = [D]\{d\varepsilon - d\varepsilon_0\} \tag{2.7}$$

where the initial strains are function of temperature such as thermal strains and has the following relation.

$$\{d\varepsilon_0\} = \{d\varepsilon^T\} = \{\alpha\}dT \tag{2.8}$$

Using this relation, the increment of stress, equation (2.7), can be rewritten in the following form.

$$\{d\sigma\} = [D]\{d\varepsilon\} - [C]dT \tag{2.9}$$

The relationship between the increment of the nodal force, $\{dF\}$, and the nodal displacement, $\{dw\}$, is obtained by applying the principle of virtual work as bellows.

$$\begin{aligned}\{dF\} &= \int [B]^T[D]\{d\varepsilon\}dV - \int [B]^T[C]dTdV \\ &\equiv [K]\{dw\} - \{dL\}\end{aligned} \tag{2.10}$$

where

$$[K] = \int [B]^T[D]\{d\varepsilon\}dV \text{ - The stiffness matrix} \tag{2.11}$$

$$\{dL\} = \int [B]^T[C]dTdV \text{ - The nodal force due to initial strain} \tag{2.12}$$

The equilibrium state of the whole object will be kept in satisfying the additional equilibrium condition at each step of temperature increments which are constituted with individual equilibrium equation at each node as follows.

$$\sum\{dF\} = \sum[K]\{dw\} - \sum\{dL\} \tag{2.13}$$

If there is no external force acting at the nodes, the above equation is expressed in the simple form as bellows.

$$\sum\{dL\} = \sum[K]\{dw\} \tag{2.14}$$

For the $[D]$ and $[C]$, it will be obtained from stress-strain relation in elastic and plastic range as shown in next.

b) Stress-strain relation

Yield of materials is occurred when its yield function, f, satisfy the following equation.

$$f = 0 \tag{2.15}$$

According to the associated flow rule (increment theory of plasticity), the increment of plastic strain, $\{d\varepsilon^p\}$, is given in following form.

$$\{d\varepsilon^p\} = \lambda \left\{ \frac{\partial f}{\partial \sigma} \right\} \tag{2.16}$$

where f is plastic potential and λ is a positive scalar.

In the elasto-plastic problem, the total increment of strain is consisted of the summation of increment in elastic strain, plastic strains and thermal strains as follows.

$$\{d\varepsilon\} = \{d\varepsilon^e\} + \{d\varepsilon^p\} + \{d\varepsilon^T\} \tag{2.17}$$

2.1.3 Temperature dependency of material properties

In this study, temperature dependency of material properties has been considered all over the elastic and plastic fields. Fig. 2.1and Fig. 2.2 shows the temperature dependent mechanical and physical properties of

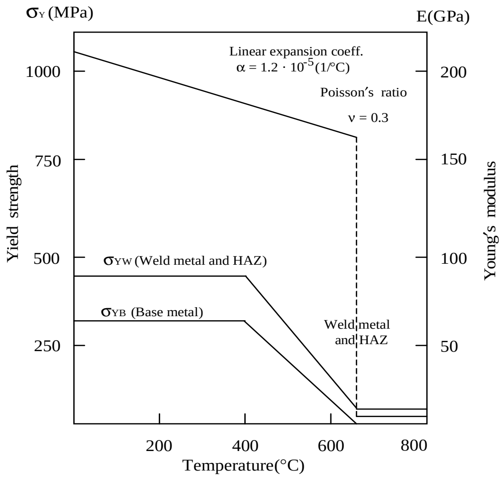


Fig. 2.1 Mechanical properties of Galvanized steel(SS400)

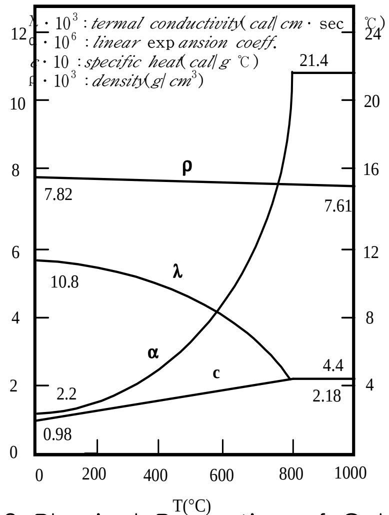


Fig. 2.2 Physical Properties of Galvanized steel

2.2 Analysis Model and Method of Hybrid welding

2.2.1 Analysis Conditions

Based on basic theory of heat conduction has been discussed in this chapter. The spatial and temporal temperature distribution satisfies the governing equation of unstationary heat conduction. Welding heat source is assumed as an instantaneous heat source and two dimensional four-noded isoparametric element is used.

Boundary conditions are such that heat conduction exists inside the heat source model and atmosphere. The material is assumed as an isotropic material. The workpiece is initially at 20℃. Convective flow in the weld pool, vaporization in the keyhole and radiation heat transfer was not considered. Fig. 2.3 shows the boundary condition for heat conduction and thermal elasto-plastic analysis.

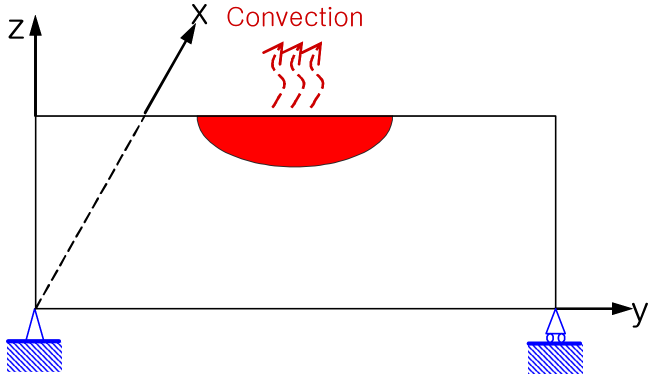


Fig. 2.3 Boundary conditions for Heat conduction and Thermal elasto-plastic analysis

Nominal dimension of specimen used was taken as 200×100×1mm ($W\times L\times T$) considering the effect of thermal shrinkage and expansion.
The schematic of the workpiece is shown in Fig. 2.4. A graded meshing is provided so that weld zone mesh size was mm×mm and mesh size gradually increase toward transverse direction.
The total number of element were 3420, and 3773 nodes.

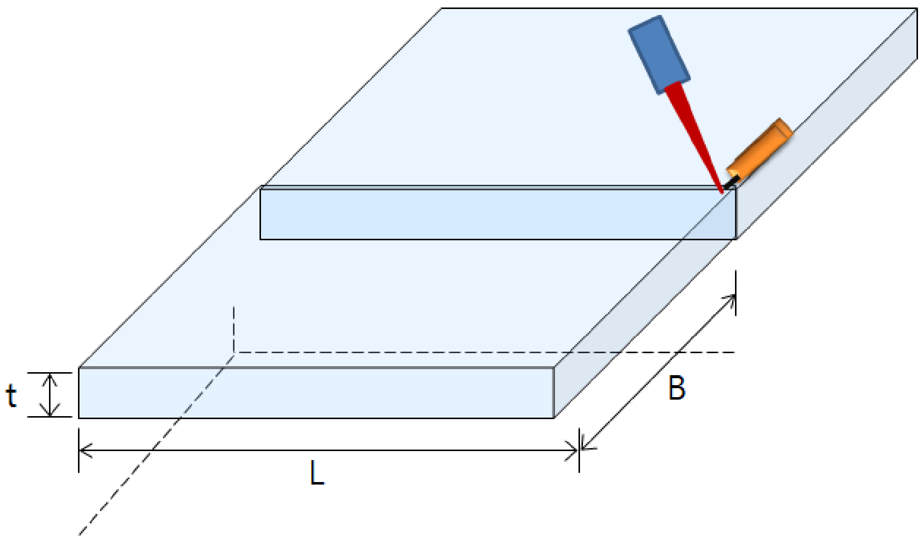


Fig. 2.4 Configuration of Hybrid welded specimen and coordinates

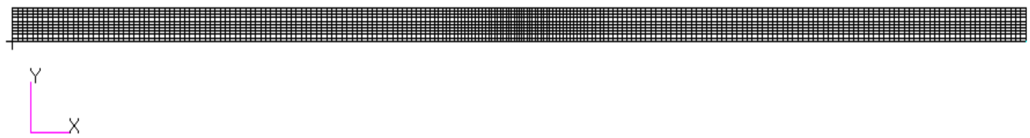


Fig. 2.5 Finite element model for numerical analysis of hybrid welded joints

Fig. 2.5 shows the mesh division used for the heat transfer and residual stress analysis of hybrid welding.

Also temperature dependent material properties like thermal conductivity, specific heat, heat transfer coefficient, density, elastic modulus, yield strength, etc. are considered as described previously.

2.2.2 Finite Element Model for Heat Source of Hybrid Welding

The welding heat source for analysis can be sorted out non-split type and split type as shown in Fig. 2.6. Non-split type has uniform flux (CASE.1) and split type is divided into volume-volume heat source (CASE.2) and volume-surface heat source (CASE.3). In this study CASE.2 was selected for analysis because it was proved that CASE.2 is proper method for heat source analysis of hybrid welding. Fig. 2.7 is schematic diagram of heat source.

