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Application of High-Power Vacuum Laser Welding Technology to Steel Plate Production Process

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Abstract:

In high-power laser welding of thick steel plates with over 10 kW laser power, problems such as spatter formation during welding and weld failures including underfill sometimes occur. Laser welding, which is generally carried out in the atmosphere, performed in vacuum reduces spatter formation and avoids weld failures. Moreover it increases penetration depth and provides satisfactory welded joints. As an application to fully utilize the advantage of laser welding in vacuum, slab assembly welding technology in a rolled clad plate production process was developed. By applying optimally designed focusing optics to reduce focus shift caused by thermal lens effect, the world-first 30 kW class high-power vacuum laser welding system was installed at the rolled clad plate production line in JFE Steel.

1. Introduction

Laser welding is a welding method in which a laser beam is focused on a small diameter spot and utilized as a high energy density heat source, and has merits such as high speed, deep penetration, and high quality compared with arc welding. Since the first CO_2 laser oscillator with kW class output was put on the market in the 1970s, enhancement of laser oscillator power has advanced, and laser welding has spread to various industrial fields. In the iron and steel manufacturing process, laser welding has been applied to coil build-up welding in continuous cold rolling lines since the latter half of the 1980s[1,2], and CO_2 laser welding with high power of 10 to 45 kW has been applied to welding of steel pipes[3] and welding of sheet bars in hot rolling lines[4]. After 2000, the mainstream of the laser oscillators applied to welding changed from the CO_2 laser as a gas laser to solid-state lasers such as fiber lasers and disk lasers upgrading of laser oscillator power accelerated, and a fiber laser with an output of 100 kW was marketed and its application to the welding was examined[5,6]. Although application of such a high-power laser oscillator to welding was expected to enable deep penetration welding of steel plates of larger plate thickness than before, there were problems related to quality control such as improvement of the peripheral equipment, including an optical system which can withstand the use of a high-power laser, and prevention of welding spatter and defects. For this reason, the applications of laser welders with outputs exceeding 10 kW had been extremely limited.

As a solution to the problems of welding spatter and defects in high-power laser welding, it is known that welding in a vacuum atmosphere is effective[7–9]. In contrast to electron beam welding, which is also a type of high energy beam welding but must be performed under a high vacuum, laser welding was perceived as having the merit of enabling welding in the atmosphere. However, the vacuum laser welding attracted attention as a technology for improving welding quality in high-power laser welding with outputs up to 100 kW. This paper explains the features and merits of high-power vacuum laser welding of thick steel plates, and introduces the development of a clad slab assembly welding technology and the introduction of vacuum laser welding equipment in the hot-rolled clad steel plate manufacturing process as the world's first practical application of vacuum laser welding using a 30 kW class high-

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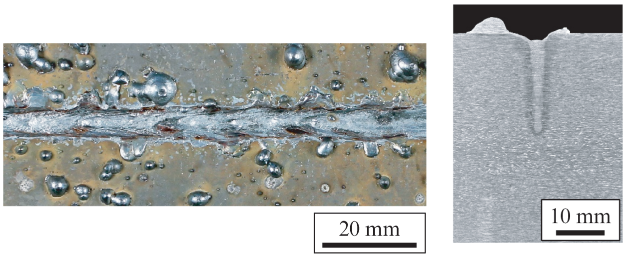
2. Problems of High-Power Laser Welding and Advantages of Vacuum Welding

As an example of high-power fiber laser welding, **Photo 1** shows the result of a melt run of carbon steel (JIS G 3106: SM490B) under the conditions of laser power of 25 kW and a welding speed of 1 m/min[6]. A large amount of spatter can be observed around the weld bead on the plate surface, and observation of the cross-sectional macrostructure confirmed that the underfill at the weld metal surface was defective due to spatter scattering. As illustrated by this example, when deep penetration welding of thick steel plates is carried out in the atmosphere with a high-power laser, a large amount of spattering is formed, as shown in **Photo 2**, because the steel evaporates rapidly immediately under the laser beam irradiation point, and molten metal is scattered by the vapor pressure of the evaporated steel. Since spattering causes welding defects such as underfill of the weld metal, it is very difficult to obtain high quality, defect-free welds in high-power laser welding.

