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Development of 45-kW Laser Welding System for Continuous Finish Rolling

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Abstract

A high power laser welding system for continuous finish-rolling has been developed. Two stabilized 45kW laser oscillators are placed just beside a hot rolling mill. The laser beams propagate about 50m to a flying-welder that comprises a beam focusing head and clampers for fixing the bars. With an automatic mirror alignment system, the laser beam position error is suppressed less than 1mm. This paper also introduces a new laser welding method which uses the laser induced plasma as a secondly heat source to improve the bead depth by about 30% compared to the conventional welding method.

1. Introduction

Lasers were invented about 40 years ago, and their application has rapidly expanded. They are now utilized in a wide variety of fields. Examples of their use can be seen in laser printers and optical fibers in the fields of information processing and optical communication; laser range finders and laser microscopes that have been found to have practical uses in the field of instrumentation; laser scalpels used in medical treatments; and laser cutting and welding in the field of material processing. Laser material processing includes (i) ablation process such as laser cutting, drilling and marking, whereby material is instantaneously vaporized by a high energy density laser beam, (ii) joining process such as welding and soldering, whereby object material is melted and then re-solidified, (iii) surface treatment such as cladding and surface hardening, and (iv) chemical reaction such as laser prototyping and laser deposition. One of the advantages of laser material processing is flexible controllability of irradiation conditions such as wavelength, irradiation time, energy density etc., and different types of lasers such as CO_2 laser[1)], YAG laser[2)], and excimer laser[3)] are selected according to required conditions. Recently 45-kW class CO_2 laser has become available for industrial use[4)], and various development projects to apply CO_2 laser are being promoted making the most of its high power and stability.

Starting with the control of magnetic domains of grain oriented silicon steel and the welding for steel sheets at cold rolling mill, Nippon Steel Corporation has promoted many laser application projects[5, 6)]. Nippon Steel Corporation has lately developed a welding system for continuous finishing-rolling at hot rolling mill. This paper outlines the developed this welding system, including laser oscillators and a long-distance laser beam propagation system, and its welding characteristics.

2. Construction of 45-kW Class Laser Welding System for Full-continuous Hot Strip Mill

The laser welding system for the hot strip mill employs 2 units of 45-kW CO_2 laser oscillators, which is the world's largest class that is presently available for industrial use. The main facilities newly introduced at the revamp for the full-continuous rolling are as follows (see **Fig. 1**):

(i) A coil box: a facility to coil a sheet bar (30 to 40 mm in thickness and at 1,000 to 1,100˚C) coming out from a rough-

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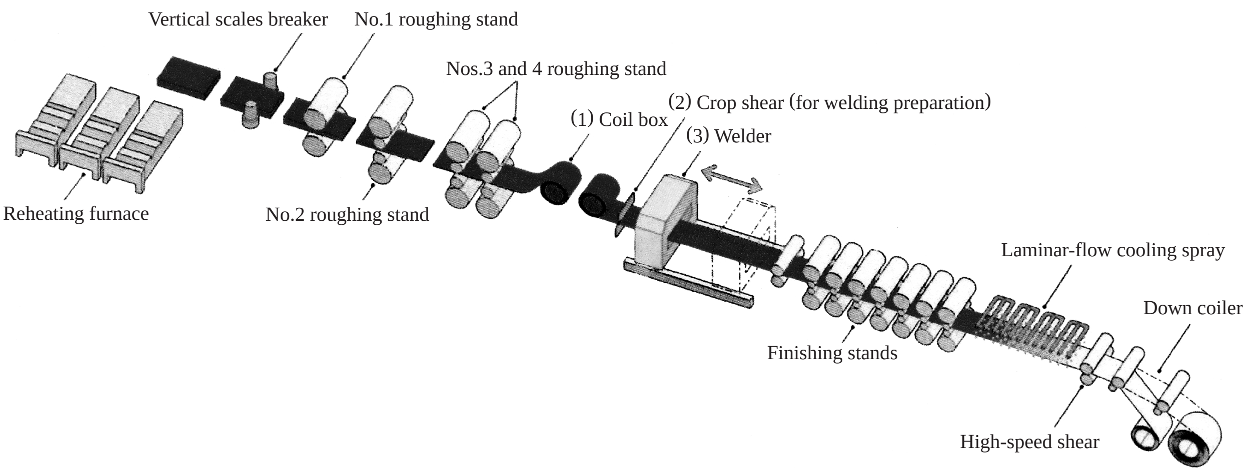

Fig. 1 Outline of 45 kW CO_2 laser welding system for full-continuous rolling of hot strip mill

ing mill stand, hold it at the temperature, and uncoil and feed it to the welder.