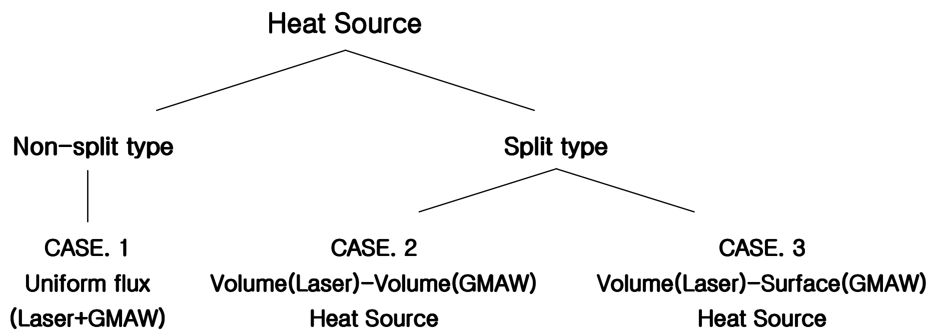


Fig. 2.6 Heat sources for analysis

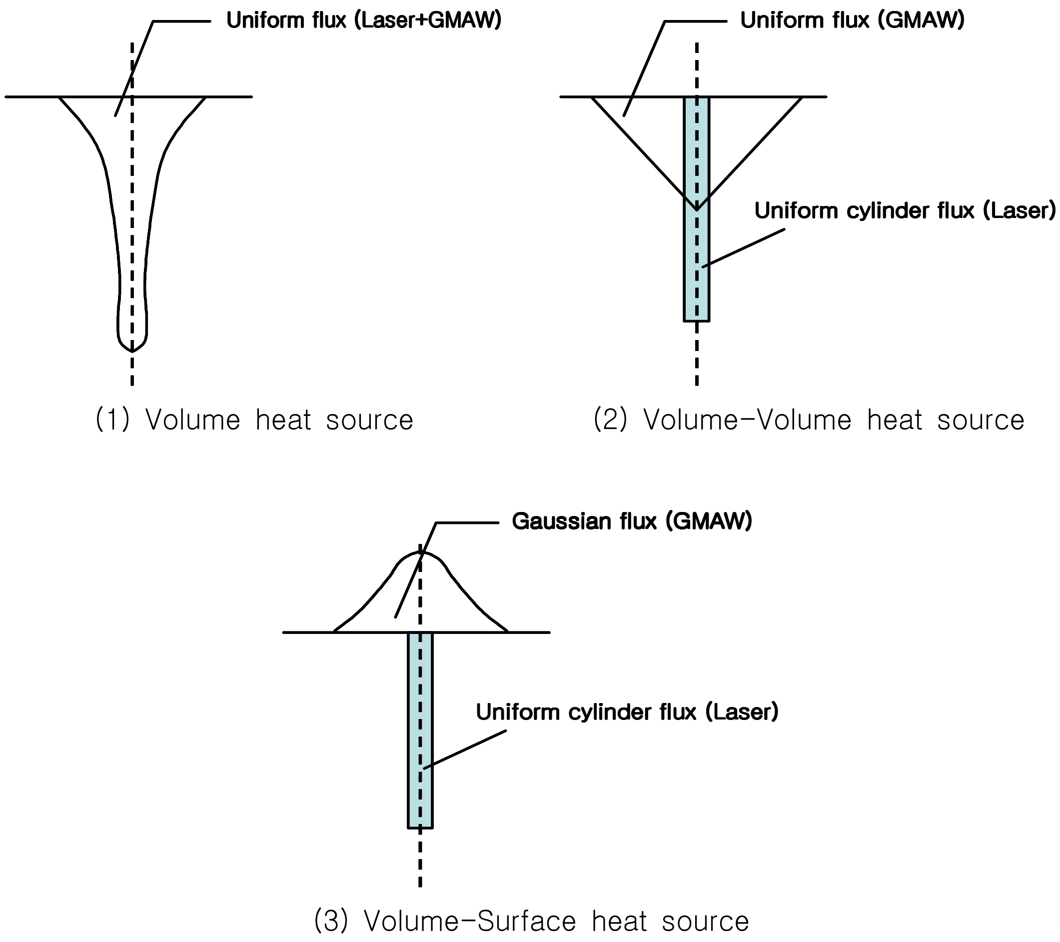


Fig. 2.7 Schematic diagram of heat source

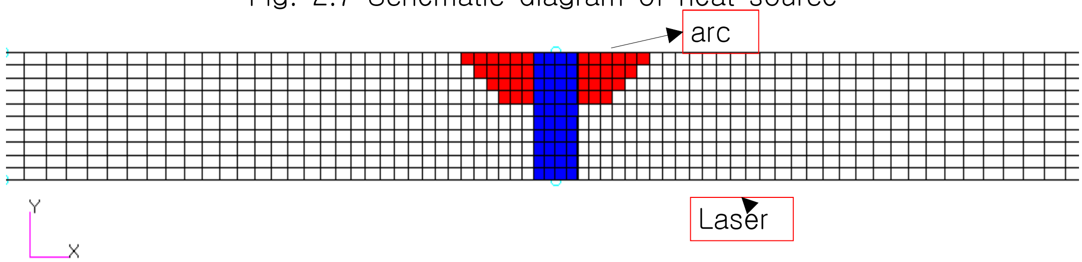


Fig. 2.8 Finite element model of heat source in laser+TIG hybrid welding

Fig. 2.8 is the 2-D model for heat source analysis of hybrid welding. It shows a coupled model of laser and arc welding

2.2.3 Calculation of Heat Input for Analysis of Hybrid welding

A. TIG welding

Heat input equation used in numerical simulation of TIG is,

$$Q = \eta_A \frac{VI}{W_S} \tag{2.19}$$

where

Q : Heat input
η_A : Efficiency of arc welding
V : Arc Voltage (V)
I : Arc Current (A)
W_S : Welding speed (cm/sec)

Simulation conditions for TIG are shown in Table 2.1. Efficiency of arc welding was 85%.

Table 2.1 Welding conditions for simulation in TIG Welding

Welding Conditions	Current(A)	Arc voltage(V)	Welding speed (m/min)	Efficiency of arc welding (η_A)
	300 A	29V	45mm/sec	85%

B. Laser welding

Heat input equation used in numerical simulation of laser welding is,

$$Q = \eta_L \frac{P}{W_S} \tag{2.20}$$

where

η_L : Efficiency of laser welding

P : Laser power (kW)

W_S : Welding speed (cm/sec)

Simulation conditions for Pulsed Nd:YAG laser are shown in Table 2.2. Efficiency of Pulsed Nd:YAG laser welding fixed 30% which was calculated considering total absorption and losses of Pulsed Nd:YAG laser beam

Table 2.2 Welding conditions for simulation in Pulsed Nd:YAG laser

Welding Conditions	Laser power (kW)	Welding speed (m/min)	Efficiency of Pulsed Nd:YAG laser welding (η_L)
	1.8KW	45mm/sec	30%

2.3 Results of Numerical Simulation in Hybrid welding

2.3.1Thermal, Mechanical Characteristics in Hybrid Welds

A phenomenon of heat transfer in Pulsed Nd:YAG laser+TIG hybrid welding is shown in Fig. 2.9. Centering around the welding heat source, welding heat is transferred from fusion zone to base metal. This temperature contour is also compared with the experimental results in Chapter 3. 4.

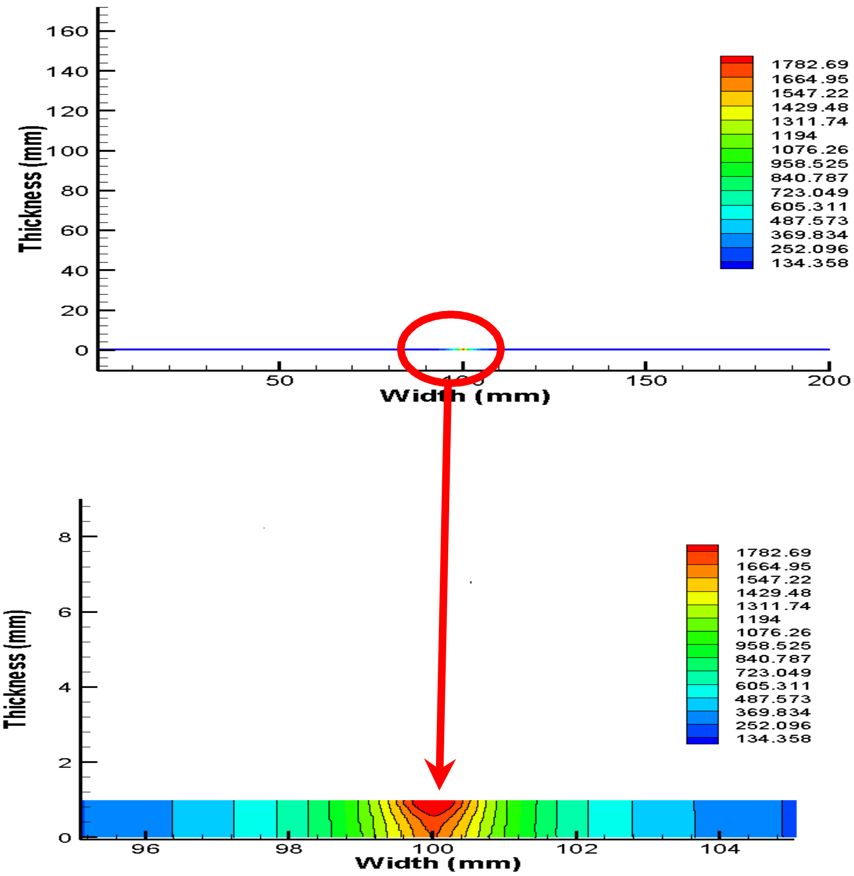


Fig. 2.9 Temperature contour of no gap in hybrid welding

Fig. 2.10 shows the thermal history curve of fusion zone and HAZ. Maximum temperature was discovered after t=0.6sec. Maximum temperature was approximately 1782℃ in fusion zone, 1664℃ in HAZ from the thermal history curve, high temperature gradient was observed near the HAZ, which has relations to the rapid cooling rate in the case of laser welding.