One solution to the problem of spatter generation is to perform high-power laser welding in a vacuum or a reduced pressure atmosphere. In a vacuum, the metal vapor generated by evaporation of the steel is instantaneously diffused without being suppressed by atmospheric pressure, and the vapor pressure does not rapidly rise immediately under laser beam irradiation point. Therefore, spatter scattering by vapor pressure can be suppressed, and good deep penetration welding can be carried out without generating defects such as underfill. As an example of high-power laser welding in a vacuum, **Photo 3** shows the result of a melt run in a chamber with an atmospheric pressure 100 Pa (1/1,000 of atmospheric pressure) under the conditions of fiber laser power of 25 kW and a welding speed of 0.5 m/min. The surface appearance of the weld shows no adhesion of spatter around the weld bead on the plate surface, and observation of the cross-sectional macrostructure confirms that a good quality weld without weld defects such as the underfill can be obtained.

Figure 1 shows a comparison of the penetration depth of carbon steel (JIS G 3106: SM 490 B) in the atmosphere (100 kPa) and in a vacuum (100 Pa) when melt run was performed at a laser power of 10 to 50 kW and a welding speed of 0.5 m/min. Although the penetration depth increased with increasing laser power under both ambient conditions, the penetration depth tended to be larger in vacuum welding than in atmosphere welding. In the atmosphere, even if the laser power is increased 5 times, from 10 kW to 50 kW, the penetration depth increases only 3 times, from about 10 mm to about 30 mm. On the other hand, in vacuum, the ratio of the increase of penetration depth to the increase of laser power is large, and when laser power is increased from 10 kW to 50 kW, i.e., by 5 times, the penetration depth increases from about



(a) Appearance of weld bead surface (b) Cross sectional macrostructure of weld

Photo 1 Example of high-power fiber laser welding (Laser power: 25 kW, Welding speed: 1 m/min, Melt run)

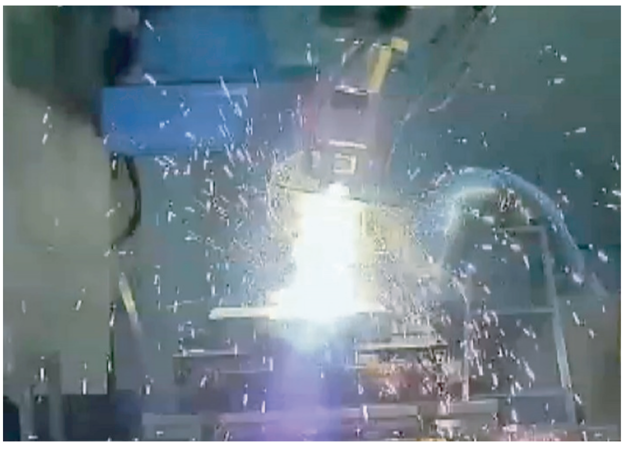
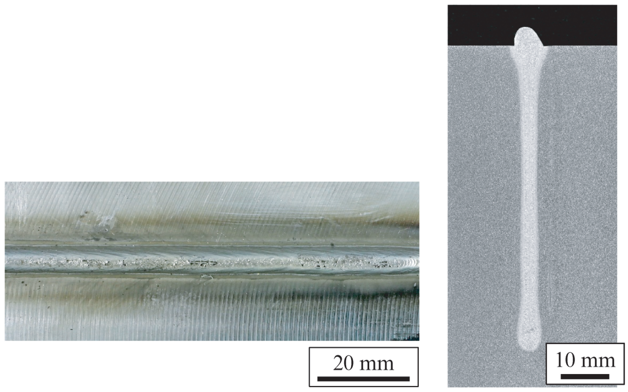


Photo 2 Spatter formation of high-power fiber laser welding



(a) Appearance of weld bead surface (b) Cross sectional macrostructure of weld

Photo 3 Example of high-power fiber laser welding in vacuum (Atmospheric pressure: 100 Pa, Laser power: 25 kW, Welding speed: 0.5 m/min, Melt run)

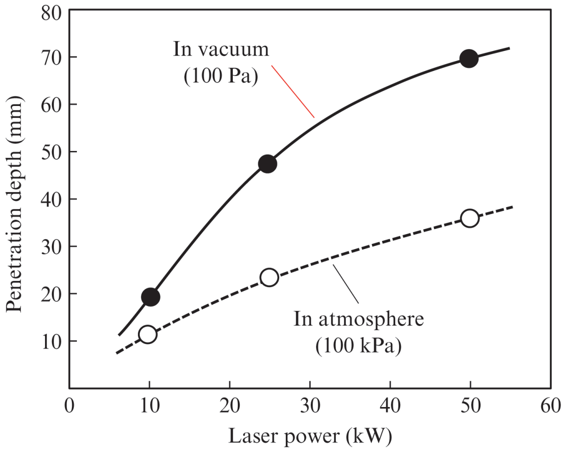


Fig. 1 Comparison of penetration depth of laser welding between in atmosphere and in vacuum (Welding speed: 0.5 m/min, Melt run)

20 mm to about 70 mm, or by 3.5 times. Thus, laser welding in a vacuum achieves a penetration depth more than double that in welding in the atmosphere, and has the merit that high efficiency deep penetration welding of thick plates is possible.

