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A Study on Thermal and Mechanical Characteristics in Hybrid Fillet Welding (CO_2 Laser+MIG) of Mild Steel

Graduate School of Chosun University

Department of Ship Application and Technology

Cho Sang-Seon

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하이브리드(CO_2 Laser+MIG) 필렛 용접부에 대한 연강의
열적 거동 및 역학적 특성에 관한 연구

February 2008

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Department of Ship Application and
Technology

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A Study on Thermal and Mechanical Characteristics in Hybrid Fillet Welding (CO_2 Laser+MIG) of Mild Steel

Advisor : Professor Han-Sur Bang

A Thesis submitted for the degree of

Master of Engineering

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Technology

Cho Sang-Seon

趙相善의 碩士學位 論文을 認准함

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ABSTRACT

A Study on Thermal and Mechanical characteristics in Hybrid fillet welding (CO_2 Laser+MIG) of Mild steel

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아크 용접은 갭에 대한 대응성, 아크 안정성, 저비용, 경제적 효율성 등 많은 장점을 가지고 있어서 선박 건조 시 주로 사용하는 용접방법이다. 하지만 이러한 많은 장점에도 불구하고 근본적으로 해결하기 힘든 단점을 가지고 있는데, 첫째는 용접 속도에 대한 제한이며, 둘째는 용접 후 변형 발생이다. 속도제한 및 변형 발생은 생산성 저하는 물론이고 공정 지연까지 악영향을 미치고 있어 반드시 해결이 필요한 과제이다. 따라서 본 논문에서는 이에 대한 대책의 일환으로 아크 용접의 장점과 레이저 용접의 장점만을 접목한 레이저-아크 하이브리드 용접기법을 도입하여 비교 평가하고 신뢰성 확보에 대한 연구를 수행하였다. 레이저-아크 하이브리드 용접의 신뢰성 및 건전성 확보를 위하여 실험을 통한 비교분석, 수치해석을 통한 열적 역학적 거동 파악 및 기계적, 금속학적 특성을 파악하였다.

실험 결과 레이저-아크 하이브리드 용접 기법이 기존 아크 용접 대비 초고속 용접(2m/min 이상)이 가능하고 용접 후 나타난 변형량이 약 50% 감소함을 보여주었고, 용접부의 물성은 요구하는 기준을 만족하여 건전하게 나타났다.

추가적으로 시스템 규모나 경제성, 효과 등을 보완 연구하면 레이저-아크 하이브리드 용접이 조선산업 용접에 적용 가능하고, 용접 속도 증가에 따른 생산성 향상, 용접 후 변형 감소에 따른 품질향상, 자동화에 따른 공수 절감등 매우 큰 효과가 있을 것으로 생각된다.

This thesis presents a theoretical and experimental investigation of laser arc hybrid welding. The arc welding is one of the main welding process in shipbuilding, and this process has many merit such as stability of arc, gap bridging, less expensive and economical efficiency etc. But the limited welding speed and angular distortion after welding is inevitable in shipbuilding stage. Especially with the thinner plate which were used as pure car carrier deck in thickness 6 to 15mm had more welding deformation.

Even though the shipbuilders try to increase the productivity and high quality, the deformation caused by arc welding made many problem and low speed decreased the productivity. The manufacturer have to pay additional man-power and man-hour for straightening, which sometimes creates processing problem. To overcome this problem, a distortion control method should be applied to reduce the welding deformation at each welding stage and new welding technology should be applied to increase productivity.

It is necessary to develop the accurate welding method to reduce the welding deformation and to increase the productivity. For this purpose, this paper suggest the laser arc hybrid welding a better method to overcome the problems caused by conventional arc welding. Laser arc hybrid welding was introduced and observed the weldability and feasibility in fillet joints for complementing the disadvantages of conventional arc welding.

The application possibility of laser arc hybrid welding to fillet joints of mild steel are confirmed. The welding speed of laser arc hybrid welding reached up to 2m/min and the welding deformation reduced about 50%. After more comprehensive investigation, It is found that laser arc hybrid welding process could be used successfully in shipbuilding.

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Chapter 1. Introduction

1.1 Backgrounds & Purposes

The arc welding is a main welding process in shipbuilding, and this process has many merit such as stability of arc, gap bridging, less expensive and economical efficiency etc. But the limited welding speed and angular distortion after welding is inevitable in shipbuilding stage. Especially the thinner plate which were used as pure car carrier deck in thickness 6 to 15mm had more welding deformation.

Even though the ship builders try to increase the productivity and high quality, the deformation made many problem and low speed decreased the productivity. The manufacturer have to pay additional man-power and man-hour for straightening, sometimes it creates processing problem. To overcome this problem, a distortion control method should be applied to reduce the welding deformation at each welding stage and new welding technology should be applied to increase productivity.

At present, korean shipbuilding industries are best in word wide but there are many competitors such as japan, china and european shipbuilders. To keep the head, it is necessary to develop new welding technology in manufacturing of ship structure. In this study, new welding technology is introduced to substitute conventional arc welding which produced welding deformation.

It is necessary to develop the accurate welding method to reduce the welding deformation and to increase the productivity. For this purpose, this paper suggest the laser arc hybrid welding instead of conventional arc welding. Laser arc hybrid welding was introduced and observed the weldability and feasibility in fillet joints for complementing the disadvantages of conventional arc welding. The steels were fillet jointed by CO_2 laser+MIG hybrid welding. The fillet joint of welding consists about 80% of total weld joint in ship.

In this study, firstly characteristics of thermal distribution and residual stress distribution in weldment by hybrid welding were surveyed using numerical analysis. Secondly the optimum parameters of hybrid welding were determined based on experiments. And mechanical testing and residual stress measurement were carried out and compared with the numerical analysis.

One of the remarkable characteristics of laser welding is the narrow and deep configuration of the weld. This narrow weld is the result of the high energy concentration of the process and the high welding speed which result in a low heat input into the workpiece. Several applications take advantage of this narrow weld characteristic and high speed processing, but for a lot of other applications the laser process is too expensive and its narrow weld leads to some difficult metallurgical and fit-up problems. To avoid these problems a hybrid welding technique has been developed which combines the laser welding process with an arc process.

In laser arc hybrid welding, a laser is combined to an arc process. This combination allows us to benefit from the advantages of both processes. The laser beam offers the possibility of producing deeper welds in one pass, whereas the arc energy is used to increase welding speed and to fill the fit-up defects between the pieces to be joined.

Laser welding involves focusing the beam of a high power laser on the joint between two work pieces. This high energy concentration produces a weld with a high depth to width ratio and with minimal thermal distortion. The process is also quite fast, which is of interest when looking at productivity. But this deep and narrow shape of the weld, which has many advantages, is also one of the main drawbacks to the process because it requires careful and accurate machining and positioning of the work pieces.

Arc welding is a welding process based on the creation of an electrical arc between a welding torch and the workpiece. Heat is transferred to the workpiece through a plasma. The intensity of the power input is lower than laser welding and this process produces a weld of small depth and medium width. The welding speed is also lower than the one provided by the laser process and this can result in some distortion of the workpiece, which often needs to be corrected.

The combination of a laser beam and an electric arc can produce welds with many of the technical advantages of those made using just a laser, for example, deep penetration and low distortion. This process where both the laser and arc act in the same melt pool gives higher speeds, with even deeper penetration and greater tolerance to fit-up compared to the laser alone. Laser arc hybrid welding allows high completion rates in comparison with laser processes, with a decrease in the necessary laser power and a clear improvement of the joining process reliability. Laser arc hybrid welding is thus cheaper than laser welding and retains, or even improves the technical benefits of laser welding.

The phenomena and mechanical experiments of laser arc hybrid welding have been researched several institute for a long time. On the other hands the laser arc hybrid welding didn't apply in shipbuilding actually.

So in this study, the characteristics of heat source in laser arc hybrid welding were researched by numerical analysis and compared to experimental results. And also this process will be decided to apply ship fabrication.