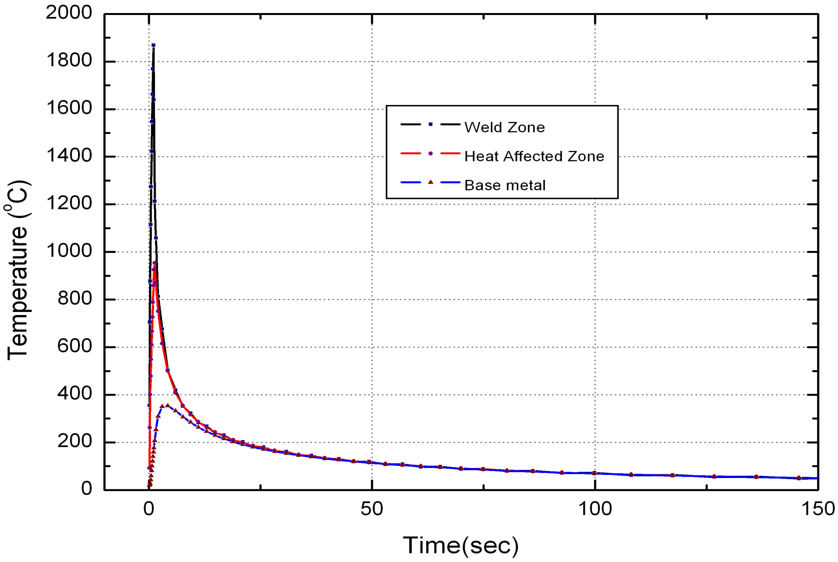


Fig. 2.10 Thermal history of hybrid welding

2.3.2 Residual Stress characteristics of Hybrid welds

Residual stress was measured in longitudinal direction of hybrid welds. It has been confirmed that results of numerical simulation was almost accord with experimental results. Compressive residual stress occurred near HAZ and tensile residual stress in fusion zone. Maximum residual stress value was 6Mpa

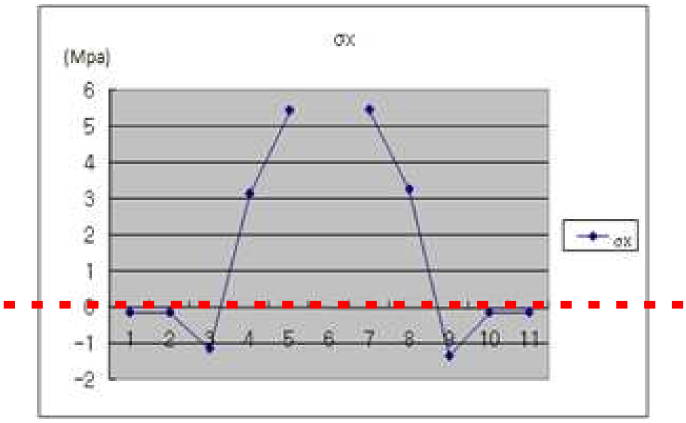


Fig. 2.11 Experimental results of residual stress

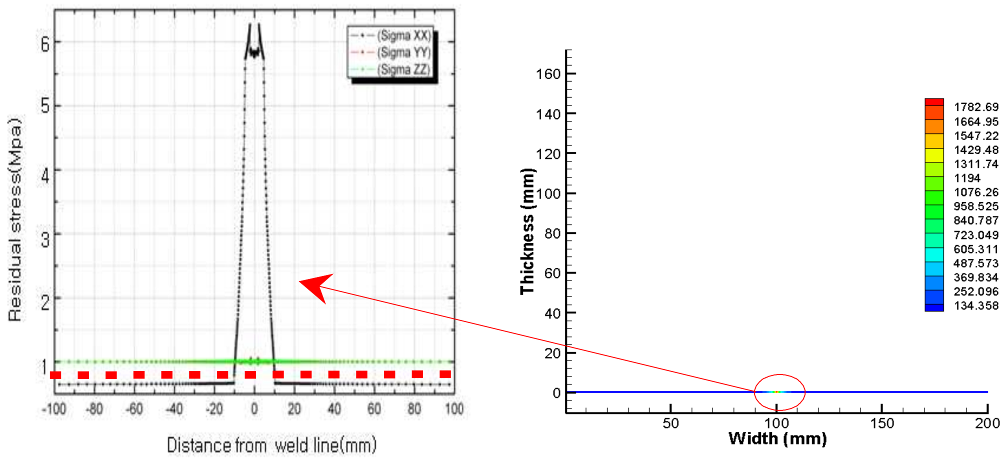


Fig. 2.12 Numerical results of residual stress

CHAPTER 3. Experiments of Pulsed Nd:YAG laser+TIG Hybrid welding

3.1 Various Parameters of Hybrid welding Process

3.1.1 TIG welding

- Welding current
- Welding arc voltage
- Polarity
- Welding speed
- Electrode diameter
- Angle of torch
- Shielding gas

Arc voltage is continuous with current directly and it is increased with arc length. Also it is under the control the shielding gas and electrode extension.

3.1.2 Pulsed Nd:YAG Laser welding

- Incident laser beam power
- Incident laser beam diameter
- Focal length
- Absorptivity
- Welding speed

The depth of penetration with laser welding is directly related to the power density of the laser beam and is a function of incident beam power and beam diameter.

Laser beam diameter is the important factor which determines the power density. For example, beam diameter is related to the focal length, power density of beam diameter is changed when varying the focal length. Also if focal point is above(+) or under(−) the surface, the position of incident beam focal point will be different and the power density will be low.

Absorptivity is one of standards which measure the efficiency of laser welding. The infrared absorption of metals largely depends on the conductivity absorption by free electrons. Therefore, absorptivity is a function of the electrical resistivity of the substrate material. Also absorptivity is depend upon surface condition, temperature-dependent of material and wavelength of laser beam.

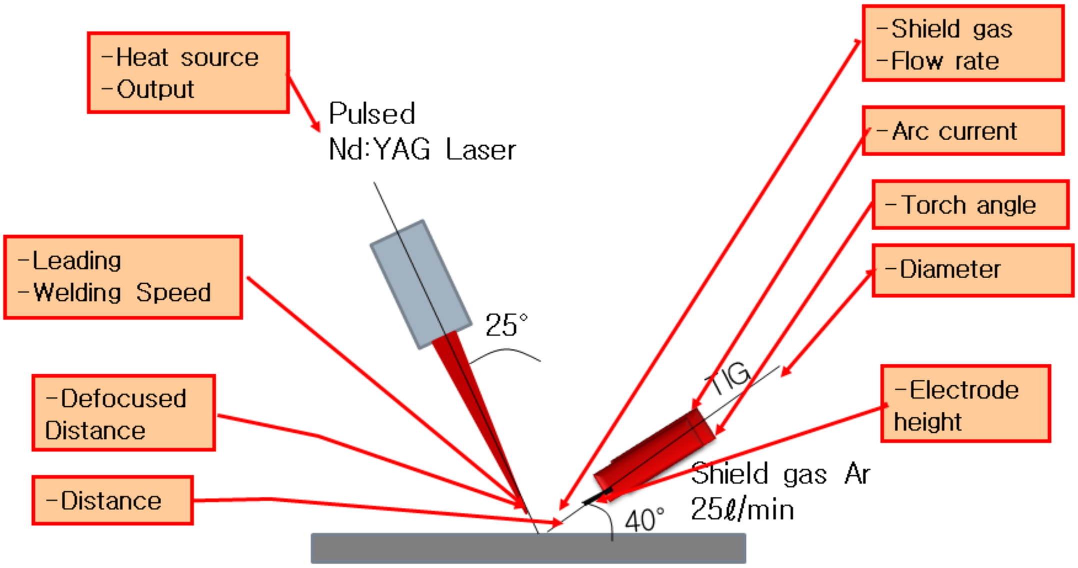


Fig. 3.1 Considered parameters of Pulsed Nd:YAG laser+TIG hybrid welding

3.2 Hybrid welding Experiments

As previously stated, considering various parameters, butt joint of Galvanized steel1 by Pulsed Nd:YAG laser+TIG hybrid welding were carried out.

2-axis robot used in these experiments was with a Miyachikorea Pulsed Nd:YAG laser and TIG torch on the robot head for making hybrid welding process. Fig. 3.2 shows the equipment of Pulsed Nd:YAG laser+TIG hybrid welding, Fig. 3.3 is the head of Pulsed Nd:YAG laser+TIG hybrid welding.