As described above, laser welding in a vacuum can prevent spatter generation, which is a problem in the atmospheric welding, and makes it possible to obtain a larger penetration depth than in the atmosphere at the same laser power. This feature becomes remarkable at larger laser powers and greater penetration depths, and is a great advantage for solving the problem of weld quality degradation in high-power laser welding with laser outputs over 10 kW. Moreover, this advantage appears at a vacuum degree of about 100 Pa[10], which means that high quality welding can be realized at a considerably lower vacuum degree than the vacuum degree of about 0.001 Pa which is generally required for electron beam welding. Because laser welding in a vacuum requires vacuum equipment which is unnecessary for laser welding in the atmosphere, the equipment composition is complicated and equipment costs increase, but simple welding is possible with a lower vacuum degree than in electron beam welding. For this reason, vacuum laser welding is more versatile than electron beam welding, in which high vacuum equipment is a constraint, and use in a wider range of applications can be expected.

3. Application of High-Power Vacuum Laser Welding to Production Process of Rolled Clad Steel Sheets

JFE Steel developed a clad slab assembly welding technology for the hot-rolled clad steel plate production line as an application utilizing the above-mentioned merits of high-power vacuum laser welding. Clad steel plates are a type of composite steel plate in which the whole surface of a steel plate (base metal) of carbon steel or low alloy steel is coated with another metal, and the boundary surface between steel plate and the coated metal (cladding) is metallographically bonded. As the cladding material, a metal such as stainless steel, a nickel alloy, or a copper alloy, which possesses corrosion resistance, heat resistance, or other properties which carbon steel and low alloy steel do not have, is chosen. Methods of manufacturing clad steel plates include rolling, overlaying welding, and explosive bonding[11]. JFE Steel manufactures clad steel plates by the rolling method using a hot rolling line (**Fig. 2**). Two types of slab assemblies are used in the production of clad steel plates, the open type and the sandwich type, as shown in **Fig. 3**. In the open type, slabs for rolling are assembled by welding the overlapped surfaces of the base material and the cladding material, and in the sandwich type, by welding the overlapped surfaces of the base material slabs and spacers. The manufacturing procedure for hot-rolled clad steel plates including slab assembly is as follows.

(1) The base material and cladding material to be combined as the cladding are manufactured in a preceding hot rolling process.