(ii) A crop shear: a facility to cut the tail end of a preceding sheet bar and the top end of a following sheet bar to form the required edge shapes for welding.

(iii) A welder: a facility to clamp the tail end of the preceding sheet bar and the top end of the following sheet bar and weld at a welding speed of 3 to 10 m/min. using two laser welding torches that travel orthogonally to the rolling direction of the mill tracking automatically the edges to be welded. The facility is designed to weld while travelling in the rolling direction in synchronization with the entry speed of the sheet bar to the finish rolling mill (up to 90 m/min.).

(iv) Two laser oscillators (not shown in the figure): placed on the ground level on both the sides of the rolling mill line. The laser beams from the oscillators are propagated through expandable wave-guides over a distance of up to 50 m to the welder and irradiated to the edges of the sheet bars to be welded. The bead width is approximately 4 mm, and the penetration depth about 30 mm.

3. Outlines of Laser Oscillators and Laser Beam Propagation and Focusing System

3.1 Laser oscillators

The CO_2 laser oscillators used for the developed system have a rated output of 45 kW (manufactured by Convergent Prima, U.S.A.). Since they were to be used in a high-temperature and high-humidity environment near the hot strip mill, they were installed at the inside of respective compartments that are kept at constant temperatures and humidity. In order to have them work stably around the clock, it was necessary to take measures against the thermal strain that is caused by an electric discharge device and to predict the occurrence of an arc that occur more frequently as the components of the discharge device aged. In consideration of the above, the following measures were taken: (i) as a measure against thermal strain, the capacity of the cooling equipment such as a heat exchanger provided in each of the oscillators was increased to stabilize their output; and (ii) an equipment diagnosis system was set up to monitor the discharge voltage and current on-line. Furthermore, maintenance guidelines were established based on the diagnosis system.

3.2 Laser beam propagation and focusing system

Two laser oscillators were installed one on each side of the mill line, and they were linked to the welder with expandable wave-guides. The laser beams from the oscillators are propagated through them and focused at the sheet bar edges to be welded together (see **Fig. 2**). The inside of the wave-guides is kept clean by blowing dry air continuously.

Laser beam propagation over a maximum distance of 50 m was made possible by providing two concave collimate mirrors at the inside of the wave-guides to control the diameter and divergence angle of the laser beams (see **Fig. 3**).

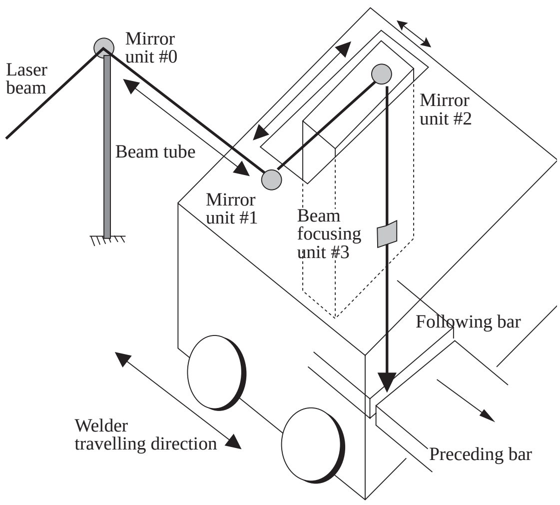

Fig. 2 Schematic view of optical system for laser transmission and condensation

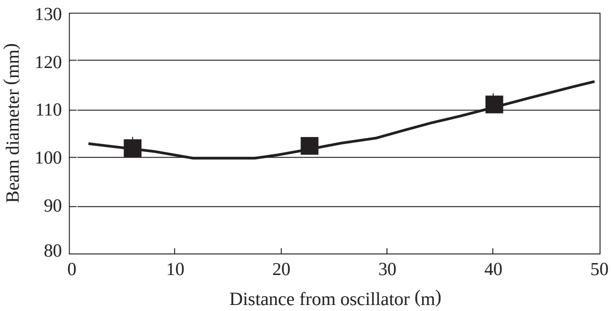

Fig. 3 Laser beam diameter at long-distance transmission

As the fact that using a conventional propagating system, the focusing characteristics of a laser beam changed depending on the propagation distance. The focused diameter by the installed beam propagation system, in contrast, changed the least (the position of 0 mm along the abscissa of **Fig. 4**).