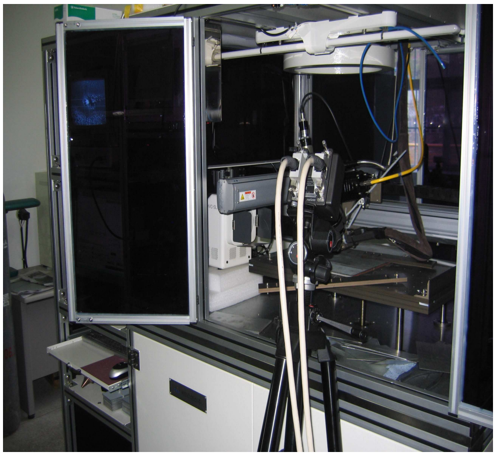


Fig.3.2 Laser-arc Hybrid welding equipment

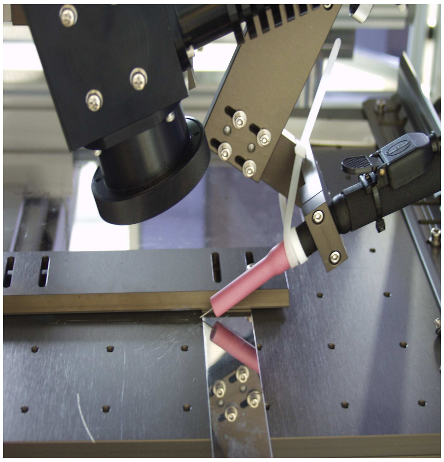


Fig.3.3 Laser-arc Hybrid welding Head

Only Ar was used for shielding gas which was supplied through a TIG torch located at the side of laser head and nozzles located at the side of laser head.

A Specimen size was 100mm wide, 200mm long and 1mm thickness. Before welding the surface of specimen was cleaned using a Alcohol for Galvanized steel

3.3 Optimization of Hybrid welding Process

Welding parameters of hybrid welding are most complicated than any other welding methods because two welding methods were combined. Interactional parameters in two welding should be considered, not to be included of each parameter. For the evaluation of welding variable from the hybrid welding it accomplished Bead-on-plate (BOP) experiments first and the hybrid welding experiment against the matching welding against the gap of 0~0.5mm sizes it accomplished It shows the hybrid experimental condition which is used in experiment in Table 3 Experiment 1~4 BOP experiment ship constructions and experiment 5 condition of optimum is matching welding condition from and Table 3 experiment 6~9 each Cabinet conference condition about under the fringe land matching are the condition which it welds The hybrid welding compares in the independence welding and the welding speed improvement possibility is with augmentation of penetration efficiency and, welding condition of optimum it selected with the method which welding speed improvement and after control from the economical efficiency side which is a requirement of the enterprise to productivity improvement keynote to let, is not. It will reach to respect, the maximum speed from under the condition which above pulse laser reiteration ratio 50% percent it shows first it sought output of arc and the laser after words that after from seeking welding condition optimumly, if under controlling, the condition which is visible 80~90% penetrations with the base which will reach it adopted

3.3.1 Optimization of laser arc for distance

First, for the optimization of laser arc for distance until 0~6mm it changed the distance of the laser and arc for and it saw, the laser arc for distance the bead which is good substitutionally under cut with minutely from 0mm and compared to this it occurred and the bead which is most good appeared from 2mm It under cut but from above 4mm and very was deepened and until 6mm it was visible the tendency which increases gradually with the enemy

Distance of laser arc for 4mm excess and at the time of under one it under cut and in order to observation the actual condition which appears compared

to uses a laser illumination high-speed photo graphing which with 3000fps and the result in picture 3.4 it executes it shows
High-speed photographing resultant laser arc for distance from below 2mm capacity of arc the laser investigation about under disrupting it under cut intermittently and compared to the 2mm over became under cut with the thing and from 2mm excess same actual condition the laser which does not appear when dual anger and arc for heat source could not accomplish low my molten pool from with 2mm under and they became, from judged in the defect in compliance with the synergic effective decrease of trade name for all
it tried to observe depth of penetration of the bead which it follows in the laser arc for distance against hereupon from Fig 3.5
If laser arc for distance from 0mm under increasing that from penetration about under increasing the bead appearance is most good, the penetration appeared most on a large scale from as many as 2mm where it is judged. The tendency which the penetration diminishes but rather from above that it seemed and proves the synergic effective decrease in compliance with a heat source dual anger directly the result which it showed and the laser and the distance of arc for optimum confirmed is 2mm.

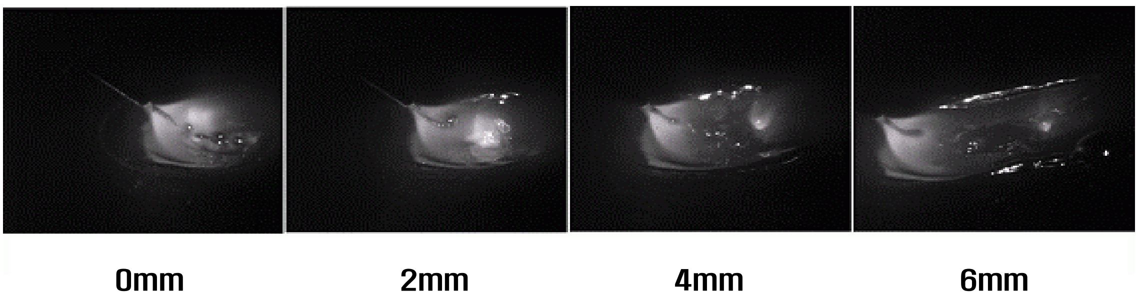


Fig. 3.4 High speed images for hybrid welding of galvanized steel sheets : 3000f

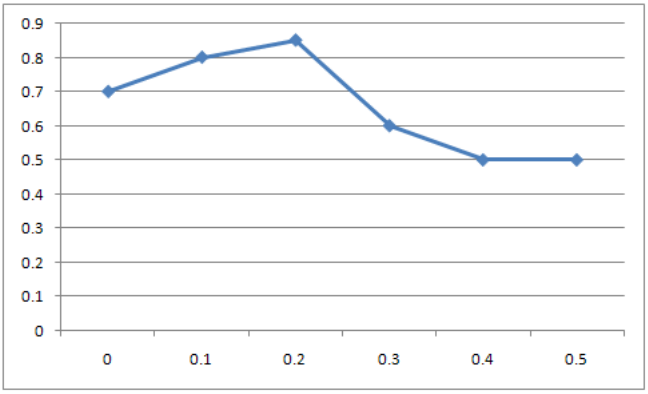


Fig. 3.5 Change distance of the laser and arc

The hybrid welding the laser output increases with the traitor to follow, depth of penetration the tendency which increases appears but the depth of penetration increase effect which it follows in welding current increase it is deficient, with experiment 1 of the hazard Table 3 which investigates the welding department quality which it follows first in welding current change together BOP weldings accomplishes it is big the possibility of knowing there was an effect against the flesh of the resultant welding current welding department which tries to observe the effect which goes mad to the welding department welding current. (Experiment1).

3.3.2 Optimization of PPS, Speed

It is like that it tried to observe the effect which in order to do investigation and the optimum escape, from Experiment 3 and 4 Peak Power and follows the effect regarding a laser output in PPS changes. Experiment 3, 4 results, with it puts out specially there to be it will be able to confirm the depth of penetration increase which the laser output follows with it indicates in Fig 3.7 together in increase indolently in Fig 3.8 together above 50% where it is necessary from the laser power pulse laser it will be able to confirm a charge from above 150 PPS where it shows the reiteration ratio. Experiment from under 4 conditions BOP welding quality evaluation results under welding condition of optimum with a base speed 45~49mm/s and PPS above 150, Peak Power output (Experiment 5), executed the hybrid welding from laser investigation output the above namely 490w the above 1.5kw and 2.8J. With city one together in that resultant Fig 3.6 this time, welding condition Experiment 5 of optimum (with it puts out indolently in Experiment 6 together it is 45~49mm/s it will be able to confirm the speed which is satisfied resultant depth of penetration about 80% it tries to observe the welding department quality which from (20070703-2-4) lows it follows in welding speed change. it wants condition of optimum of 80~90% where penetrations escape the sectional photograph in that Book of Psalms there to be a possibility of doing, from condition of optimum the welding preceding after trying, in Fig 3.6 (a, b and c) it shows.(Experiment 5). With this after selecting welding condition of same optimum it sought the effect where each Cabinet conference welding method goes mad from condition of optimum and to execute each Cabinet conference independent welding from the hazard which it sees it tried.