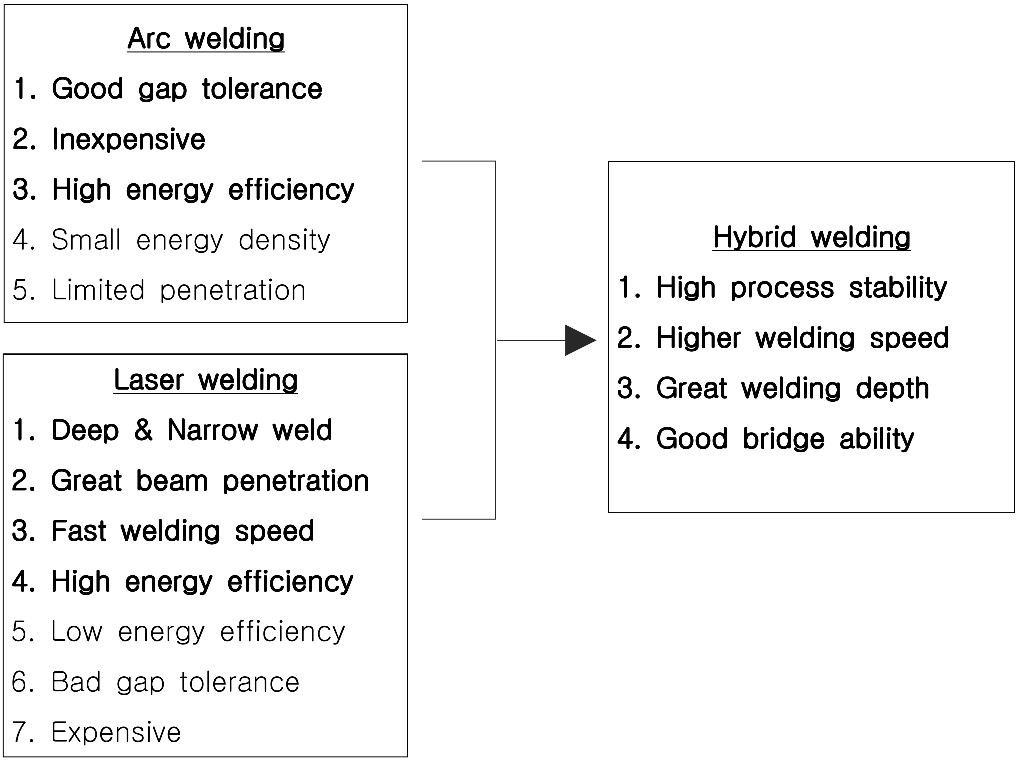


Fig. 1.1 Synergy effects of Laser+Arc hybrid welding process

1.2 Scope of Study

The application of fillet joint in ship building is more to compare butt joints in fabrication of ship. The development of new fillet welding technology affects many merits to shipbuilding. Therefore, in this study, fundamental information about heat source laser arc hybrid fillet welding used for its numerical simulation, and various experiments on laser arc hybrid fillet welding and conventional arc fillet welding have been performed.

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

Analysis of mechanical characteristics will be done between laser arc hybrid welding and conventional arc welding. Also several items which affects to weld soundness and confidence were compared in both welding. Comparison of deformation, welding speed and mechanical properties will be reviewed.

Finally, effect of hybrid welding application in shipbuilding will be reviewed.

Chapter 2. Numerical Simulation of Hybrid Welding

2.1 Theoretical Basis for Analysis

2.1.1 Heat Conduction 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

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

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

2.1.2 Thermo-elastic-plastic Theory

A. Basic theory for thermal stress 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.

$$\{d\varepsilon\} = [B]\{dw\} \tag{2.6}$$

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.

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

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

$$\{d\sigma\} = [D]\{d\varepsilon - d\varepsilon_0\} \tag{2.8}$$

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

$$\{d\varepsilon_0\} = \{d\varepsilon^T\} = \{\alpha\}dT \tag{2.9}$$

Using this relation, the increment of stress, equation (2.8), can be rewritten in the following form.

$$\{d\sigma\} = [D]\{d\varepsilon\} - [C]dT \tag{2.10}$$

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.

$$\begin{aligned}\{dF\} &= \int [B]^T[D]\{d\varepsilon\}dV - \int [B]^T[C]dTdV \\ &\equiv [K]\{dw\} - \{dL\}\end{aligned} \tag{2.11}$$

B. Stress and strain relation dependent upon temperature

1) Stress-strain relation in elastic range

In the elastic range, the increment of total strain consists of increment of elastic strain $\{d\varepsilon^{e}\}$ and the increment of thermal expansion strain $\{d\varepsilon^{T}\}$ as bellows.

$$\{d\varepsilon\} = \{d\varepsilon^{e}\} + \{d\varepsilon^{p}\} \tag{2.12}$$

The increment of thermal expansion strain is expressed using the coefficient of linear expansion.

$$\{d\varepsilon^{T}\} = \{\alpha\} dT \tag{2.13}$$

When the elasticity matrix, $[D^{e}]$, changes as temperature increase, the increment of elastic strain is given in the following form.

$$\begin{aligned}\{d\varepsilon^{e}\} &= [D^{e}]^{-1}\{d\sigma\} + \frac{\partial [D^{e}]^{-1}}{\partial T}\{\sigma\} dT \\ &\equiv \{d\varepsilon^{e'}\} + \{d\varepsilon^{T'}\}\end{aligned} \tag{2.14}$$

2) Stress-strain relation in plastic range

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.

C. Temperature dependency of material properties

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

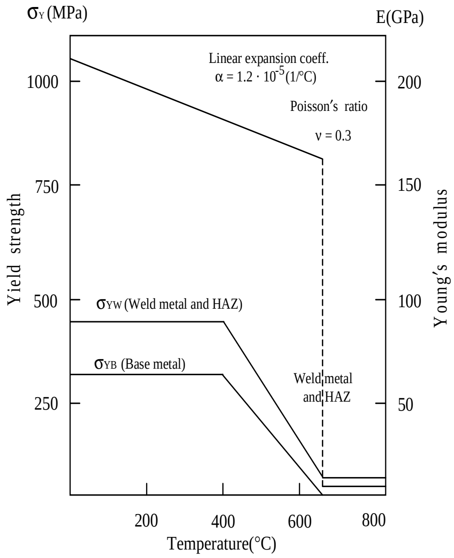


Fig. 2.1 Mechanical properties of A-Grade

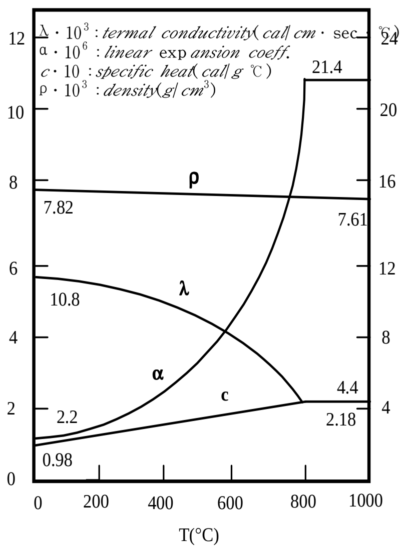


Fig. 2.2 Physical properties of A-Grade

2.2 Analysis Conditions and Finite Element Model

2.2.1 General

Based on basic theory of heat transfer 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 iso-parametric element is used.

Boundary conditions are such that heat transfer 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 elastic-plastic analysis.

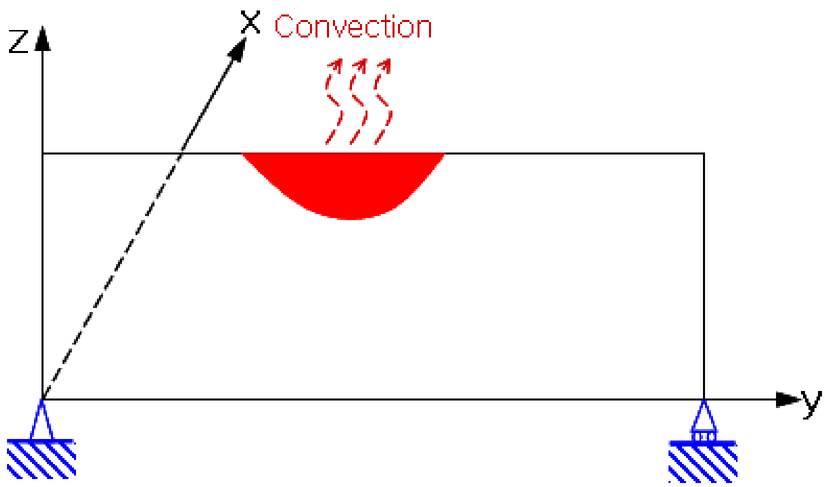


Fig. 2.3 Boundary conditions for heat conduction and thermal elastic-plastic analysis

Nominal dimension of specimen used was taken as 400mm×300mm×6mm ($W \times L \times T$) 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 0.5mm×0.5mm and mesh size gradually increase toward transverse direction.

The total number of element were 3288, and 3608 nodes. Fig. 2.5 shows the mesh division used for the heat transfer and residual stress analysis of laser arc hybrid welding.