In addition, a beam position stabilizing system was developed, wherein four He-Ne laser beams parallel to the CO_2 laser beam were arranged to surround it. The positional deviation of the He-Ne laser beams was detected and corrected by controlling the angle of the #0 transmission mirror (see **Fig. 5**). In addition to the above, an imaging type seam tracking device as shown in **Fig. 6** was provided to stabilize the beam propagation against the thermal deformation of the system; as a result, the beam tracking error at the butt seam was reduced to ±1 mm or less. **Fig. 7** shows the distribution of the tracking errors of the laser beam in actual welding work under seam tracking control; a result of $3\sigma = 0.33$ mm (n = 1,217) was obtained.

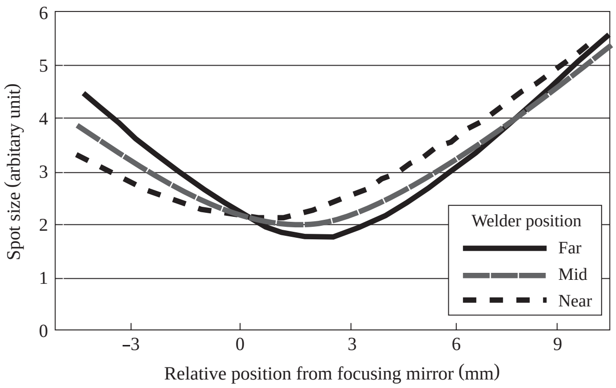

Fig. 4 Beam diameter near focal point at different transmission distances

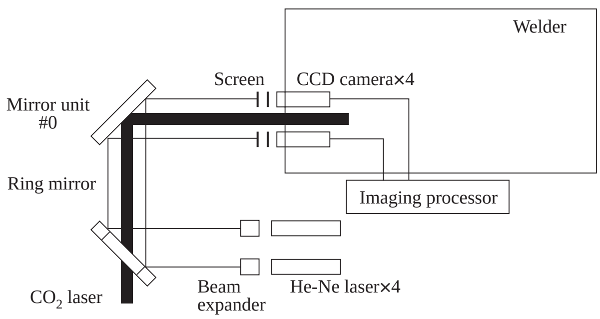

Fig. 5 Beam position stabilizing system

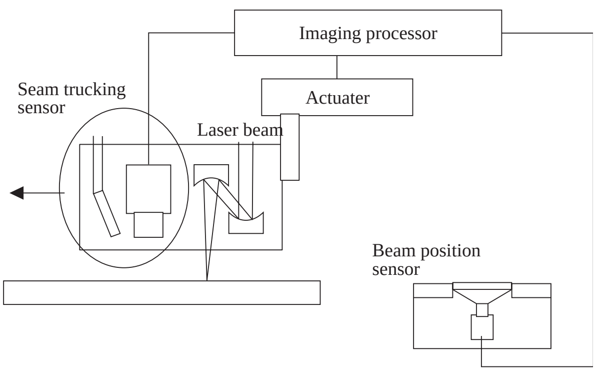

Fig. 6 Imaging type seam tracking device

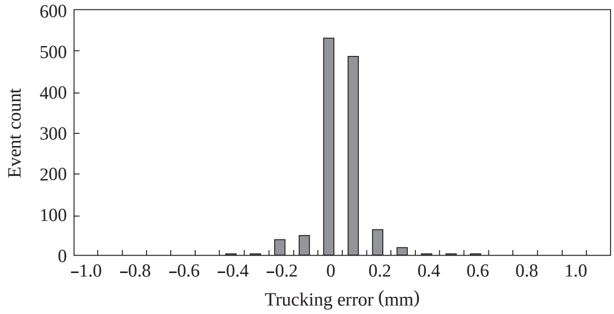

Fig. 7 Evaluation of seam tracking errors

4. Laser Welding Method and Welding Characteristics

4.1 Plasma utilization welding method

It is important in laser welding to control the beam power density at the irradiation point and the laser-induced plasma; it is possible to obtain the desired welding characteristics by adequately controlling these two. Steel easily evaporates and forms plasma during welding, especially when it is welded during hot rolling. This is because its temperature is near the melting point, and the free electron density in the plasma is expected to be higher than in the case of welding at room temperature. In the case especially of welding by CO_2 laser, the absorption of an incident beam due to inverse bremsstrahlung tends to be large[7]. For this reason, there is the fear that the thermal advantage of welding steel materials at high temperature cannot be fully enjoyed if the conditions of laser welding at room temperature are simply applied. In consideration of this, a plasma utilization welding method[8] (hereinafter called the PU welding method) to use the heat of the plasma as a secondary heat source for welding was developed and applied to the welding system.