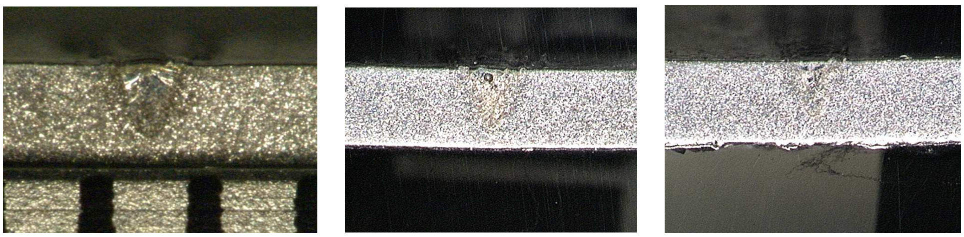


Fig. 3.6 Cross section

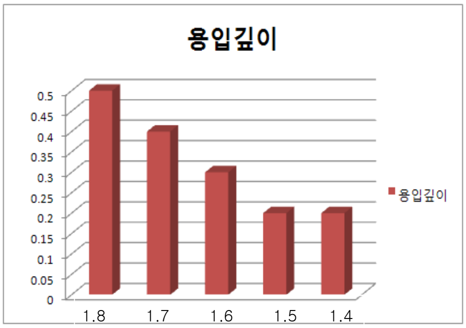


Fig. 3.7 Penetration Depth(Only laser)

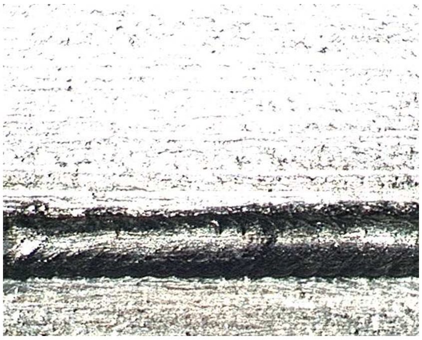
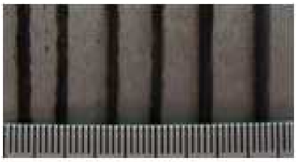


Fig. 3.8 PPS 150

No	ARC Power	Input Power	PPS	Average Power	Laser Power
1	200A	1,8kw	100	383,8w	3,8J

No	ARC Power	InputPower	PPS	Average Power	Laser Power
1	300A	1,4kw	170	458,5w	2,6J



No	ARC Power	Input Power	PPS	Average Power	Laser Power
1	200A	1,0kw	150	297,1w	1,9J

No	ARC Power	Input Power	PPS	Average Power	Laser Power
1	300A	1,8kw	150	511,8w	3,4J

Fig. 3.9 Change parameter of the laser and arc

Table 3. welding condition

Experiment 1.(Bead on Plate/ Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070605-1-1	100A	2.0kw	100	383.8w	3.8J
20070605-1-2	120A	2.0kw	100	383.8w	3.8J
20070605-1-3	140A	2.0kw	100	383.8w	3.8J
20070605-1-4	160A	2.0kw	100	383.8w	3.8J
20070605-1-5	180A	2.0kw	100	383.8w	3.8J
20070605-1-6	200A	2.0kw	100	383.8w	3.8J
20070605-1-7	220A	2.0kw	100	383.8w	3.8J

Experiment 2.(Bead on Plate/ Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070605-2-1	100A	2.0kw	100	383.8w	3.8J
20070605-2-2	100A	2.1kw	100	402.6w	4.0J
20070605-2-3	100A	2.2kw	100	421.2w	4.2J
20070605-2-4	100A	2.3kw	100	439.7w	4.3J
20070605-2-5	100A	2.4kw	100	459.0w	4.5
20070605-2-6	100A	2.5kw	100	479.1w	4.7J
20070605-2-7	100A	2.6kw	100	w	J

Experiment 3.(Bead on Plate/ Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070613-1-1	200A	1.0kw	50	99.7w	1.9J
20070613-1-2	200A	1.0kw	100	199.5w	1.9J
20070613-1-3	200A	1.0kw	110	219.0w	1.9J
20070613-1-4	200A	1.0kw	120	238.6w	1.9J
20070613-1-5	200A	1.0kw	130	257.9w	1.9J
20070613-1-6	200A	1.0kw	140	277.6w	1.9J
20070613-1-7	200A	1.0kw	150	297.1w	1.9J
20070613-1-7	200A	1.0kw	160	316.3w	1.9J
20070613-1-7	200A	1.0kw	170	335.1w	1.9J

Experiment 4.(Bead on Plate/ Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070703-1-1	100A	1.4kw	170	458.5w	2.6J
20070703-1-2	200A	1.4kw	170	458.5w	2.6J
20070703-1-3	300A	1.4kw	170	458.5w	2.6J
20070703-1-4	400A	1.4kw	170	458.5w	2.6J
20070703-1-5	500A	1.4kw	170	458.5w	2.6J
20070703-1-6	100A	1.4kw	160	432.4w	2.7J

20070703-1-7	200A	1.4kw	150	406.4w	2.7J
20070703-1-8	300A	1.4kw	140	380.3w	2.7J
20070703-1-9	400A	1.4kw	130	353.5w	2.7J
20070703-1-10	500A	1.4kw	120	326.9w	2.7J
20070703-1-11	300A	1.0kw	150	296.9w	1.9J
20070703-1-12	300A	1.1kw	150	324.6w	2.1J
20070703-1-13	300A	1.2kw	150	352.6w	2.3J
20070703-1-14	300A	1.3kw	150	380.1w	2.5J
20070703-1-15	300A	1.4kw	150	408.1w	2.7J
20070703-1-16	300A	1.5kw	150	435.1w	2.8J
20070703-1-17	300A	1.6kw	150	463.0w	3.0J
20070703-1-18	300A	1.7kw	150	489.9w	3.2J
20070703-1-19	300A	1.8kw	150	518.2w	3.4J

Experiment 5.(Butt Joints/Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070703-2-1	300A	1.4kw	150	407.6w	2.7J
20070703-2-2	300A	1.5kw	150	435.5w	2.8J
20070703-2-3	300A	1.6kw	150	463.2w	3.0J
20070703-2-4	300A	1.7kw	150	489.9w	3.2J
20070703-2-5	300A	1.8kw	150	519w	3.4J

Experiment 6.(Butt Joints/Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power	Speed
20070703-3-1	300A	1.7kw	150	512.3w	2.7J	50mm/s
20070703-3-2	300A	1.7kw	150	512.3w	2.8J	49mm/s
20070703-3-3	300A	1.7kw	150	512.3w	3.0J	48mm/s
20070703-3-4	300A	1.7kw	150	512.3w	3.2J	47mm/s
20070703-3-5	300A	1.7kw	150	512.3w	3.4J	46mm/s
20070703-3-5	300A	1.7kw	150	512.3w	3.4J	45mm/s

Experiment 7.(Butt Joins-Only Laser)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070704-1-1	Close	1.4kw	150	407.6w	2.7J
20070704-1-2	Close	1.5kw	150	435.5w	2.8J
20070704-1-3	Close	1.6kw	150	463.2w	3.0J
20070704-1-4	Close	1.7kw	150	489.9w	3.2J
20070704-1-5	Close	1.8kw	150	519w	3.4J

Experiment 8.(Butt Joints-Only TIG)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power
20070704-2-1	100A	Close			
20070704-2-2	200A	Close			
20070704-2-3	300A	Close			

20070704-2-4	400A	Close			
20070704-2-5	500A	Close			

Experiment 9.(Butt Joints/Hybrid welding)

No	Arc Power	Peak Power	PPS	Average Power	Laser Power	Thickness
20070705-1-1	300A	1.4kw	150	404.9w	2.7J	0.8
20070705-1-2	300A	1.5kw	150	431.4w	2.8J	0.8
20070705-1-3	300A	1.6kw	150	457.2w	3.0J	0.8
20070705-1-4	300A	1.7kw	150	483.9w	3.2J	0.8
20070705-1-5	300A	1.8kw	150	511.8w	3.4J	0.8
20070705-1-6	300A	1.4kw	150	403.94w	2.6J	1.0
20070705-1-7	300A	1.5kw	150	430.3w	2.8J	1.0
20070705-1-8	300A	1.6kw	150	456.2w	3.0J	1.0
20070705-1-9	300A	1.7kw	150	483.0w	3.2J	1.0
20070705-1-10	300A	1.8kw	150	511.3w	3.4J	1.0
20070705-1-11	300A	1.4kw	150	405.1w	2.6J	1.2
20070705-1-12	300A	1.5kw	150	431.2w	2.8J	1.2
20070705-1-13	300A	1.6kw	150	457.6w	3.0J	1.2
20070705-1-14	300A	1.7kw	150	483.4w	3.2J	1.2
20070705-1-15	300A	1.8kw	150	511.7w	3.4J	1.2

Table 3.1 Laser-arc hybrid welding Conditions

Experiment number	Laser(Input)	Laser(output)	Laser(output)	TIG welding	Speed
1	1.8kw	3.4J	511.3w	300A	45mm/s
2	1.7kw	3.2J	483.0w	300A	45mm/s
3	1.6kw	3.0J	456.2w	300A	45mm/s
4	1.5kw	2.8J	430.2w	300A	45mm/s
5	1.4kw	2.6J	403.9w	300A	45mm/s

3.3.3 Only laser welding

The possibility of knowing from Cross section of the resultant Fig 3.10 which tries to enforce the welding with the laser grade poison it was this depth of penetration hybrid welding preparation 70~80% to confirm the penetration which corresponds and, the defect of the perforation which hinders the continuity of the bead the zinc vapor and oxidation producer and the Blow occurred. Also many spatter from the high speed camera confirmation welding department and it occurs it will be able to confirm.