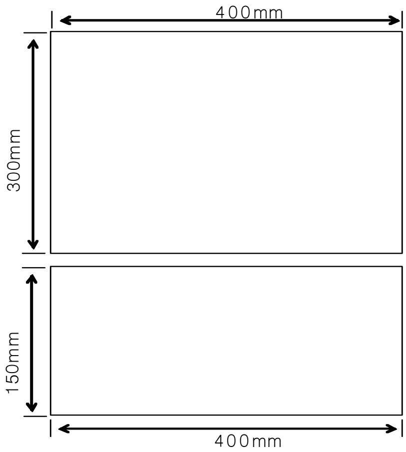


Fig. 2.4 Dimension of specimen for analysis

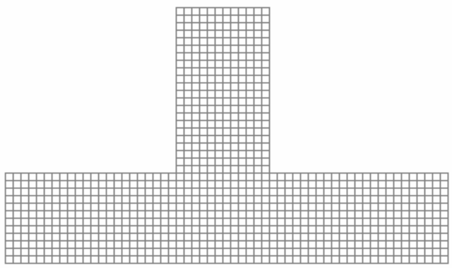


Fig. 2.5 2-D Mesh division of fillet welded specimen by hybrid welding

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 to volume heat source (CASE.2) and volume to 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 laser arc hybrid welding. Fig. 2.7 is schematic diagram of heat source.

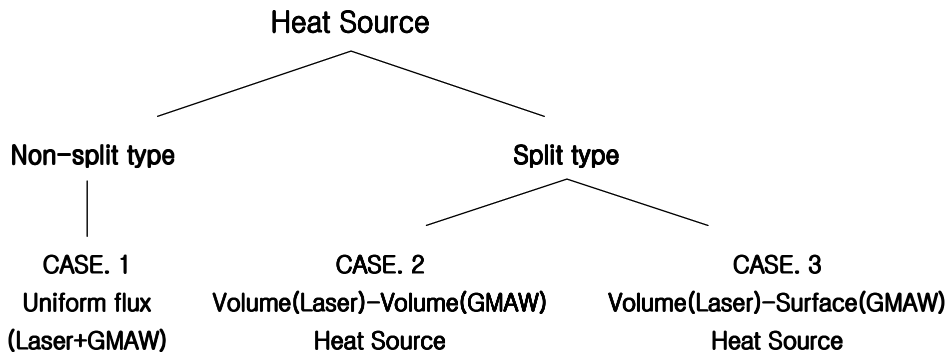
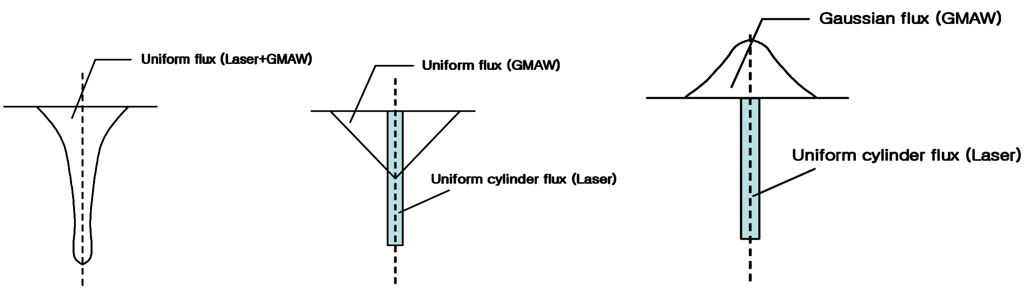


Fig. 2.6 Heat sources for analysis



(1) Volume heat source (2) Volume-Volume heat source (3) Volume-Surface heat source

Fig. 2.7 Schematic diagram of heat source

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

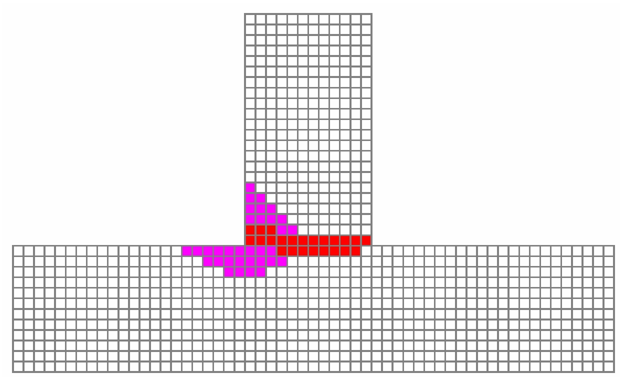


Fig. 2.8 Finite element model of heat source in laser+MIG hybrid welding

2.2.3 Heat input Equation of Heat Source

A. Gas Metal Arc welding

Heat input equation used in numerical simulation of GMAW is,

$$Q = \eta_A \frac{VI}{W_S} \tag{2.42}$$

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 GMAW are shown in Table 2.1. Efficiency of arc welding was 85%.

Table 2.1 Welding conditions for simulation in GMAW

Welding Conditions	Current(A)	Arc voltage(V)	Welding speed (m/min)	Efficiency of arc welding (η_A)
	280A	26V	1.5m/min	85%

B. Laser welding

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

$$Q = \eta_L \frac{P}{W_S} \tag{2.43}$$

where

η_L : Efficiency of laser welding

P : Laser power (kW)

W_S : Welding speed (cm/sec)

Simulation conditions for CO_2 laser are shown in Table 2.2. Efficiency of CO_2 laser welding fixed 35% which was calculated considering total absorption and losses of laser beam.

Table 2.2 Welding conditions for simulation in CO_2 laser

Welding Conditions	Laser power (kW)	Welding speed (m/min)	Efficiency of CO_2 laser welding (η_L)
	8kW	1.5m/min	35%

2.3 Results

2.3.1 Thermal Characteristics in Hybrid Welding

Fig. 2.9 and Fig. 2.10 shows the temperature distribution phenomenon of laser+MIG hybrid fillet weldment and FCAW fillet weldment. The welding heat source penetrates the welds and conducts along the flange and web of workpiece in weldment as a line heat source does. The welding condition applied for simulation is described at Chapter 3.

