Development of High Power Laser Pipe Welding Process

by Moriaki ONO**, Tsuyoshi SHIOZAKI**, Yukio SHINBO**, Yukio SEKINE***, Ken-ichi IWASAKI***
and Masanobu TAKAHASHI***

Abstract

The world's first 25 kW laser welding machines at its 24-inch pipe mill has been installed. The technology for the high-power laser pipe welding process that assures welds with the same properties as those of the base metal while maintaining high productivity has been started to develop. Key technologies for this process such as high power laser welding, high-accuracy seam tracking and nondestructive inspection have been successfully established. The results obtained are as follows.

- (1) The productivity of this process is much higher than conventional fusion weldings, e.g., SAW for less than steel plate 16 mm thick.*
- (2) High energy density of laser beam helps to produce finely distributed oxides.*
- (3) Fine oxide particles with a size of 0.1-0.2 μm were found in weld metal. And they also prevent the heat-affected zones from deteriorating low temperature toughness and so on, a problem that occurs in conventional fusion weldings.*
- (4) The performance of the welds was as sound as the base metal by using the heat treatment process after high-power laser welding.*
- (5) The characteristics of low temperature toughness and SSCC etc. of the laser welds are almost at the same level as the base metal.*

Key words: *High power 25 kW CO₂ laser, Laser pipe welding process, high-accuracy seam tracking, blowhole, squeeze roll, low temperature toughness*

1. Introduction

Laser beam is now drawing attention as a heat source for welding. Laser beam welding (LBW) provides a high energy density, and therefore allows high welding speeds with low heat input. Furthermore, LBW does not generate X-rays, unlike electron beam welding (EBW).

In the steel industry, LBW has been used for manufacturing small diameter stainless steel welded pipes¹⁾, and for welding hot or cold rolled steel sheets in the continuous coil welding lines²⁾. However, only small capacity laser welding equipment of up to 10 kW has been used, and the applications have been limited to welding steel sheet less than 5 mm thick because of technological limitations on laser output power capacity and the need for consistent product quality.

It has often been cited that there were no welding methods in use that provided both high quality welding performance and high productivity. Therefore, the attainment of both has long been a technical challenge in this field. For example, fusion welding methods, such as

submerged arc welding (SAW), tungsten inert gas welding (TIG), and plasma welding method, provide high performance, but the productivity is low.

On the other hand, pressure welding methods, such as electric resistance welding (ERW), yield high productivity, but their application is limited due to the lower qualities of the weld seam.

However, recent technological advances and improvements in laser welding equipment have resulted in high power lasers with outputs of 45 kW. High productivity in combination with high performance is expected by the use of high power lasers.

The world's first 25 kW laser welding machines at its 24-inch pipe mill has been installed. Since then, the technology for the high-power laser pipe welding process that assures welds with the same properties as those of the base metal while maintaining high productivity has been started to develop.

This report presents an outline of the developed laser welding process for pipe production and describes characteristics of the resulting welds.

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2. Configuration and technologies for the HPLW process

2.1 Configuration of HPLW process

An outline of the 25 kW laser pipe welding process is shown in Fig. 1. The on-line pipe manufacturing process consists of tubing, seam tracking, laser welding and continuous heat treatment. The process begins with milling the coil edges. The coil is then continuously rolled into an open pipe by forming rolls (multi-level rolls and squeeze rolls). While the edges of the coil are heated by high frequency current, the seam edge image is detected by an optical seam-tracking device to control the point of laser irradiation. The welds are continuously heat treated after laser welding and bead trimming.

The specifications of the 25 kW laser pipe welding equipment used in the process are listed in Table 1. The new process can manufacture pipes with outside diameters up to 609 mm and wall thickness up to 16 mm. The 25 kW carbon dioxide laser oscillator, which was the world's largest ever used in a commercial manufacturing line, was introduced into the 24-inch pipe mill.

At the same time, a high-accuracy seam-tracking device was added because precise control is required for positioning the point of laser irradiation. In addition, equipment for monitoring welding conditions and for nondestructive inspection of welds was incorporated into the production line to assure consistent product

Fig. 1 Schematic diagram of 25 kW laser welding process.