3.3.4 Only TIG welding

Welding visual inspection and high speed camera entirely it does not become accomplished it will can confirm the resultant welding which it confirms but the welding speed is quick in and TIG grade poisons it became feed with the result where the welding becomes accomplished with automatic

Only TIG	Only Laser	Hybrid Welding (TIG leading)	Hybrid Welding (Laser leading)
Not welding			

Fig. 3.10 Comparison of penetration depth in welded joints

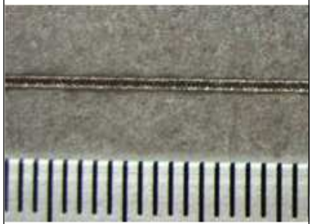
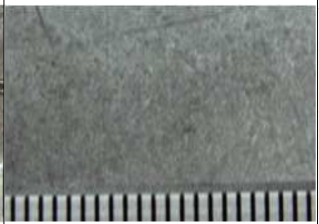
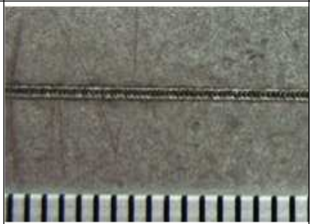
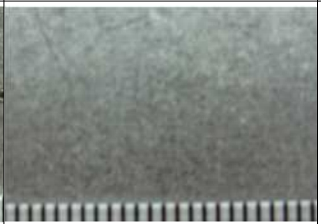
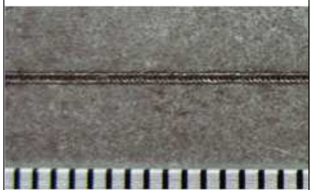
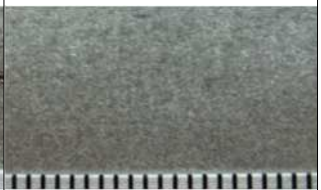
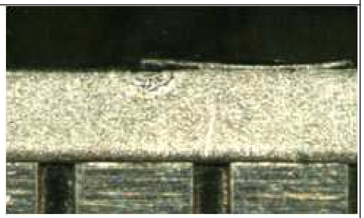
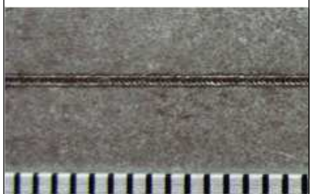
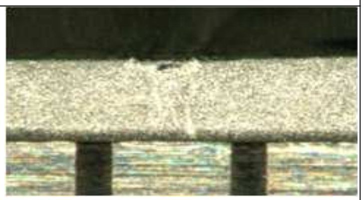
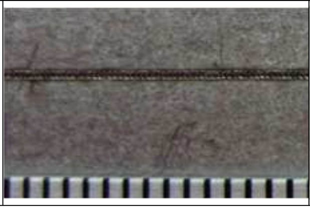
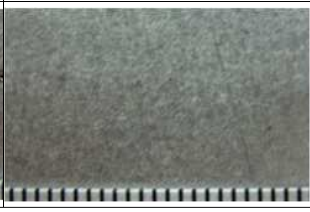
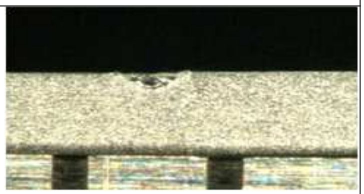
No	Top surface	Bottom surface	Cross section
1			
2			
3			
4			
5			

Fig. 3.11 Only Nd:YAG Pulsed Laser weld

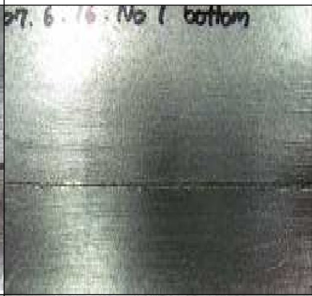
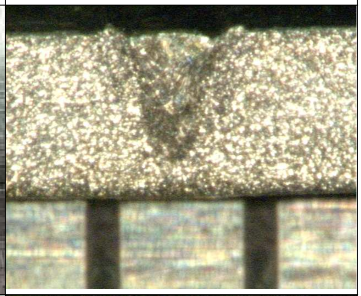
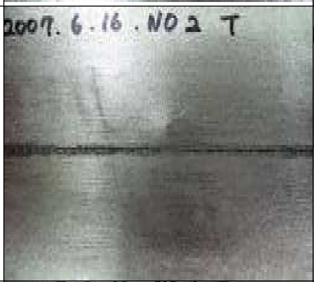
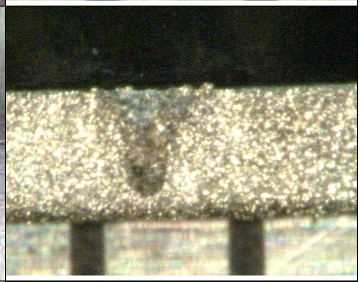
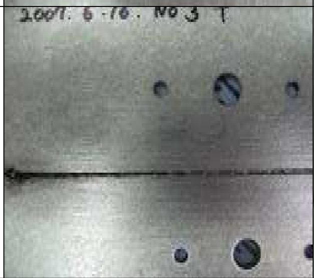
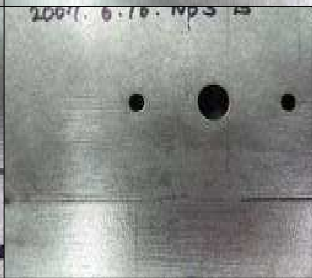
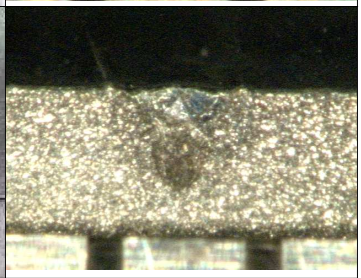
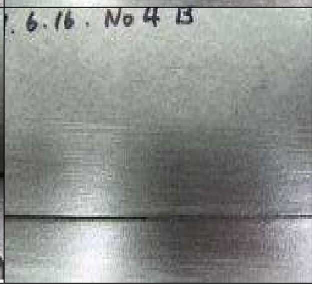
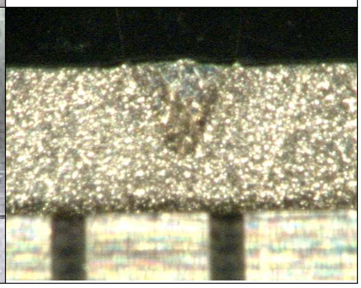
NO	Top surface	Bottom surface	Cross section
1			
2			
3			
4			

Fig. 3.12 Hybrid welding (TIG Leading)

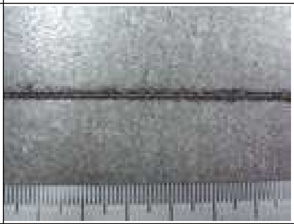
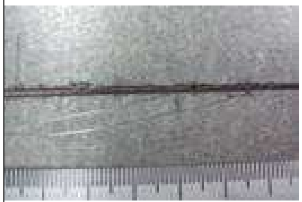
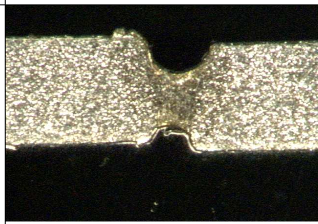
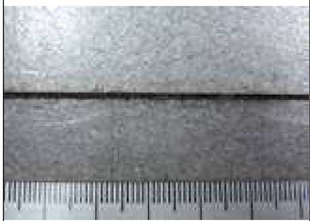
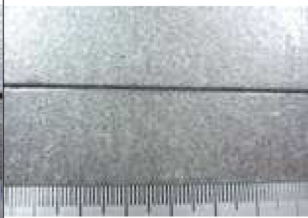
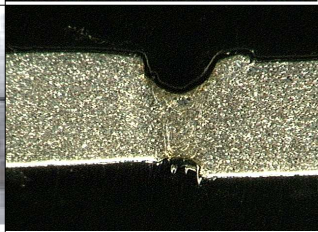
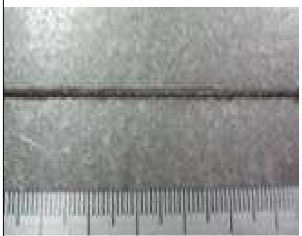
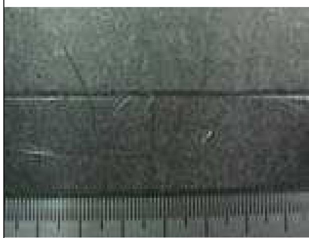
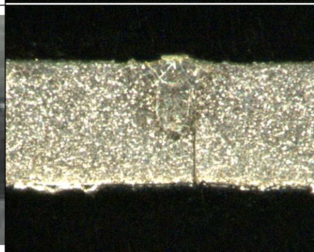
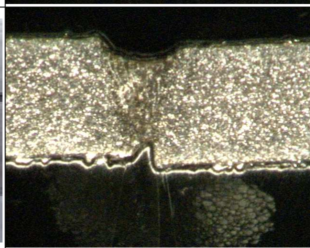
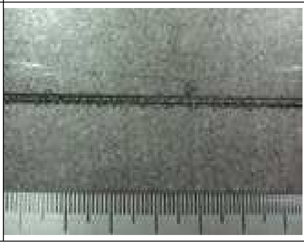
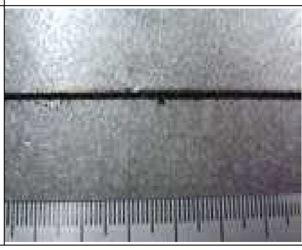
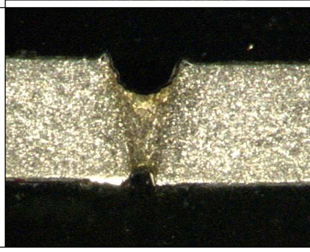
NO	Top surface	Bottom surface	Cross section
1			
2			
3			
4			
5			

Fig. 3.13 Bottom surface and Cross-section bead shape of Hybrid welding (Laser leading)

CHAPTER 4. Mechanical Characteristics of Hybrid welds

4.1 Micro-structure

Analysis result of hybrid welding department

Until 1 μ from after 1% HN03 Polishing one and etchant of 1ml + 99% ethyl alcohol 99ml about under 25~30 first edition etching it micro structure an analysis with the mark against a weld zone form

Galvanized the base metal micro structure photograph and the hybrid welding of steel (SS400) steels deposit metal it will call and CGHAZ and ICHAZ the result which from the optical science microscope it photographs by 100 boats with Fig 4.1 is same.