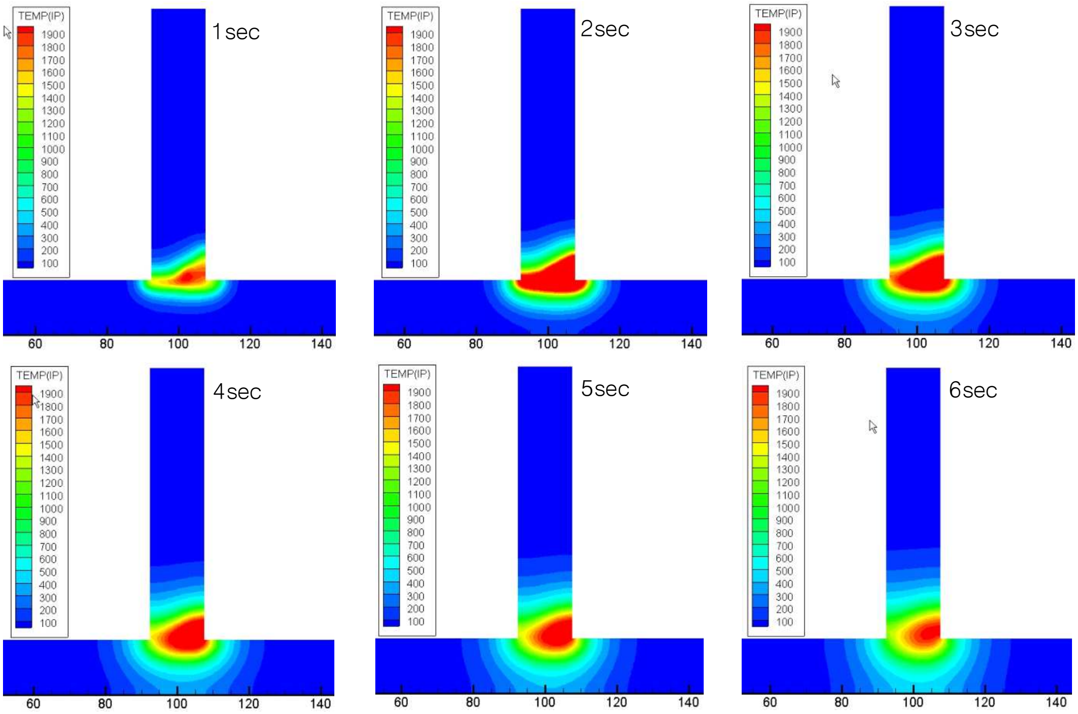


Fig. 2.9 Temperature Contour in Hybrid welding

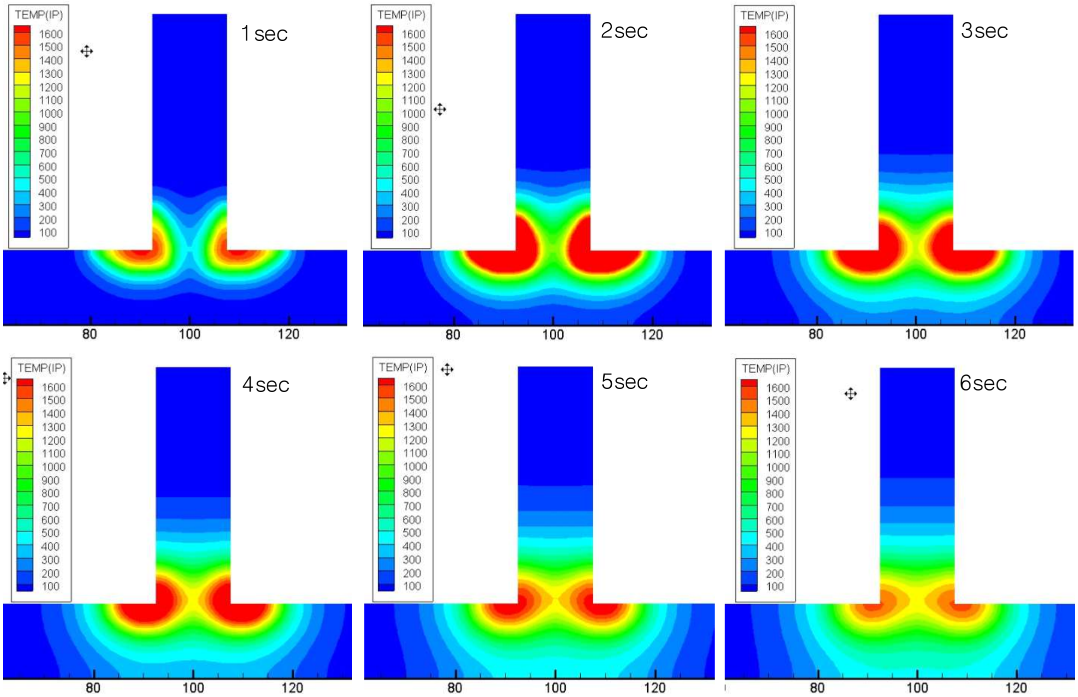


Fig. 2.10 Temperature Contour in FCAW

The welding heat flows into flange and web of workpiece along all the directions uniformly in laser+MIG hybrid fillet weldments and FCAW fillet weldments. Laser+MIG hybrid heat spreads more deeply and narrowly into flange and web of the workpiece. To compare the area of heat distribution between laser+MIG hybrid welding and FCAW, the heat distribution of FCAW are widely spreaded than the laser+MIG hybrid welding. This means that FCAW welding had more heat affected area, so the welding deformation was happened more than laser+MIG hybrid welding.

Fig. 2.11 and Fig. 2.12 describe the temperature increase, decrease and cooling rate in weld metal, heat affected zone and base metal as a function of temperature and time.

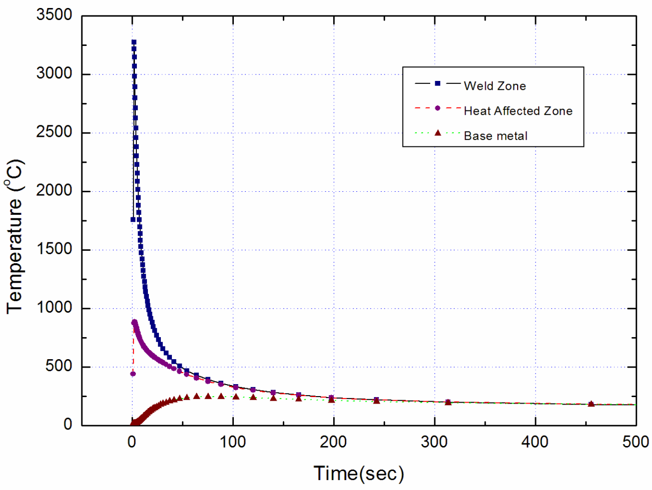


Fig. 2.11 Thermal history of fillet welding in hybrid

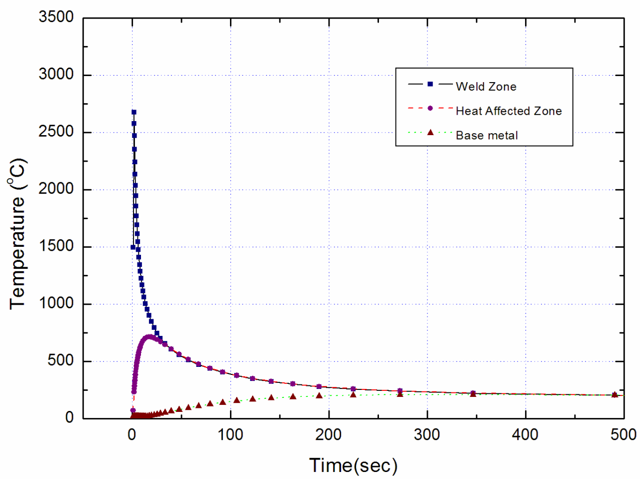


Fig. 2.12 Thermal history of fillet welding in FCAW

From the thermal history curves in both fillet weldments, it can be assumed that the heat generated by welding heat source dissipates at a slightly different rate to the area near the welds. The cooling rate in laser+MIG hybrid fillet weldment is slightly faster than FCAW, so this made the difference of welding deformation.

2.3.2 Mechanical Characteristics in Hybrid Welding

During the welding, the weldment is heated locally by the welding and undergoes temperature change that causes the complex strains. After welding, the residual stresses produced by the strain remains in weldment. This section mainly concentrates on the welding residual stresses caused by welding in laser+MIG hybrid fillet weldments and FCAW fillet weldments, especially, the longitudinal stresses acting parallel to the direction of the weld bead.

In order to analyze the welding residual stresses in laser+MIG hybrid and FCAW fillet weldment using the thermal elastic-plastic numerical simulation program, the following conditions are adopted, and the thermal histories obtained from the heat distribution analysis is used as the input data.

A. The temperature dependencies of mechanical properties (yield stress, Young's thermal expansion coefficient) of mild steels are considered.
B. The solid is isotropic media.
C. The plane deformation (plane stress, plane strain) is assumed in weldment for the two-dimensional thermal elastic-plastic analysis.