The principle of the PU welding method is shown in **Fig. 8**. By ordinary laser welding methods, a common practice is that the plasma is strongly blown away by an assist gas that is blown obliquely from the front of the welding direction in order to reduce the absorption of the incident beam by plasma. In the case of welding hot steel materials, however, the free electron density in plasma is increased as stated earlier and as a consequence, the removal of the plasma is insufficient by the above practice. It is difficult to improve thermal efficiency.

By the PU welding method, in contrast, a side nozzle (PU nozzle) for the assist gas is provided rather smaller incident angle at the up-

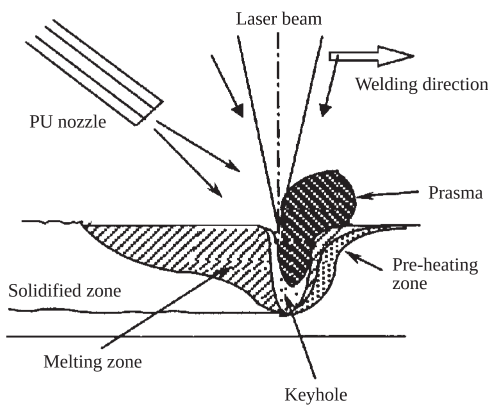

Fig. 8 Principle of plasma utilization welding method

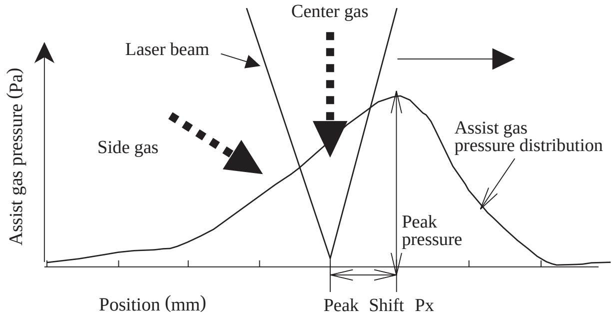

Fig. 9 Distribution of assist gas pressure in PU welding method

per rear of the welding direction and by the combination of the assist gas from the PU nozzle with that blown from a center nozzle provided coaxially with the laser beam, the plasma is pressed to the leading edge of the welding position, as shown in **Fig. 9**. In addition, in the case where a filler wire is used to prevent porosity, it is necessary by common laser welding practices to feed the filler wire to the laser beam irradiation point. However, this significantly deteriorates welding performance. In the PU welding method, in contrast, high-temperature plasma exists in front of the keyhole and the filler wire is melted by the thermal energy of the plasma. Thus, the PU welding method has another advantage that a filler wire can be used without deteriorating welding performance. This advantage is significant especially in welding hot steel materials where oxides are likely to form.

4.2 Welding characteristics

Bead-on-plate tests of the developed laser welding system were carried out using hot specimens of SS400 steel heated to 1,000˚C. A gold-plated parabolic focusing mirror having a focal length of 381 mm (off-axis angle: 22.5˚) was used. Helium was blown as the assist gas through the center and PU nozzles, and the flow rate was set in a range from 60 to 200 l/min. in accordance with the condition of the test described later.

Fig. 10 plots the change of penetration depth versus different shift amounts of the backpressure peak. The peak assist gas pressure was set constantly at 400 Pa, the optimum value defined through a preliminary test. The laser output was 45 kW, the specimen travelling speed 2 m/min., and the out-of-focus amount 0 mm. A maximum penetration depth was obtained at a backpressure peak shift amount of 3 mm. When the backpressure peak position was shifted by 1 mm, the penetration depth decreased by 10% or more. As a result of a comparison of penetration depths changing the back-pressure peak shift amount from the optimum value, the decrease in the penetration depth was found somewhat smaller in the larger shift amount side than in the smaller side. In the smaller backpressure peak shift side, the plasma that remained near the beam focusing point increased and disturbed the irradiated laser beam. In the larger back-pressure peak shift side, on the other hand, the plasma shifted significantly from the weld point and the penetration depth was substantially the same as that in conventional methods. This is presumably because the preheating of the leading edge was decreased.