Fig 4.1 a) it is to show an organization photo shoot location, execute the hybrid welding butt welding.

b) the base metal of Galvanized steel(SS400 steels) it will call and to photograph the direction which is rolled, this base metal with the river where 0.06% carbon which it blows contains, it follows and Ferrite (White colors) with Pearlite belts (the black color) is a possibility of seeing the fact that it becomes accomplished with structure. c) ICHAZ regions from each welding (top the territory where ten temperatures were risen between A1~A3) the place where it is showing, this region will like that be maintaining the belt shape organization of the base metal from and, only Pearlite will get up an organized pervert from this territory, Ferrite average wave triangular position sizes base metal step to be minute all the position thing it will be able to confirm.

The case and cooling rate of the hybrid welding department will be quick and in welding process Austenite where it is formed from high temperature fusion almost it will be able to confirm upper perverted one features with the whole quantity Martensite, it will reach and to lead the longitude quality of the hybrid welding department it step of the arc welding departments it will be able to predict with the fact that an all far it will have higher price.

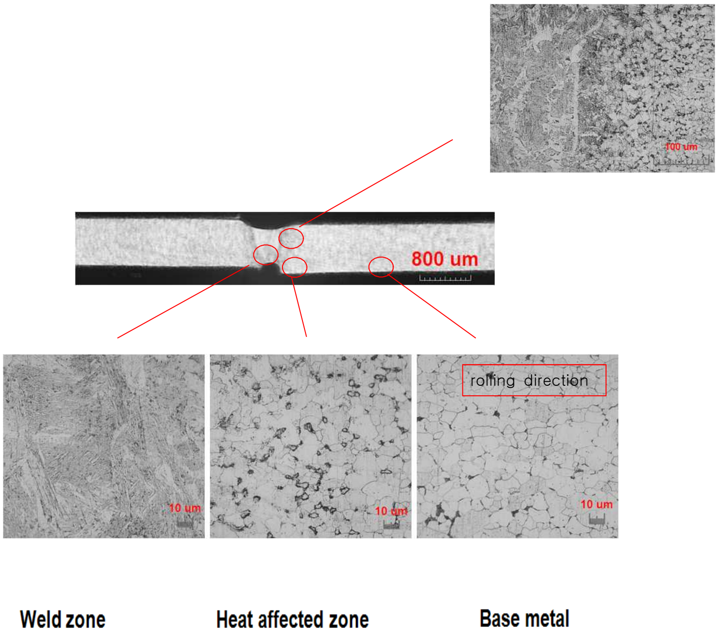


Fig. 4.1 Micro Structure of Hybrid welded joints

4.2 Hardness Test in Hybrid welds

The hardness of transverse section which was welded by optimum parameters was measured by vickers hardness tester. A load of 0.1kgf and a spacing of 0.1mm and 0.1mm between the indentations were used. The measured hardness values are shown in Fig. 4.2

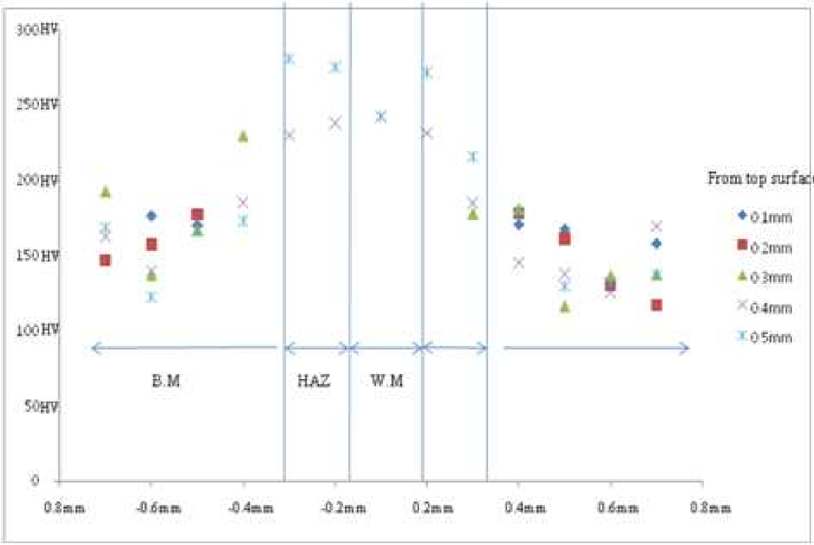


Fig. 4.2 Hardness value in Pulsed Nd:YAG+TIG hybrid welds

As shown in Fig. 4.2, lowest value of hardness occurred in weld metal. Where as toward the base metal, hardness value increases. This phenomenon can be explained by alloying elements and heat input. In other words, mechanical properties of welded materials has been affected by heat input which vaporizes the alloying elements.

Comparing the hardness value of each area, hardness value of HAZ mediates between weld metal and base metal. Hardness of weld metal was between 240~250Hv, HAZ was 260~280 Hv and base metal was 150~170 Hv.

It will be seen Fig 4.2 and, the possibility which even from the minute organized prosecuting attorney of after it will know it was and the metal department the whole quantity ferrite and bainite with site to change it became and a longitude price relatively to follow it was visible. With above the possibility of knowing from same longitude distribution it is this laser welding with the general welding department which it blows and, as many as ten effect bringing up for discussion sizes on a large scale different point to be discovered are narrow very

4.3 Tensile Test

Galvanized the hazard which evaluates steel (SS400) welding characteristics the specimen which it welds KS0801-5 It dances, the specimen the Tensile test an examination about under processing
Hybrid and general base metal Galvanized steel (SS400) seal holds an examination about under the result which investigates the Tensile test result with Table 4 is same. SS400 steels yield point the Tensile test result above 400MPa comes out from KS, standards to 235MPa the place where it calls the steel where, from the resultant base metal department an actual Tensile test an examination the Tensile test result and the yield strength all standard price it is satisfactory, the butt welding one result final rupture it knows the tension test about under executing from the base metal vice- piece all rupture to happen, that it happens from the weld zone piece, the welding department healthily, it became junction it will be able to give proof a fact.

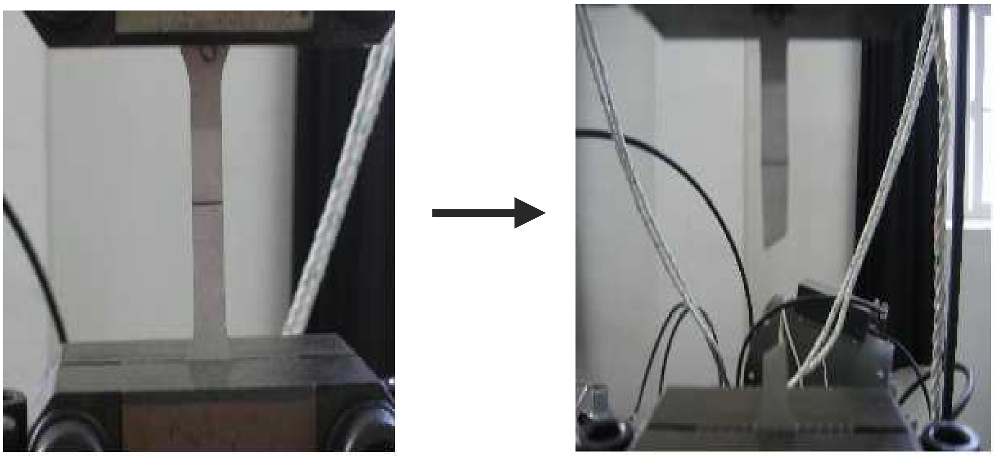
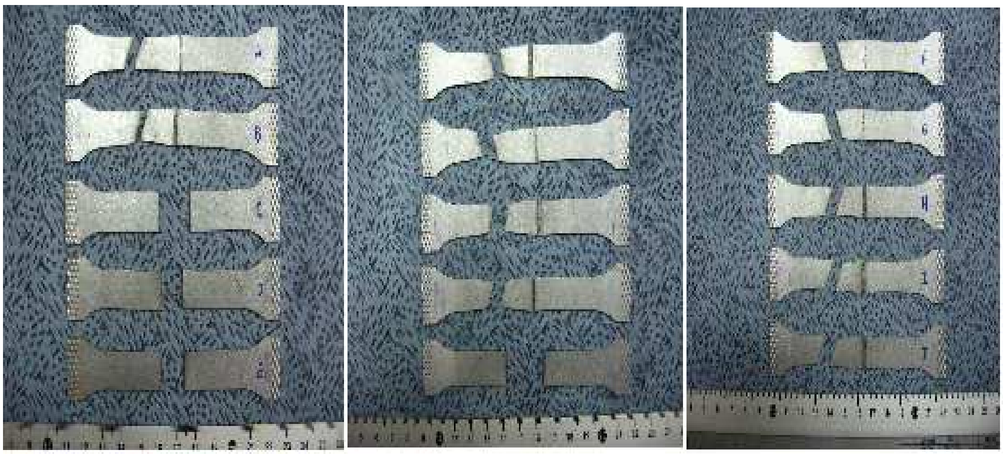
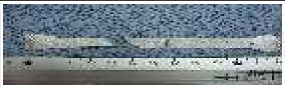
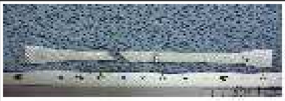
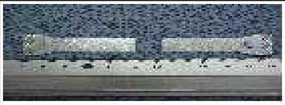
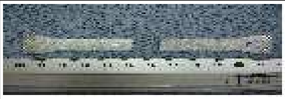
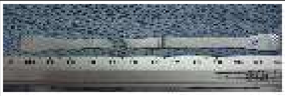
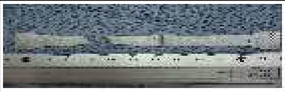
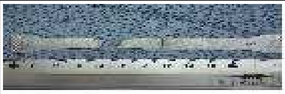