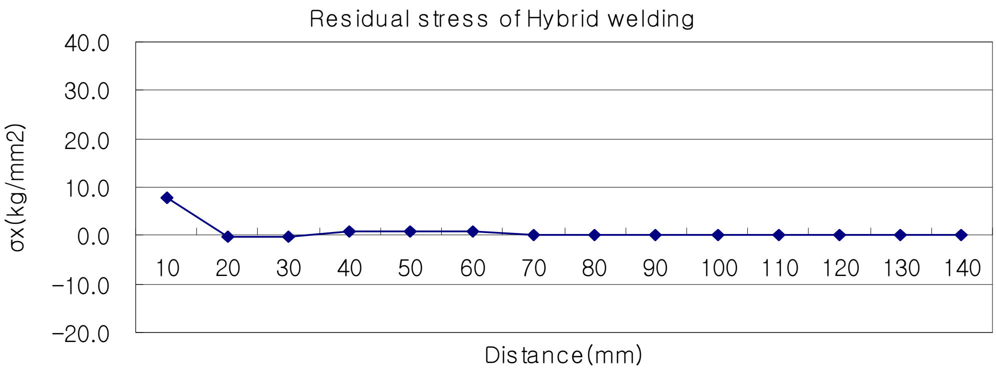


Fig. 2.13 Experimental results of residual stress in hybrid welding

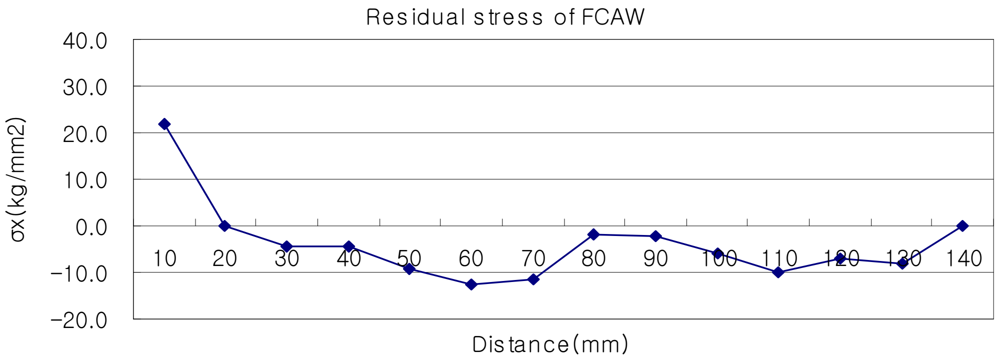


Fig. 2.14 Experimental results of residual stress in FCAW

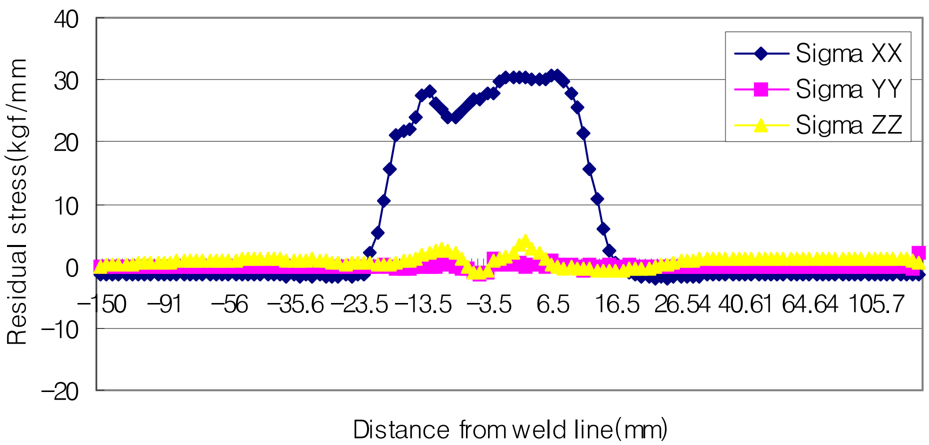


Fig. 2.15 Numerical results of residual stress in hybrid welding

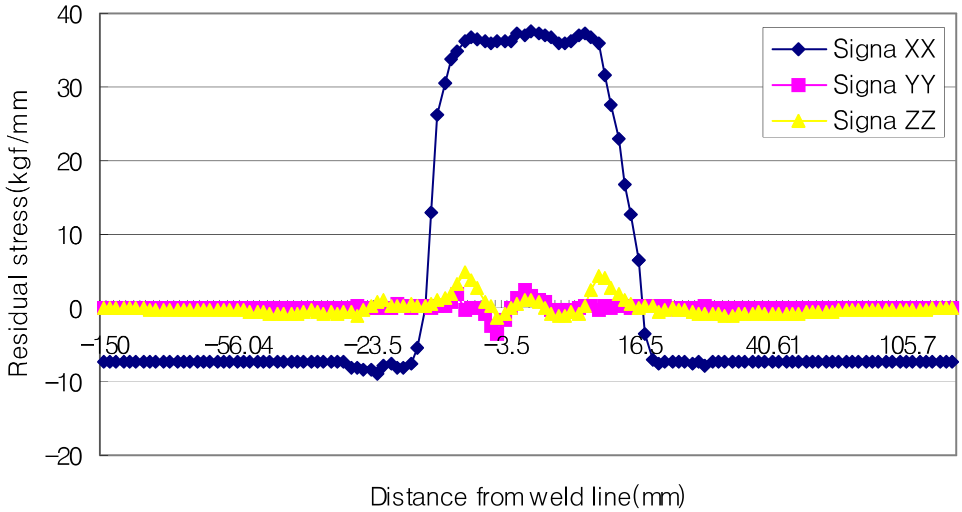


Fig. 2.16 Numerical results of residual stress in FCAW

Fig. 2.13 and Fig. 2.14 shows the experimental residual stress of laser+MIG hybrid fillet weldment and FCAW fillet weldment. The maximum experimental residual stress along welding direction in hybrid welding is 7.8kg/mm^2 and in case of FCAW fillet welding is 21.7kg/mm^2. The experimental residual stress of conventional arc welding was oserved high. This means that conventional arc welding makes more welding deformation than laser arc hybrid welding.

Fig. 2.15 and Fig. 2.16 shows the results of numerical residual stress. The maximum numerical residual stress in hybrid welding is 30.2kg/mm^2 and in case of FCAW fillet welding is 37.5kg/mm^2. The numerical residual stress of hybrid welding is slightly less than FCAW. This also means that arc welding makes more deformation than hybrid welding.

To compare of experimental and numerical residual stress for confidence, the numerical residual stress is almost similar to experimental residual stress in both welding.

Chapter 3. Hybrid Welding Process and Parameters

3.1 Effect of Welding Process

3.1.1 The Concept

One of the remarkable characteristics of laser welding is the narrow and deep configuration of the weld. This narrow weld is the result of the high energy concentration of the process and the high welding speed which result in a low heat input into the workpiece. Several applications take advantage of this narrow weld characteristic and high speed processing, but for a lot of other applications the laser process is too expensive and its narrow weld leads to some difficult metallurgical and fit-up problems. To avoid these problems a hybrid welding technique has been developed which combines the laser welding process with an arc process, namely laser arc hybrid welding.

In laser arc hybrid welding, a laser (CO_2 or YAG) is combined to an arc process (TIG, MIG, MAG or plasma). This combination allows us to benefit from the advantages of both processes. The laser beam offers the possibility of producing deeper welds in one pass, whereas the arc energy is used to increase welding speed and to fill the fit-up defects between the pieces to be joined.

3.1.2 Laser Welding

Laser welding involves focusing the beam of a high power laser on the joint between two work pieces. Nowadays, the power of these lasers is often in the range of 5-10kW (up to 50kW in some cases) for the CO_2 lasers, and

0.3-3kW (6kW lasers are available) for Nd:YAG lasers. This energy is very concentrated, with an intensity of power input at the weld surface of around 10^6 W/cm^2, which is one of the highest among the different welding processes available. This high energy concentration produces a weld with a high depth to width ratio and with minimal thermal distortion. The process is also quite fast, which is of interest when looking at productivity. But this deep and narrow shape of the weld, which has many advantages, is also one of the main drawbacks to the process because it requires careful and accurate machining and positioning of the work pieces.

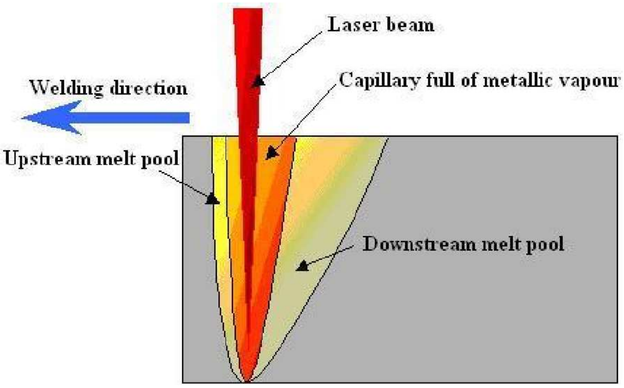


Fig. 3.1 Schematic of the laser welding process

To sum-up, laser welding is an interesting process because of the following advantages:

-Good quality: Narrow, deep weld seam
-High completion rates
-Low consumable costs (no filler required)
-Low but concentrated heat input, which results in low and predictable distortion levels
-Reduced post weld rework
-No mechanical contact between the laser equipment and the workpieces
-Joining of widely dissimilar materials is possible

But laser welding has also some drawbacks which are:

-High cost of equipment and maintenance

-Poor gap bridging ability, which leads to high requirements on joint preparation

-Poor electrical efficiency

-Occasional metallurgical problems due to the high cooling rates

3.1.3 MIG Welding

MIG welding is a welding process based on the creation of an electrical arc between a welding torch and the workpiece. Heat is transferred to the workpiece through a plasma. The intensity of the power input of this process is around 10^3 W/cm^2 (significantly lower than for laser welding), which produces a weld of small depth and medium width. The welding speed is also lower than the one provided by the laser process and this can result in some distortion of the workpiece, which often needs to be machined afterwards. But MIG welding is interesting from an industrial point of view because it has a good bridging ability, the equipment costs are low compared to laser welding, and this process is also very energy efficient (60 to 80%).