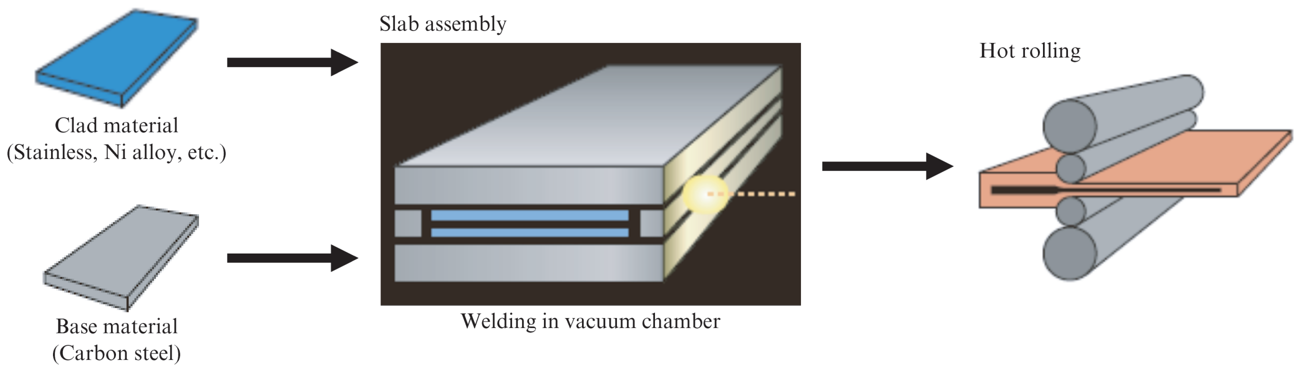


Fig. 2 Outline of production process of hot rolled clad steel

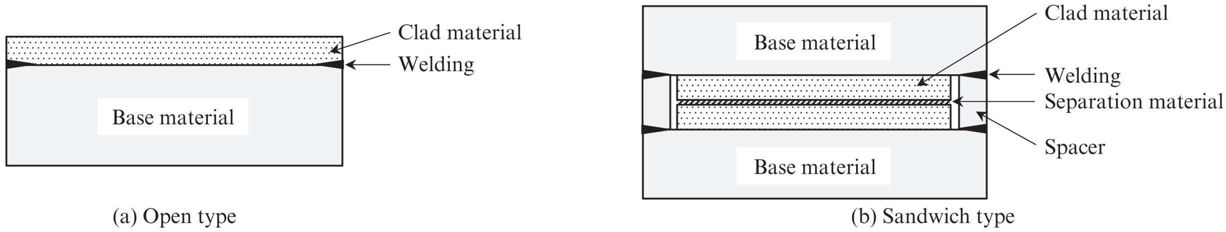


Fig. 3 Slab assembly types of hot rolled clad steel production

(2) In the open type, the cladding material is overlapped on the base material in the finished condition, and the interface between the cladding material and the base material is tack welded. In the sandwich type, two slabs of the base material and the cladding material are layered vertically back-to-back, and the base material and spacers, which are inserted in the clearance between the upper and lower base materials in a form that encapsulates the cladding material, are tack welded.

(3) The tack welded slab is welded at the four sides of the joint interface of the base metal and the cladding material (open type) or at the joint interfaces of the base metal slabs and the spacers (sandwich type) in a vacuum atmosphere in a large chamber, thereby producing an assembly slab with a sealed joint interface for rolling.

(4) The welded assembled slab is hot rolled again and adjusted to the prescribed product plate thickness, and the interface between the base metal and the cladding material is joined metallographically to complete the rolled clad steel plate.

The slab assembly welding in step (3) requires welded joint characteristics that can withstand the from heating to rolling during hot rolling in step (4). That is, in order to prevent delamination of the cladding material due to the thermal stress generated at the interface between the base material and the cladding material, which have different linear expansion coefficients, and to avoid generation of joint defects due to oxidation caused by oxygen penetration into the interface between the base material and the cladding material during rolling, it is necessary to secure welding strength by maintaining the prescribed penetration depth and guarantee sealability without generating defects in the weld part.

Electron beam welding in a large vacuum chamber was conventionally applied as a suitable welding method for slab assembly welding. However, in electron beam welding, the electron beam is deflected by the electromagnetic effect of the thermoelectromotive force generated during welding[12] because assembly welding of an open-type clad slab requires welding the dissimilar metals of the base metal and cladding material. This beam deflection phenomenon causes problems such as difficulty in obtaining the prescribed penetration depth and the necessity of setting welding conditions considering beam deflection for each base metal/cladding material combination, and thus causes welding defects and reduces welding efficiency with some cladding slab assemblies.

Laser welding has the merit of not generating an thermoelectromotive force, even in dissimilar metal welding, since a laser (light) beam is used as the heat source, and enables stable deep penetration welding without changing the welding conditions depending on the combination of the base metal and cladding material. Moreover, because of the merits of vacuum laser welding mentioned above, high expectations are placed on high-power vacuum laser welding as a very promising clad slab assembly welding method which can replace electron beam welding. However, there were also problems in the practical application of high-power vacuum laser welding to the manufacturing process. One important issue is welding stability in high-power laser welding, i.e., it must be possible to obtain a stable constant penetration shape during high-power welding over an extended period of time. **Figure 4** shows the change in the penetration shape with welding time when vacuum welding (atmospheric pressure: 100 Pa) of carbon steel (SM490B) was performed at a laser power of 20 kW and a welding speed of 0.5 m/min. The penetration depth gradually increased and the penetration width decreased with increasing distance from the start of welding, in other words, laser irradiation time. This change of the penetration shape was caused by the thermal lens effect[13], in which thermal deformation of the lens which condenses the laser beam occurs as a result of absorption of laser beam energy, and it became difficult to maintain a stable penetration shape due to the phenomenon of focus shift, that is, movement of the laser beam focal position caused by the thermal lens effect. Especially in high-power laser welding of 20 kW or more, the change in the penetration shape caused by the thermal lens effect becomes a more serious problem in high-power vacuum laser welding not only due to the larger amount of absorbed laser beam energy, even assuming a lens with