Fig. 11 shows the behavior of penetration depth in relation to the change of peak pressure; here, the shift amount of the backpressure peak is fixed at 3 mm. The other conditions were the same as in the tests of changing the backpressure peak shift amount described earlier. The penetration depth was the largest at a peak pressure of 400 Pa. When the peak pressure was changed by 100 Pa from the optimum value, the penetration depth decreased by about 5%. The decrease in the penetration depth was smaller in the larger peak pressure side than in the smaller side. The reason for the above is presumed to be that in the smaller peak pressure case, more laser energy was absorbed by the plasma staying on the steel material surface just like the case explained earlier in relation to Fig. 8; in the larger peak pressure case, while the plasma was confined inside the keyhole, the absorption in the upper part of the keyhole increased. Consequently, the sectional width of the bead was larger in the middle and the penetration depth was smaller.

Further tests were carried out at different welding speeds while fixing the conditions of the backpressure peak shift and the peak pressure at the respective optimum values in accordance with the results of Figs. 10 and 11. The behaviors of the penetration depth and the bead width at the tests are shown in **Fig. 12**. A typical cross-sectional bead shape is shown in **Fig. 13**. A maximum penetration depth of 38 mm was obtained at a welding speed of 1 m/min.; the bead width was 4.0 mm under this condition. An increase in penetration depth by about 30% over the welding of cold materials was achieved. By conventional plasma removal methods, the penetration

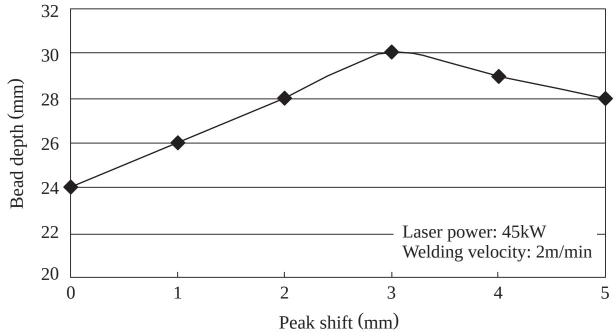

Fig. 10 Penetration depth versus peak position of assist gas pressure

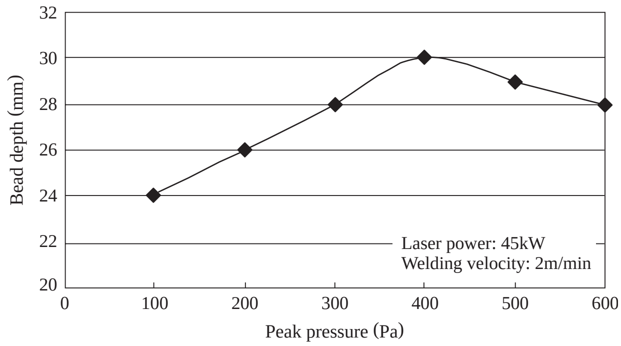

Fig. 11 Penetration depth versus peak pressure of assist gas

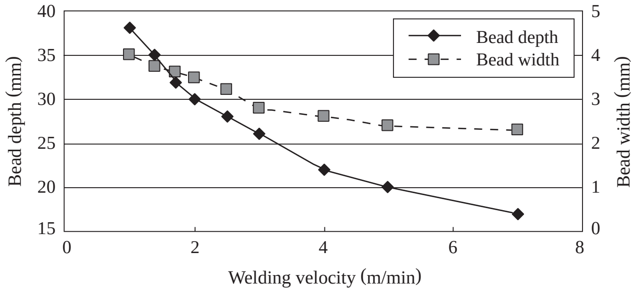

Fig. 12 Evaluation of welding characteristics of 45 kW laser welder

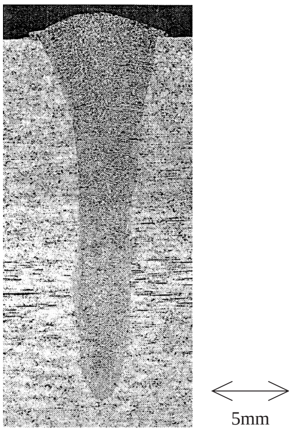

Fig. 13 Cross-section of the laser welded bead (45 kW, 3 m/min)

depth at laser welding of hot steel is nearly the same as or rather smaller than that at welding of cold steel. As stated above, the developed PU welding method proved to be superior to the conventional methods in welding efficiency.

5. Summary

A long-distance laser beam propagation and focusing system and a plasma utilization welding method were developed. Thanks to the developed technologies and stable operation of laser oscillators, a laser welding system operating around the clock has been established and applied to the full-continuous rolling of a hot strip mill. The new welding system was put into commercial operation at the hot strip mill of Nippon Steel's Oita Woks in April, 1998, and as a result, has significantly contributed to the enhancement of productivity of the mill and the shape and gauge accuracy of its products.

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