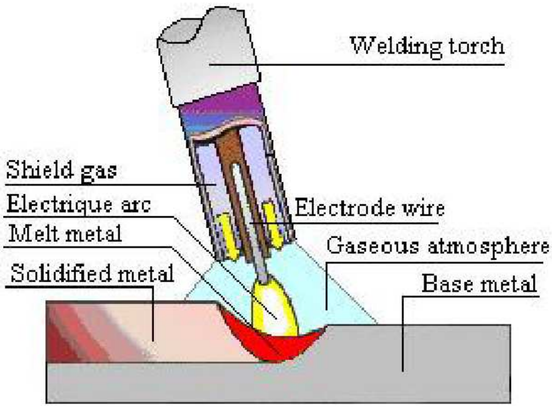


Fig. 3.2 Schematic of the MIG welding process

To sum-up, the main advantages of the MIG welding process are:

-Excellent gap bridging ability, -Low cost of equipment

-High efficiency of the process (60~80%)

But this process has also some drawbacks which are:

-Energy density and welding speed lower compared to laser welding. This causes high heat input to the work and consequent thermal distortions.

-Low speed

3.1.4 Hybrid(Laser+MIG) welding

It has been known for many years that the combination of a laser beam and an electric arc can produce welds with many of the technical advantages of those made using just a laser, for example; deep penetration and low distortion. This process where both the laser and arc act in the same melt pool gives higher speeds, with even deeper penetration and greater tolerance to fit-up compared to the laser alone. Laser+MIG hybrid welding allows high completion rates in comparison with laser processes, with a decrease in the necessary laser power and a clear improvement of the joining process reliability. Laser arc hybrid welding is thus cheaper than laser welding and retains, or even improves the technical benefits of laser welding.

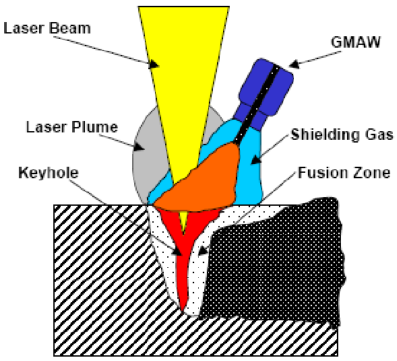


Fig. 3.3 Schematic of the laser+MIG hybrid welding process

Hybrid welding minimizes the drawbacks of both the single laser and the MIG process to obtain an optimized welding technique. The main advantages of laser arc hybrid welding compared to laser welding are:

- Lower capital cost, reduction of 30-40% compared to laser alone due to reduction in laser power requirement
- Higher welding speeds
- Reduction of edge preparation accuracy needs
- Control of seam width
- Control of metallurgical variables through the addition of filler wire
- Less material hardening
- Improved process reliability
- Higher electrical efficiency, up to 50% reduction in power consumption.

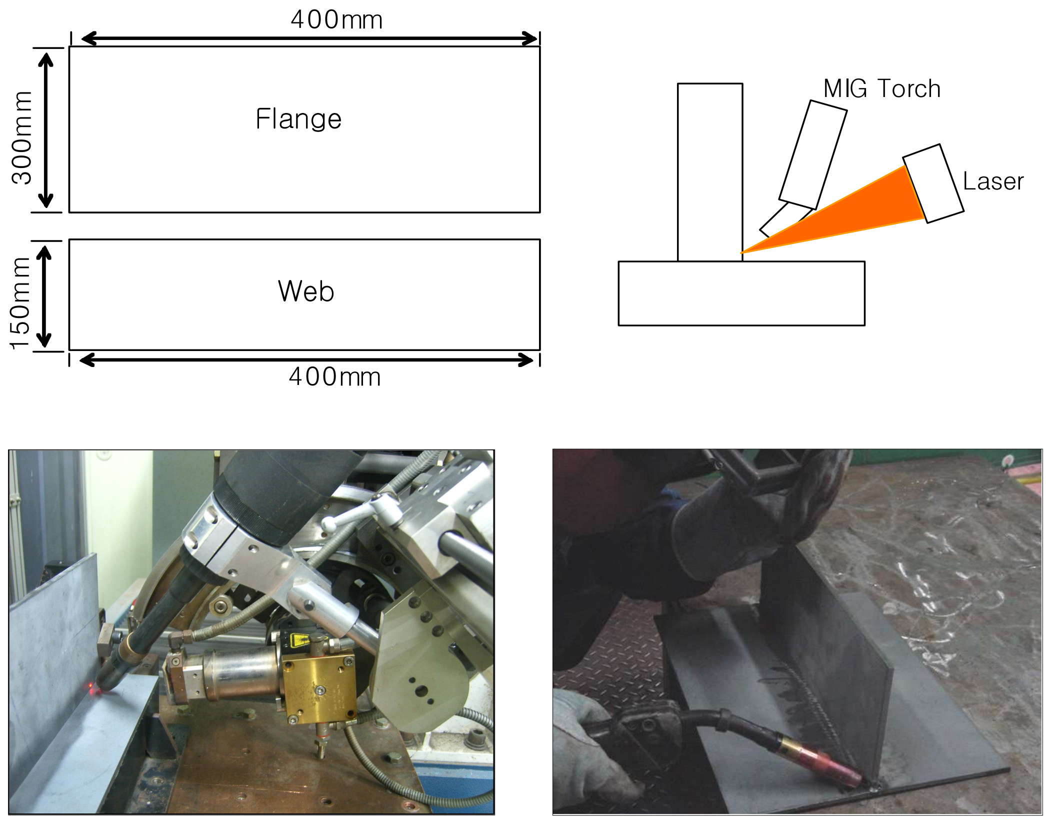
However, a large number of parameters have to be correctly set to achieve these improvements;

- Laser power
- Welding speed
- Relative arrangement of the laser and the MIG torch
- Focal point position
- Angle of electrode
- Shield gas composition
- Power modulation of the arc welding source
- Joint gap
- Edge preparation

3.2 Effect of Welding Parameters

3.2.1 Welding Process

The selected material for this study is A-Grade steel. Experimental set-up for CO_2 Laser+MIG hybrid welding and FCAW are shown Fig 3. 1. The used specimen size is 300mm width and 400mm length & 6mm thickness. The surface of primer was cleaned by brush. The employed welding conditions for CO_2 Laser+MIG hybrid welding and FCAW are shown in Table 3. 1



Hybrid welding FCAW

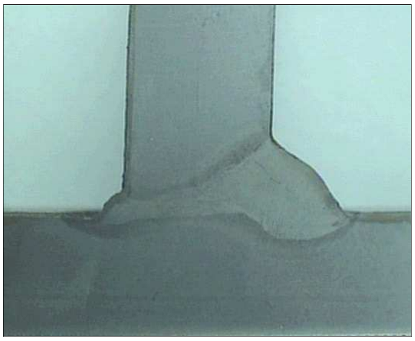
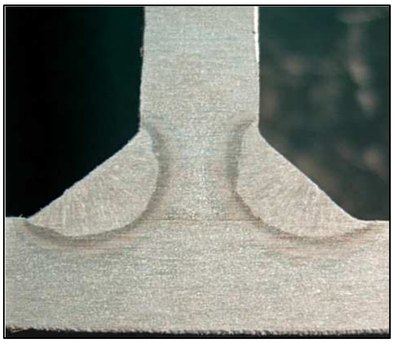
Fig. 3. 4 Principle of experimental set-up for hybrid welding and FCAW

Table. 3. 1 Range of welding parameters

Welding process	Welding condition	Parameters
CO_2 laser	Laser power(kW)	8kW
	Laser head angle	80°
	Defocused depth (mm)	-2mm
	Focal length (mm)	250mm
MIG	Current(A)	280A
	Voltage(v)	26V
	Torch angle	45°
	CTWD	20mm
-Welding speed (m/min) : 1.5m/min -Laser-arc distance : 1.5mm -Shielding gas : He 70% + Ar 18% + CO2 12%		

Welding process	Welding condition	Parameters
FCAW	Current(A)	1850A
	Voltage(v)	23V
	Torch angle	45°
	CTWD	20mm
-Welding speed (m/min) : 0.45m/min -Shielding gas : CO2 100%		

Fig. 3. 5 Cross section of welding process

Process	Hybrid Welding	FCAW
Cross section		

3.2.2 Focusing position

There are many parameters for set up the hybrid welding. One of important parameters is laser focusing position. Experimental set-up for focusing position was shown Fig 3.6. The employed welding conditions for laser arc hybrid welding are shown in Table 3. 2. Fig. 3.7 shows the bead appearance of surface and root for focus and Fig. 3.8 shows the cross section for focus.