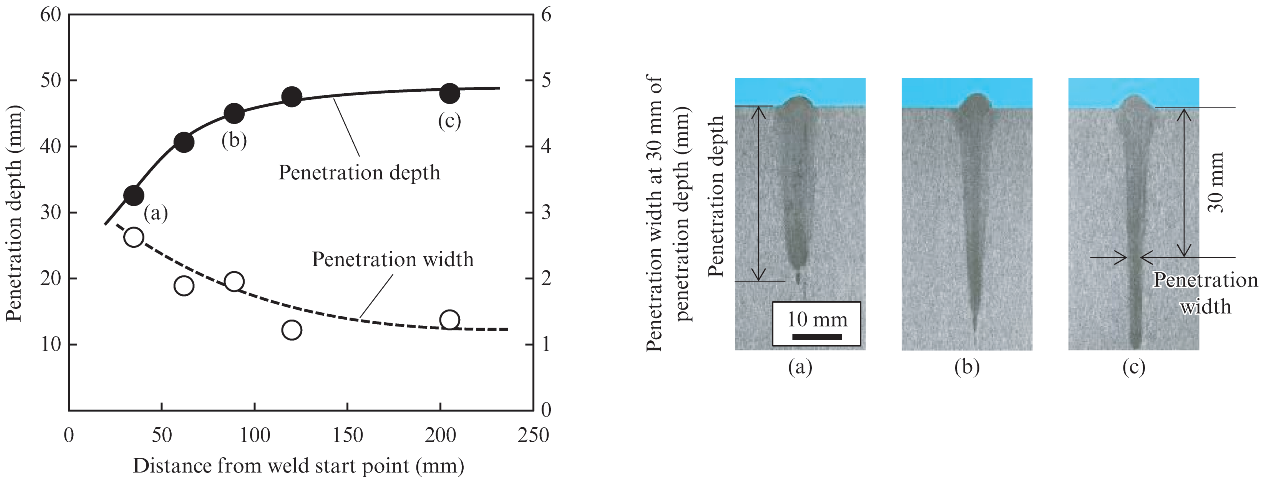


Fig. 4 Penetration shape change with elapsed welding time
(Atmospheric pressure: 100 Pa, Laser power: 20 kW, Welding speed: 0.5 m/min, Melt run)

high beam permeability is used, but also because temperature rise in the condenser lens occurs more easily in a vacuum, where there is no air cooling effect, than in the atmosphere.

In order to reduce the thermal lens effect, the lens configuration, lens material and coating, water cooling mechanism, *etc.* were optimized as a focusing optical system for high-power vacuum laser welding. An optimized lens composition that enables focusing with one lens was adopted in place of the conventional optical system, which is generally composed of multiple lenses such as a collimation lens and a focusing lens, and an optical system capable of minimizing focus shift by the thermal lens effect was manufactured. **Figure 5** shows the measurement results of the focus shift during irradiation with a laser power of 20 kW before and after optimization of the optical system. The results confirmed that the focus shift at the laser irradiation time of 120 s was drastically reduced, from about 30 mm to about 4 mm, by optimization of the optical system. **Figure 6** shows the penetration shape change in high-power vacuum laser welding using the optimized optics. Even in laser welding with a high power of 30 kW, the penetration shape change was dramatically reduced, and a stable penetration shape could be obtained.

In addition to the countermeasures for the thermal lens effect described above, many other problems peculiar to high-power laser welding in a vacuum were solved, such as setting of the proper welding conditions including the laser power, welding speed, and laser beam focal position to obtain the penetration depth and width necessary for assembly welding of clad slabs, and installation of a shielding gas mechanism to protect the focusing optical system from contamination by welding fumes during extended welding in a vacuum.