Table 1 Specifications of 25 kW laser welding equipment.

Size range	Outside diameter max 609mm Wall thickness max 16mm
Variety of products	Carbon steel, High alloyed steel Stainless steel
Laser type, Laser power	CO ₂ laser, Cross flow type max 25kW
Seam tracking	Optical seam tracking system (Dynamic digital analyzing system)

quality.

2.2 Development of technologies for manufacturing laser welded pipe

This section presents the seam tracking device and the laser welding methods that are key technologies for this new process.

2.2.1 Seam tracking device

The laser irradiation point must be controlled very precisely for seam welding of pipes because the laser beam is focused into a spot that is less than 1 mm in diameter. Hence, a highly accurate seam-tracking device was developed that precisely detects the edges of the coil and controls the laser irradiation point.

The image detector for seam tracking consists of a CCD camera and a light source. And it is installed ahead by 100 mm of laser radiation point.

The detector is installed in the gap between the top squeeze rolls, so that the image of the coil edges is taken from above the seam. The seam-tracking device detects movements of the seam position using the image of the edges from the detector and controls the laser radiation point.

Laser radiation point can be controlled according to the signal of movements of the seam position in the range of welding speed up to 30 m/min.

The accuracy of the seam tracking needs to be within 0.1 mm.

An experiment was conducted in which the position of the coil edge was intentionally varied to check the accuracy of the device.

Fig. 2 shows the variations of the detected position of the seam and the actual laser irradiation point as controlled by the seam-tracking device. This result demonstrated that the accuracy of the tracking system is within 0.1 mm. The seam-tracking device was installed in the production line and has operated without any problems.

Fig. 2 Example chart of on-line seam tracking.

2.2.2 Increased welding speed by preheating and other measures

Plasma easily generated by laser beams absorbs the energy of the beam and decreases the amount of energy transferred to the part, reducing the penetration³⁾. Suppression of plasma generation is important for ensuring stable, high welding performance, especially when using lasers greater than 10 kW. Therefore, plasma suppression technology that uses helium gas with an optimized gas flow rate and gas flow angle was developed first. Helium was selected because of its high thermal conductivity and ionization potential. Helium

gas with the flow rate of 100 l/min was supplied from the front side against the laser beam using the copper nozzle with the inner diameter of 8 mm. And Argon gas was supplied as the back shielding gas.

The relationship between the penetration depth and welding speed when using the plasma suppression technology is shown in Fig. 3 for various laser powers. This result is obtained by bead on plate welding test.

For example, a 12 kW laser achieves a 10 mm penetration depth when the welding speed is 2.5 m/min., while a 25 kW laser achieves the same penetration depth at 5 m/min. High-speed welding using the 25 kW laser was confirmed.

Furthermore, the effect of preheating on increasing the welding speed was investigated using pipe fabrication line with the plate thickness of 10 mm carbon steel. Only the edge of the steel plate was heated by the high frequency heat source.

The relationship between the preheat temperature and welding speed to obtain full penetration is shown in Fig. 4. The welding speed for obtaining full penetration increased with increasing preheat temperatures. For example, the welding speed for obtaining full penetration at a preheat temperature of 800°C was about two times that at room temperature.

As for the full penetration weld, the keyhole must pierce to the steel plate.

At the maximum full penetration welding speed, it thinks that the keyhole diameter at the bottom of steel plate is constant approximately and experimentally the weld shape is approximately constant in spite of preheating temperature.

Melting efficiency η_M at the maximum full penetration welding speed is about 0.483 according to Wells's approximate analysis⁵⁾.

In the case of Q : welding heat input (J/cm), T_M : melting temperature (°C), V_{FP} : full penetration welding speed (cm/s), W : width of weld metal (cm), K : heat conduction rate (J/°C.s.cm) and k : heat diffusion rate (cm²/s), Wells gave the following formula of melting efficiency η_M .

$$Q = 8KT_M(0.2 + V_{FP}W/4k) \quad (1)$$

And melting efficiency η_M is shown at the ratio of the heat capacity which is necessary to form the molten metal to the welding heat input and becomes formula (2).

$$\eta_M = \{SV_{FP}\rho[c(T_M - T_0) + H_L]\} / \alpha Q \quad (2)$$

α : laser beam absorption rate, S : area of weld metal (cm²), c : specific heat (J/°C.g), ρ : density of molten metal (g/cm³), H_L : melting latent heat (J/g).