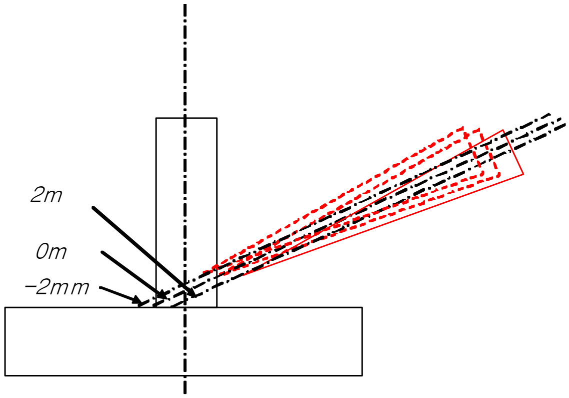


Fig. 3.6 Experimental set-up for focus

Table. 3.2 Range of welding parameters for focus

Welding process	Welding condition	Parameters
CO_2 laser	Laser power(kW)	8kW
	Laser head angle	80°
	Defocused depth (mm)	-2, 0, 2mm
	Focal length (mm)	250mm
MIG	Current(A)	280A
	Voltage(v)	26V
	Torch angle	45°
	CTWD	20mm
-Welding speed (m/min) : 1.5m/min -Laser-arc distance : 1.5mm -Shielding gas : He 70% + Ar 18% + CO2 12%		

Fig. 3.7 Bead appearance of surface and root for focus

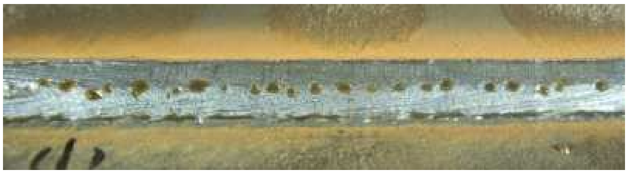
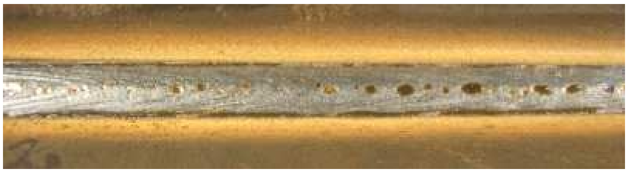
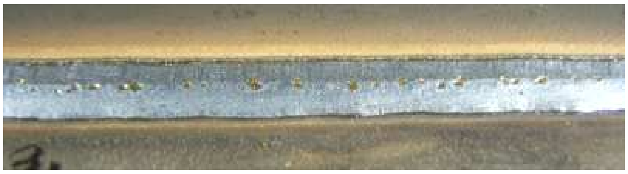
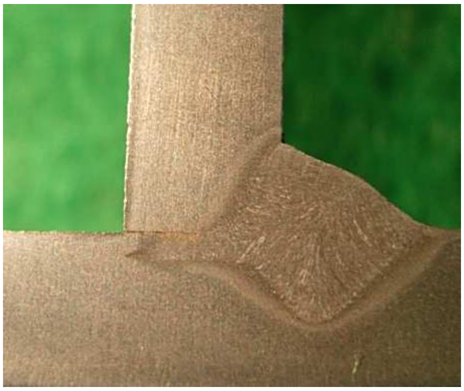
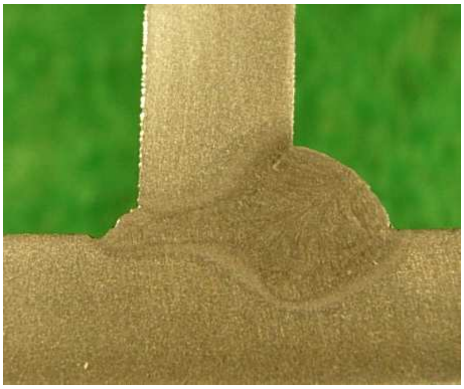
Focus	Position	Bead appearance
F= −2mm	Surface	
	Root	
F= 0mm	Surface	
	Root	
F= 2mm	Surface	
	Root	

Fig. 3.8 Cross section for focus position

Focus	Cross section
F= 2mm	
F= 0mm	
F= -2mm	

3.2.3 Welding speed

For comparison of conventional arc welding, one of special parameters is welding speed. Experimental set-up for welding speed was shown Fig 3.9. The employed welding conditions for hybrid welding are shown in Table 3. 3. Fig. 3.10 shows the bead appearance of surface and root for welding speed, and Fig. 3.11 shows the cross section for welding speed. In test results, it was found that the hybrid welding speed reached up to 2m/min.

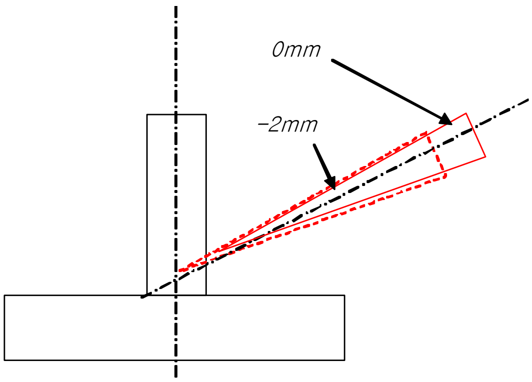


Fig. 3.9 Experimental set-up for welding speed

Table. 3.3 Range of welding parameters for welding speed

Welding process	Welding condition	Parameters
CO_2 laser	Laser power(kW)	8kW
	Laser head angle	80°
	Defocused depth (mm)	-2mm
	Focal length (mm)	250mm
MIG	Current(A)	280A
	Voltage(v)	26V
	Torch angle	45°
	CTWD	20mm
-Welding speed (m/min) : 1.5m/min, 1.8m/min, 2.0m/min -Laser-arc distance : 1.5mm -Shielding gas : He 70% + Ar 18% + CO2 12%		

Figure. 3.10 Bead appearance of surface and root for speed

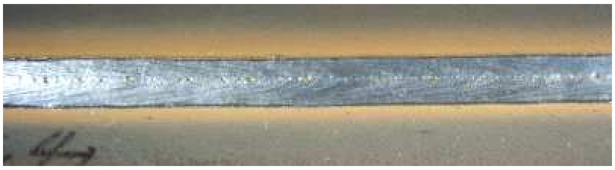
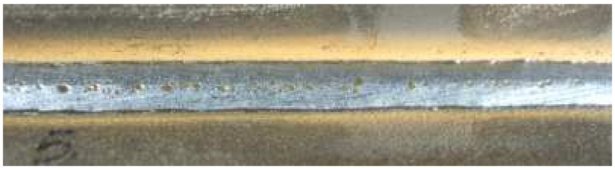
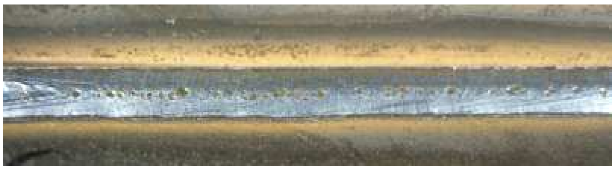
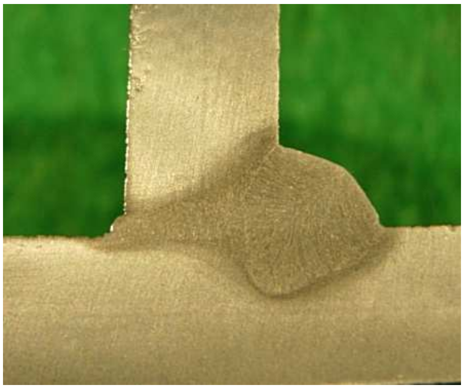
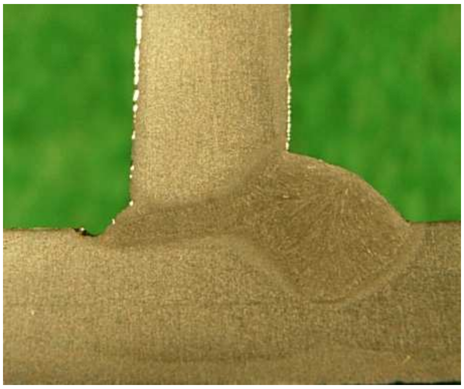
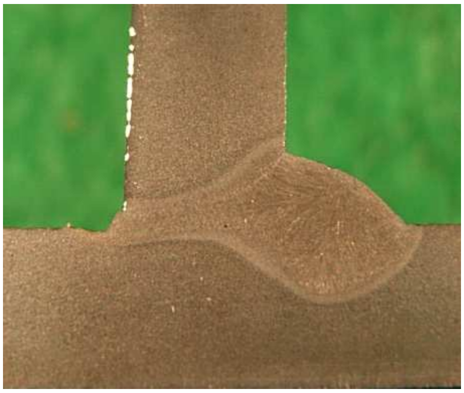
Speed	Position	Bead appearance
V=1.5m/min (P=8kW)	Surface	
	Root	
V=1.8m/min (P=9kW)	Surface	
	Root	
V=2.0m/min (P=10kW)	Surface	
	Root	

Figure. 3. 11 Cross section for welding speed

Speed	Cross section
V=1.5m/min (P=8kW)	
V=1.8m/min (P=9kW)	
V=2.0m/min (P=10kW)	

3.3 Comparison of welding deformation

The angular distortion had happened in both welding process. The distortion angle of laser arc hybrid welding is 0.76° and maximum distortion height is 2mm. The distortion angle of FCAW welding is 1.53° and maximum distortion height is 4mm. The laser arc hybrid welding's distortion angle and maximum distortion height is less about 50% than FCAW welding's. This means that the laser arc hybrid welding make less distortion because of parameters like as less heat input and fast welding speed.