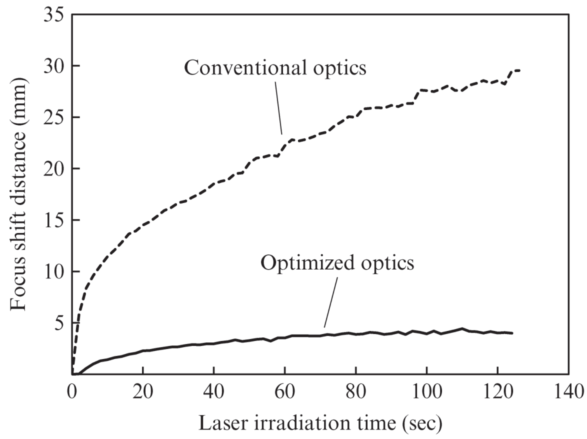


Fig. 5 Comparison of laser beam focus shift distance between before and after optimization of focusing optics
(Laser power: 20 kW)

As a result, a vacuum laser welding system using a 30 kW class high-power fiber laser, which is the first of its kind in the world, was introduced in the hot-rolled clad steel plate manufacturing process at the plate mill at JFE Steel West Japan Works (Fukuyama District). **Figure 7** shows the outline of the system configuration, and **Photo 4** shows an assembled slab being inserted into the vacuum chamber of the system. A laser beam is guided from a 30 kW class fiber laser oscillator to the laser welding head in the large vacuum chamber through a process fiber for beam transmission. The welding head includes the above-mentioned optimized optics which minimize the thermal lens effect, as well as other optimized mechanisms, and moves along the four sides of the periphery of the assembled slab, welding the base metal and the cladding material or the overlapping surface of the base metal slabs and spacers in the horizontal and lateral orientation. As a result, a

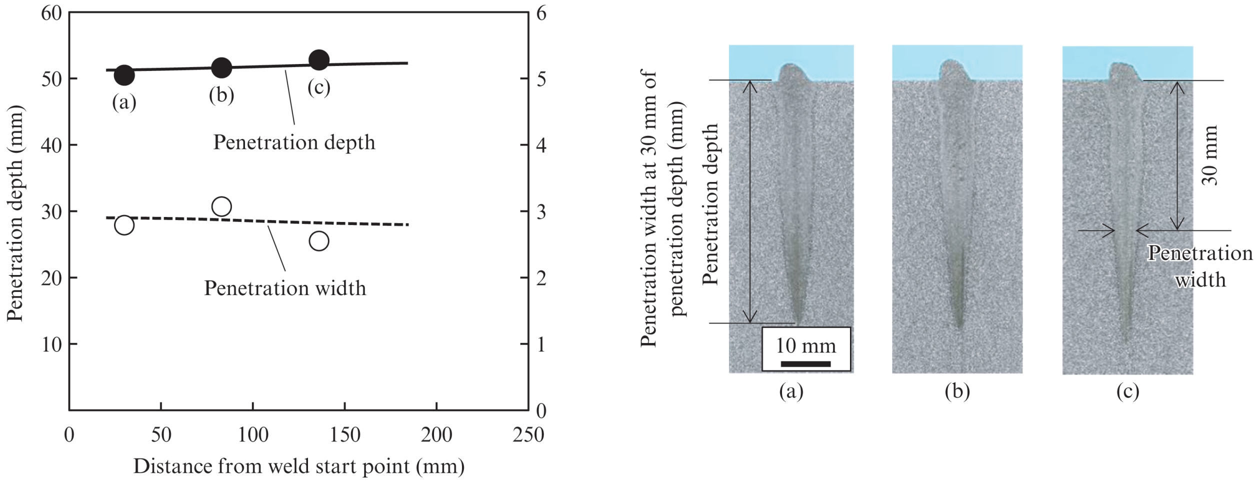


Fig. 6 Penetration shape change with elapsed welding time after optimization of focusing optics (Atmospheric pressure: 100 Pa, Laser power: 30 kW, Welding speed: 0.5 m/min, Melt run)