Fig. 3 Relation between welding speed and penetration depth at various laser powers.

Fig. 4 Increase in maximum welding speed for full penetration as a function of preheat temperature.

In the case of $M=1/\eta_M$, formula (3) is shown from formulas (1) and (2).

$$M=1/\eta_M=2[1/5(V_{FP}W/4k)+1] \quad (3)$$

Because the laser welding speed is much higher than the arc welding speed, M becomes about 2 in the formula (3). And melting efficiency η_M becomes about 0.5.

Therefore, full penetration welding speed ratio (V_P/V_R) of preheating temperature T_P to room temperature T_R is shown below from the formula (2) when supposing $(T_M - T_0) + H_L \doteq c(T_M - T_0)$.

V_P shows the full penetration welding speed of preheating temperature T_P , and V_R shows full penetration welding speed of room temperature T_R .

$$V_P/V_R = (T_M - T_R)/(T_M - T_P) \quad (4)$$

The value calculated by the formula (4) is shown in Fig. 4. The experimental and the calculated values agree approximately.

The effect of preheating on increasing the welding speed is estimated by the simple formula which is shown at the ratio of temperature difference $\Delta T (=T_M - T_P)$.

Fig. 5 shows the relationship between welding speed and plate thickness for various pipe welding processes and compares their productivity. For steel plate over 15 mm thick, the LBW welding speed without preheating was the same as that for SAW.

On the other hand, for steel plate less than 15 mm thick, laser welding speeds with preheating were more than three times faster than SAW, and the LBW welding speed increased rapidly with decreasing thickness.

Fig. 5 Comparison of productivity of various fusion welding methods.

2.2.3 Weld defect suppression technology

Because laser beams have the same high energy density as electron beams, the mechanism of laser weld formation is thought to be the same as that of electron beam weld formation as follows³. When the laser beam irradiates a steel sheet, it evaporates metal and momentarily forms cavities. Molten metal around the cavities fill them up and solidifies very rapidly as the beam moves. Therefore, blowholes are easily generated in LBW and EBW⁴. It has been pointed out that blowholes are also generated by the reaction between the molten metal and the atmosphere surrounding the weld pool.

The extent of blowholes varies with the type of shielding gas.

In this case, shielding gas means back shielding. Without back shielding gas, oxygen from the atmosphere combines with carbon in the molten metal, bubbling out as carbon monoxide and resulting in entrapped blowholes. With nitrogen shielding, blowholes are generated by the difference in nitrogen solubility between the solid and liquid phases. Argon does not react with the molten metal, and reduces CO generation and the amount of blowholes.

Fig. 6 shows a longitudinal macrosection of a laser weld made on carbon steel with argon back shielding.

Very small blowholes with the diameter of less than 0.1 mm are generated.

Because the blowholes are extremely small, the detection of the gas species in the blowholes is difficult. Gas species in the blowholes were mainly argon. The quality of this weld metal is the most severe B grade in ISO

Fig. 6 Effect of argon shielding on blowhole suppression in longitudinal macrosections of laser weld metal.

standard.

This demonstrated that inert gas back shielding is essential to reduce blowholes when welding carbon steel.

Next, the effect of upsetting by squeeze rolls on the reduction of blowholes was investigated. Strong upsetting is not necessary because LBW is a fusion welding process.

Upsetting position is the same as the position of laser radiation.

Longitudinal and transverse macrosections of the welds were made for tests by weak upsetting in a commercial production line, as shown in Fig. 7.

Macrosections of a bead on plate weld without upsetting is also shown for comparison. Upsetting narrowed the width of the weld, and entrapped blowholes in the solidifying weld were greatly reduced. This result occurs because blowholes are excluded from the weld pool by the force of the squeeze rolls.

Blowholes decrease by upsetting is the reason why the remaining gas of the surface of the steel plate edges was excluded.

These results confirmed that a sound weld could be obtained by optimizing the plasma suppression gas

(helium gas flow rate 100 l/min), back shielding gas (argon gas flow rate 20 l/min) and by using extrusion pressure by squeeze rolls.