Fig. 4.3 Photo of tensile test equipment



1.2t 1.0t 0.8t

Fig 4.4 The result of tensile test of Hybrid welded joints

No	Thickness	specimen	Strength(Mpa)	parameter	Result
a	1t	**20070905-1-1**	435	**20070705-1-10**	
b	1t	**20070905-1-2**	429	**20070705-1-9**	
c	1t	**20070905-1-3**	321	**20070705-1-8**	
d	1t	**20070905-1-4**	403	**20070705-1-7**	
e	1t	**20070905-1-5**	417	**20070705-1-6**	
f	1.2t	**20070907-1-6**	413	**20070705-1-15**	
g	1.2t	**20070907-1-7**	410	**20070705-1-14**	
h	1.2t	**20070907-1-8**	429	**20070705-1-13**	
i	1.2t	**20070907-1-9**	415	**20070705-1-12**	
j	1.2t	**20070907-1-10**	397	**20070705-1-11**	
k	0.8t	**20070907-1-11**	428	**20070705-1-5**	
l	0.8t	**20070907-1-12**	418	**20070705-1-4**	
m	0.8t	**20070907-1-13**	423	**20070705-1-3**	
n	0.8t	**20070907-1-14**	407	**20070705-1-2**	
o	0.8t	**20070907-1-15**	408	**20070705-1-1**	

CHAPTER 5. Conclusion

In this study, thermal behavior and mechanical characteristics of Pulsed Nd:YAG laser+TIG hybrid welding in Galvanized steel was investigated for improving weldability. And the application in industrial fields has been justified.

1) Compared with laser welding and TIG, penetration depth in laser-arc hybrid welding is increased due to improvement of laser beam absorption. Furthermore, laser beam produces a stabilized arc in hybrid welding

2) In this study, the gap size is almost zero so the laser leading condition for hybrid weld was recommended which usually make better welds than TIG leading

3) TIG welding alone does not become the welding process here due to the lack of filler metal and high welding speed which is caused due to less heat input

4) Only Laser welding alone does not become the welding process here due to the high welding speed and not enough power

5) Hybrid welding does laser independent step multi depth of penetration deeply and also the improvement of welding speed

6) It shows laser welding preparation about 3~4 assignment moral production speed improvements with the hybrid welding hour grade poison, In order to do also Gap confrontation abilities which are a difficult problem of site application maximum anger process variable control method it led and it secured Gap stresses of some

7) After before line laser arriving it removes the defect of the perforation which hinders a bead continuity fume anger and oxidation producer of the zinc and Blow actual condition with the possibility of getting the welding department where it is healthy it was at mouth ten in compliance with a preceding arc

8) Consequently the result which investigates the welding actual condition of the experiment which it sees, after before line laser arriving of the perforation which hinders a bead continuity fume anger and oxidation producer of the zinc and Blow actual condition fault clearance with the possibility of getting the welding department where it is healthy it was it will be able to confirm at mouth ten in compliance with a preceding arc. Also will not control after the post-processing in the welding department and there was a possibility of getting the surface which is beautiful at the degree.

Reference

1. D.A.Jones, N,R. Nair,Electrochemical corrosion studies on zinc coatings on steel, Corrosion 41
2. M.K Budinski, B.E. Wide,An electrochemical criterion for the development of galvanic coating alloly for steel, Corrosion 43
3. K.G. Watins,R,D. jones, K.M.Lo, electrochemical investigation of the corrosion rate of sacrifical coatings on steel, Mater. Lett
4. K.G. Watins,R,D. jones, K.M.Lo, P,G. Beahan, electrochemical investigation of the corrosion rate of 55 aluminium-zinc alloy coated steel Mater. Lett
5. M.k Budinski, Enjoying Materials Properties and Selection, 4th Edition, Prentice-Hall, Englewood Cliffs, NJ,1992
6. M.P,Graham,D,M.Hirak,H.W.Keer,D.C.Weckman, Nd:YAG laser welding of coated steel sheet, J.Laser Appl.6
7. Young-Pyo Kim, "The Study on Mechanical Behavior of Butt Joints in Al-Mg Alloys by Hybrid(CW Nd:YAG Laser+MIG) Welding", Ph.D. Thesis, Chosun University, Korea, February. 2005
8. H.S. Bang and Y.P. Kim. "Fundamental Study on The Heat Input Model of Hybrid Welding for The Finite Element Analysis". Proceeding of the 2003 Autumn Annual Meeting of Korean Welding Society, pp.36~38, 2003.(In Korea)
9. ASM International handbook Vol. 6 Welding, Brazing, and Soldering, pp. 265
10. ASM International handbook Vol. 6 Welding, Brazing, and Soldering, pp. 266
11. Sakae Fujita Science Direction corrosion science 49
12. Nao-Aki Noda Science Direction corrosion science Engineering Failure Analysis

Acknowledgments

저에게 참 으로 즐거웠으며 의미가 있었던 2년이라는 시간이 벌써 지나가고 이렇게 논문에 후기를 쓸 수 있게 된 것이 너무 감개가 무량합니다. 석사 과정이라는 한 계단을 뛰어넘기 위해 과연 난 얼마나 많은 노력을 했는지 계획한 것을 이루지 못한 것은 무엇인지를 다시금 생각하여 이를 토대로 더 한 계단 위로 올라가는 도약에 밑거름으로 삼겠습니다.

저를 낳아주시고 길러주시고 아낌없이 좋은 나무로 성장하기를 불철주야 기도와 사랑으로 감싸주신 아버지, 어머니, 그리고 누나 가족이 있었던 덕분에 이렇게 저의 자아와 싸움에서 이길 수가 있었습니다.

언제나 항상 저의 위치를 깨닫게 해주시고 좋은 길로 따끔한 질책으로 항상 초심에 마음을 잊지 않게 해주신 방한서 교수님께 먼저 깊은 감사의 말씀을 올립니다. 또한 저에게 지도와 관심을 베풀어 주신 윤덕영 교수님, 박제웅 교수님, 이귀주 교수님, 권영섭 교수님, 김도정 교수님, 좌순원 교수님, 방희선 교수님께도 감사드립니다.

또한 연구실에서 좋은 조언을 해주신 종인선배님, 그리고 잔류응력 시편을 자르느라 고생한 창식이 형, 짓궂은 장난도 잘 받아준 주혜, 미비 다들 고맙습니다.

마지막으로 하늘에 계신 하나님께 영광을 드립니다. 부족하지만 이렇게 마음에 중심이 되셔서 지켜주신 주님. 이모든 영광을 주님께 돌립니다.

2007년 12월

김 연 호 올림

저작물 이용 허락서

학 과	선박해양공학	학 번	20067112	과 정	석사
성 명	한글: 김 연 호　한문 : 金 淵 瑚　영문 : Kim Yeon-Ho				
주 소	전북익산시 영등동 제일3차 아파트 501동 704호				
연락처	E-MAIL : gooraa@naver.com				
논문제목	한글 : 하이브리드(Nd:YAG Pulsed laser+TIG) 용접을 이용한 갈바륨 강판의 열적 거동 및 역학적 특성에 관한 연구				
	영문 : A Study on the Mechanical characteristics of Galvanized steel by using Hybrid Method(Pulsed Nd:YAGLaser+TIG)				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

\- 다　　　음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집・형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 또는 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물의 이용허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

2007년 12 월 10 일

저작자: 김 연 호(서명 또는 인)

조선대학교 총장 귀하