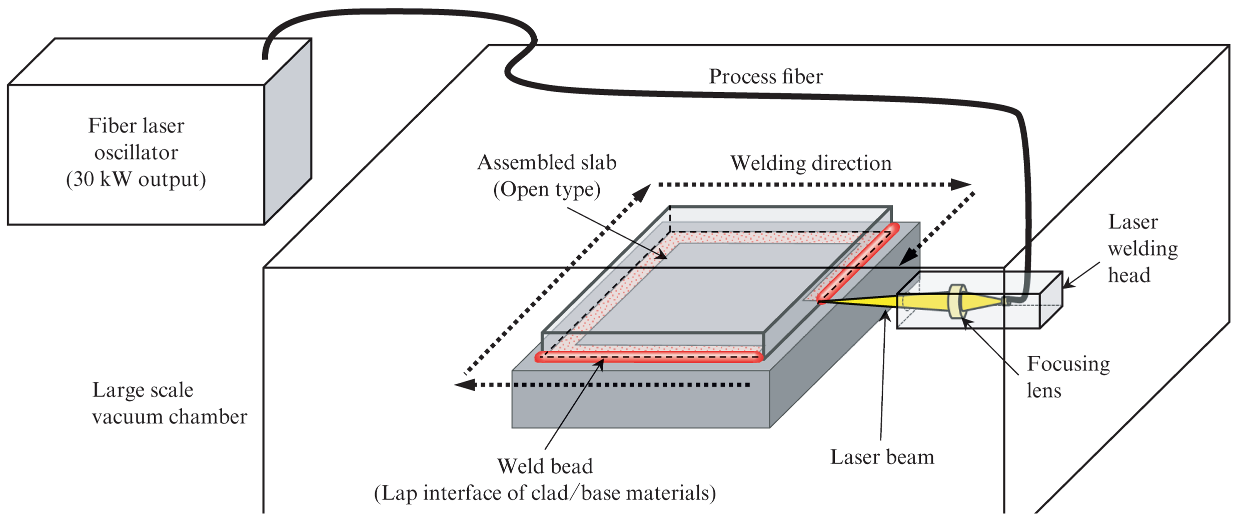
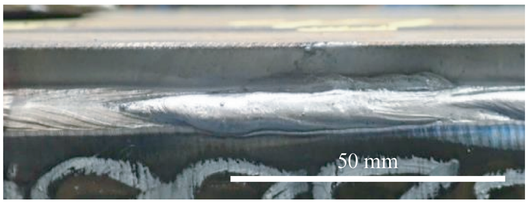


Fig. 7 Schematic illustration of vacuum laser welding system for clad slab assembly

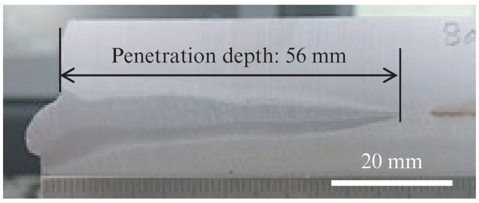
Photo 4 Entrance of vacuum chamber of clad slab assembly line

built-up slab in which the joint surface is sealed in a vacuum state is produced by welding the four sides of the clad slab in a vacuum atmosphere. In some cases, the circumferential length of the four sides of the assembled slab is more than 10 m, and when multilayered clad slabs are welded, the total welding time may be as long as several hours.

Photo 5 shows an example of observation of the surface appearance of the weld bead and cross-sectional macrostructure of an open type clad assembly slab produced using the high-power vacuum laser welding system. In this example, the base material was carbon steel (lower part of photograph) and the cladding material was stainless steel (upper side of photograph), the laser power was 30 kW, the welding speed was 0.5 m/min, the penetration width of the weld bead surface was 10 mm, and the penetration depth was 56 mm. The appearance of the weld bead shows excellent bead quality free of spatter generation, which is a



(a) Appearance of weld bead surface



(b) Cross sectional macrostructure of weld

Photo 5 Examples of weld bead appearance and cross sectional macrostructure of vacuum laser weld in clad slab assembly (Laser power: 30 kW, Welding speed: 0.5 m/min)

feature of vacuum laser welding, and observation of the cross-sectional macrostructure confirmed that the weld has good deep penetration along the lap interface, with no beam deflection or welding defects. Thus, high-power vacuum laser welding is a suitable welding technology for clad slab assembly, and has been demonstrated to be a very useful process in an actual production process. This high-power vacuum laser welding system is operated with welding efficiency surpassing that of conventional electron beam welding, and stable welding quality is guaranteed with various combinations of cladding materials. The developed system is making an important contribution to improved manufacturing efficiency of rolled clad products and to the development of new clad products.

4. Conclusion

This paper has explained features of vacuum laser welding technology, which can solve the problems of conventional high-power laser welding, and showed that it is a promising welding method for realizing deep penetration and high quality welding of thick steel plates. JFE Steel has been actively developing laser welding technologies, and succeeded in realizing a 30 kW class high-power vacuum laser welding system for the first time in the world by developing a technology suitable for the need for maximizing the merits of high-power vacuum laser welding, namely, application to slab assembly welding in the hot-rolled clad steel plate manufacturing process. The introduction of this technology in the hot-rolled clad steel plate manufacturing process is a symbolic case in which deep penetration welding of thick steel plates by a high-power laser was applied practically in a production line, and is an example of success in which a large effect was obtained in actual production. Although further progress in higher power and lower cost laser oscillators is expected, and the development of peripheral equipment such as optical systems will also be promoted in the future, vacuum laser welding technology is a promising option for utilizing high-power lasers as a practical welding method.