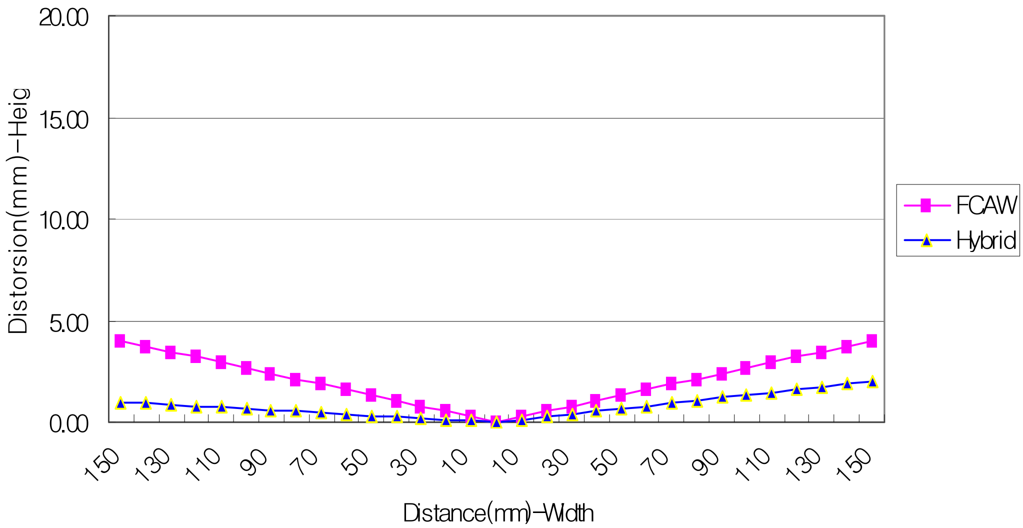


Fig. 3.12 Comparison of welding deformation

Chapter 4. Mechanical and Metallugical Characteristics

4.1 Hardness Test

A micro hardness measurement was made on transverse sections of each weldments. A load of 10kg and a spacing of 0.5mm between the indentations were used in 1mm below of top surface. Measured values of each welds are shown Fig.4.1, 4.2, and 4.3.

Fig. 4.1 Hardness values in FCAW

Fig. 4.2 Hardness values in GMAW

Fig. 4.3 Hardness values in Hybrid(Laser) Welding

From the test result of hardness shown in above figures, it is understand that the hardness of heat affected zone in arc welding has the highest value than other areas. Hardness value of the weld metal in arc welding has the intermediate value between heat affected zone and base metal. But in laser welding, it is understand that the hardness of weld metal has the highest value than other areas.

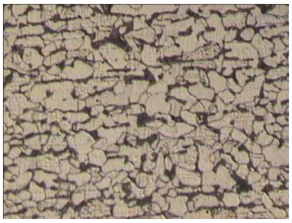
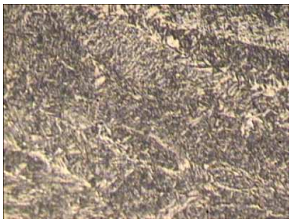
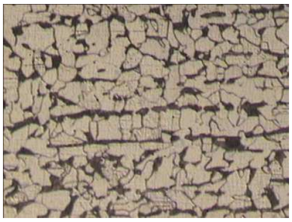
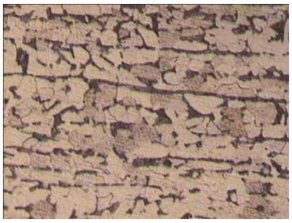
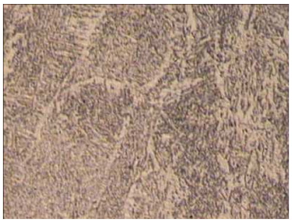
Comparing the hardness value of each welding process in weld metal and heat affected zone, the hardness of laser welds shows slightly lower value between 190Hv and 230Hv. In the case of GMAW and FCAW welding, the hardness value is formed between 200Hv and 240Hv. The difference of hardness value in both welding is small, that is, the hardness value of hybrid welding process shows the similar value to GMAW and FCAW process. It is known that strength of metal has the relation being proportional with the hardness value. Therefore, it can be estimated that the strength of the hybrid welding and FCAW is similar. This means that the soundness of hybrid welding is same level of conventional arc welding.

4.2 Metallurgical Characteristics

In general, microstructure in weld metal are affected by solidification rate that depends on the welding process. Also, heat input and molten metal follow in weld pool is varied according to the welding process. Higher rates of solidification generally produce finer microstructure with strength increase.

The specimens for optical microscopy were prepared using standard metallographic techniques for carbon steel. Transverse sections were etched 3% HNO_3 in order to observe the microstructure of the weldments using the optical microscope. Microstructures in welds and HAZ are shown in Fig. 4.4.

Fig. 4. 4 Microstructure in welds, HAZ and Base metal

Process	Base metal	HAZ	Weld Metal
Hybrid (Laser)			
Hybrid (MIG)			
FCAW			

The microstructure of base metal consists of ferrite and pearlite banded structure. It shows a typically as-rolled carbon steel plate structure.

In the case of microstructure in heat affected zone, the grain growth is observed with recrystallization in all the specimen. Further coarsening of microstructure is occurred in bond by growth of the grains adjacent to the weld fusion line in both welding.

In the case of microstructure in weld metal of laser+arc hybrid welding, the lath martensite structure is appeared, this microstructure were shown in normal carbon steel weld metal. The microstructure of FCAW also shows the lath martensite structure. This means that the microstructure of both welding were created same pattern, so the mechanical properties of both welding are similar.

Chapter 5. Conclusion

In this study, laser+MIG hybrid fillet welding process was developed for shipbuilding application using carbon mild steel. Fundamental welding phenomena of hybrid process using CO_2 laser and MIG was investigated by the experiments. In order to calculate temperature and residual stress distribution in laser+arc hybrid welding, finite element heat source model was developed on the basis of experiment results and characteristics of temperature and residual stress distribution in hybrid welding were understood from the result of simulation. Mechanical and metallurgical characteristics of hybrid welding were also analysed and compared with conventional arc welding in order to supply the fundamental information for the criteria of welding construction.

From this study, the following conclusions can be drawn:

1) As a result of this study, optimum welding condition was determined by experiments. The optimum welding conditions were as follows: laser power 8kW, arc current 280A, arc voltage 26V, welding speed 1.5m/min and 0.5mm gap tolerance. Also these conditions were obtained in arc leading case. And if the laser power is higher than 8kW, the speed could be further increased up to 2.0m/min.

2) Heat transfer and temperature history could be predicted by numerical simulation using FEM. Combination heat source model of split type (volume by GMAW and volume by CO_2 laser) has been considered to analyze the heat source of hybrid welding.

3) Thermal history with temperature gradient has been obtained from the numerical simulation results. This phenomena can be explained by laser welding which has a higher cooling time compared to arc welding.

4) Numerically determined longitudinal residual stress has been compared to experimentally determined residual stress of hybrid welding. It was confirmed that numerical value matched the experimental value.

5) The characteristics of hardness distribution in hybrid welding show the similar value of MIG and arc process. It is known that strength of metal has the relation being proportional with the hardness value. Therefore, it can be estimated that the strength of laser arc hybrid welding is similar of conventional arc welding.

6) The microstructure of base metal consists of ferrite and pearlite banded structure in both. The microstructure of weld metal show the lath martensite respectively in both hybrid welding and FCAW.

7) The angular distortion and deformation of laser+arc hybrid welding is less than conventional arc welding about 50% due to less heat input and less residual stress.

After more comprehensive investigation, It is found that hybrid laser arc welding process could be used successfully in shipbuilding.

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감사합니다.

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조 상 선 올림