3. Characteristics of laser welds

3.1 Welded pipe manufacturing conditions

Hot rolled carbon steel sheet for line pipes was used for the experiments to examine the characteristics of laser welds. Chemical composition and mechanical properties of the steel sheet are listed in Table 2. The welded pipe produced had an outer diameter of 508 mm and wall thickness of 9.5 mm. Pipes were welded with a laser output of 25 kW, welding speed of 7 m/min, plasma suppression gas of helium 100 l/min and back shielding gas of argon 20 l/min.

The welds were quenched and tempered ($970^{\circ}\text{C} \times 10 \text{ sec.} \rightarrow \text{water quench, } 710^{\circ}\text{C} \times 20 \text{ sec.} \rightarrow \text{Air cool}$).

Table 3 lists the tests carried out to examine welds cut from the welded pipes.

Laser weld metals with an oxygen content of 500–800 ppm were made by welding steel plates on which oxidation films were formed in the heat-treatment furnace.

3.2 Experimental results

3.2.1 The quality of weld metal

Fig. 8 shows the range of oxygen content in the various fusion weld metals. The oxygen and nitrogen con-

Fig. 7 Transverse and longitudinal macrosections of laser weld metal with and without upsetting.

Table 2 Chemical composition and mechanical properties of high strength hot rolled carbon steel.

C	Si	Mn	P	S	t	YS	TS	El
					mm	Mpa	Mpa	%
0.04	0.2	1.4	0.01	0.001	9.5	505	586	37.4
Others: V, Ti, Nb, Cu								

Table 3 Evaluation tests.

- (1) Macro, Microscopic examination
- (2) Distribution of oxide inclusions
- (3) Chemical compositions
- (4) Charpy impact test
- (5) SSC test

Sample location	Test conditions				
	Solution	pH	H ₂ S	Temp(°C)	Period(hr)
Weld metal	NACE TM0177	3.25	2694	25.0	720
Base metal	NACE TM0177	3.25	2694	25.0	720

- (6) HIC test

Sample location	Test conditions				
	Solution	pH	H ₂ S	Temp(°C)	Period(hr)
Weld metal	NACE TM0177	2.76	2736	25.0	96
Base metal	NACE TM0177	2.76	2736	25.0	96

Fig. 8 Oxygen contents in weld metals by various fusion welding methods.

tents and the bead configuration of SAW welds are controlled by adjusting the chemical composition of the flux. However, the oxygen content in SAW weld metal sometimes exceeds 200 ppm, depending on the operating conditions. In LBW, the inert gas can be used to protect the weld from deleterious reactions with the atmosphere that surrounds the weld pool, resulting in weld metal as pure as that by TIG.

Accordingly, the oxygen content of the laser weld metal was varied in the range of 20–300 ppm by controlling the manufacturing conditions such as welding speed and preheating temperature.

3.2.2 Microstructure and inclusion distribution in laser weld metal

The microstructure of laser weld metal is shown in Fig. 9.

For weld metal with an oxygen content of 260 ppm, the heat-affected zone can hardly be distinguished from the base metal. The laser weld metal consisted of fine ferrite with a grain size less than 10 μm . The microstructure of weld metal with an oxygen content of 800 ppm consisted of slightly coarse ferrite and upper bainite. Coarse bainite was not generated because the austenite grain size before transformation is small.

Fig. 10 shown SEM images of the inclusion distribution in the various fusion weld metals. Fine inclusions with a size of 0.1–0.2 μm were uniformly distributed in laser weld metal with an oxygen content of 260 ppm.

In general, inclusions with the size of 1–3 μm are

Fig. 9 Influence of oxygen content on weld metal microstructures.

Fig. 10 SEM images of oxide inclusions in laser and SAW weld metals.

observed in carbon steel. So inclusions in the laser weld

metal were approximately one-tenth the size of oxide particles in the base metal.

This is due to the violent agitation and rapid solidification of the molten metal in the weld pool compared to that of their fusion welding processes.

Therefore, most inclusions in the laser weld metal are homogenized and the oxide films generated during preheating are mostly vaporized in LBW and the remaining oxide films are uniformly dispersed in the weld metal.