At JFE Steel, the application of high-power vacuum laser welding to the hot-rolled clad steel sheet manufacturing process is seen as one step. In the future, we will continue to develop innovative welding technologies using high-power lasers in order to contribute to the progress of the steel manufacturing process.

Acknowledgements

In the practical application of high-power vacuum laser welding technology to the hot-rolled clad steel plate manufacturing process, Mitsubishi Heavy Industries Machine Tool Co., Ltd. provided generous cooperation in the design and manufacture of the laser welding head, including the optimized condensing optical system, and the laser welding system as a whole. The authors wish to take this opportunity to express their gratitude to all concerned.

References

1) Kawai, Y.; Nakahara, H.; Yokozawa, F.; Midorikawa, M.; Komatsu, T.; Kobayashi, Y. High Power Laser Welder for Continuous Cold Tandem Mill. Kawasaki Steel Technical Report. 1989, no. 20, p. 115–117.
2) Kitani, Y.; Yasuda, K.; Kataoka, Y.; Fukuhara, A. Post weld heat treatment for laser welded joints of high carbon steels in a continuous cold mill line. Proceedings of Laser Materials Processing Conference. 1996, no. 37, p. 73–79.
3) Ono, M.; Shiozaki, T.; Shinbo, Y.; Sekine, Y.; Iwasaki, K.; Takahashi, M. Development of High Power Laser Pipe Welding Process. Quarterly Journal of Japan Welding Society. 2001, vol. 19, no. 2, p. 233–240.
4) Kido, M.; Sugihashi, A.; Yamamoto, H.; Maeda, K.; Hamada, N.; Minamida, K.; Kikuma, T. Development of 45 kW Laser Welding System for Continuous Finish-Rolling. Nippon Steel Technical Report. 2003, no. 379, p. 80–83.
5) Katayama, S.; Mizutani, M.; Kawahito, Y.; Kohno, W.; Makino, N.; Sumimori, D.; Itoh, S.; Suzuki, K. Possibility of weldability at 100 kW high power laser. Preprints of the National Meetings of J.W.S. 2015, no. 96, p. 162–163.
6) Sumi, H.; Kitani, Y.; Ooi, K.: Sumimori, D.; Mizutani, H.; Itoh, S.; Kawahito, Y.; Katayama, S. Penetration Property of Thick Steel Plate Welding by 100 kW Laser. Preprints of the National Meetings of J.W.S. 2015, no. 97, p. 148–149.
7) Katayama, S.; Abe, Y.; Mizutani, M.; Kawahito, Y. Deep Penetration Welding with High-Power Laser under Vacuum. Transactions of JWRI, 2011, vol. 40, no. 1, p. 15–19.
8) Kawahito, Y.; Mizutani, M.; Katayama, S.; Kohno, W.; Makino, N.; Sumimori, D.; Itoh, S.; Suzuki, K. Effect of Low Vacuum on Laser Welding at Power of More Than 30 kW. Preprints of the

National Meetings of J.W.S. 2015, no. 96, p. 164–165.
9) Francis, J. A.; Holtum, N.; Olschok, S.; Roy, M. J.; Vasileiou, A. N.; Jakobs, S.; Reisgen, U.; Smith, M. C. Vacuum laser welding of SA508 steel. Journal of Materials Processing Technology, 2019, no. 274–116269, p. 1–11.
10) Katayama, S; Ido, R.; Nishimoto, K.; Mizutani, H.; Kawahito, Y. Full Penetration Welding of Thick High Tensile Strength Steel Plate with High Power Disk Laser in Low Vacuum. Quarterly Journal of the Japan Welding Society. 2015, vol. 33, no. 3, p. 262–270.
11) Fukai, H. Rolled Clad Steel Plate. Materia Japan. 1996, vol. 35, no. 9, p. 976–982.
12) Watanabe, K.; Shida, A.; Suzuki, M.; Okamura, H.; Sejima. I. A Study on Occurrence and Prevention of Defects of Electron Beam Welding (Repot 2). Journal of the Japan Welding Society. 1975, vol. 44, no. 2, p. 121–127.
13) Noda, O.; Murakami, A.; Ueguri, S.; Katayama, S. Analysis of thermal lens in a processing head with a fiber laser and a disk laser. Proceedings of Laser Materials Processing Conference. 2010, no. 73, p. 49–52.