As plasma suppression gas and back shielding gas, inert gases are used, but an oxidation film is formed by the preheating resulting in increase of oxygen content of the laser weld metal.

The majority of inclusions were larger than $0.2\ \mu\text{m}$, and some inclusions greater than $0.5\ \mu\text{m}$ were observed in weld metal with an oxygen content of 800 ppm.

The reason why the oxide inclusion's size of weld metal with an oxygen content of 800 ppm is much larger than that of weld metal with an oxygen content of 260 ppm is because the number of oxide inclusions of the former is more than that of the latter in the molten metal and the coarse oxide inclusions are formed by condensing these oxide inclusions.

On the other hand, inclusions with a size of $1\text{--}2\ \mu\text{m}$ were observed in the SAW weld metal because the solidification rate of SAW is remarkably slower than that of LBW.

In case of large oxides with the size of more than $1\ \mu\text{m}$, fine ferrite cannot be formed because large oxides don't act as nucleation sites for ferrite.

These results suggest that laser weld metal consists of fine ferrite because fine oxides act as nucleation sites for ferrite during transformation from austenite to ferrite.

3.2.3 Chemical composition of laser weld metal

Fig. 11 shows an EPMA line analysis across the weld

Fig. 11 EPMA line analyses of laser weld metal.

metal. The chemical composition of the laser weld metal did not change from the base metal, as shown in the figure, although it was feared that elements such as Mn would be reduced because of its low melting point and resulting high vapor pressure.

3.2.4 Low temperature toughness of laser weld metal

Charpy impact test results are shown in Fig. 12. Laser weld metal with oxygen contents of 260 ppm and 500 ppm had excellent low temperature toughness with transition temperatures of -100°C and -85°C , respec-

Fig. 12 Low temperature toughness of laser weld metal.

Fig. 13 Effect of oxygen content of laser weld metal on absorbed energy at -50°C .

tively.

The relationship between oxygen content and absorbed energy for laser weld metal at -50°C is shown in Fig. 13

The absorbed energies were compared, taking weld metal with 100 ppm oxygen as the base of 1.0. The low temperature toughness of laser weld metal with an oxygen content of less than 300 ppm was almost the same as that of the base metal. Furthermore, the low temperature toughness of laser weld metal with oxygen contents of more than 300 ppm decreased slowly over a range as the oxygen content increased.

The good low temperature toughness is attributed to the fine oxides (less than $0.2\ \mu\text{m}$) that act as nucleation sites for fine ferrite and that do not act as initiation points for ductile or brittle fracture.

3.2.5 Resistance to sulfide stress corrosion cracking (SSCC) and hydrogen induced cracking (HIC)

The SMYS of laser weld metal was more than 80% in the tension test per NACE TMO177-90 Metcod A. The weld metal performed the same as the base metal in terms of SMYS. This is because inclusions in the weld metal are minute, and there is no irregular metal flow close to the weld. HIC did not occur in the weld metal.

4. Conclusions

The world's first 25 kW laser welding equipment at its 24-inch pipe mill has been installed.

The High power laser welding process has been successfully developed to ensure welds with the same characteristics as those of the base metal, while maintaining high productivity.

(1)The productivity of this process is much higher than conventional fusion weldings, e.g., SAW for less than

steel plate 16 mm thick.

(2)By using the high frequency heating, the weld speed can be remarkably increased.

An increase ratio with full penetration welding speed at preheating temperature T_P to that at the room temperature T_R is given by the following formula.

$$V_P/V_R = (T_M - T_R) / (T_M - T_P)$$

(3)By compressing the weld metal and using back shielding inert gas, the blowhole can be approximately prevented.

(4)High energy density of laser beams helps to produce finely distributed oxides with a size of $0.1\text{--}0.2\ \mu\text{m}$ in weld metal.

(5)The laser weld metal consists of fine ferrite because fine oxides act as nucleation sites for ferrite during transformation from austenite to ferrite.

(6)The performance of the welds was as sound as the base metal by using the heat treatment process after high-power laser welding.

(7)The characteristics of low temperature toughness and SSCC etc. of the laser welds are almost at the same level at the base metal.

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