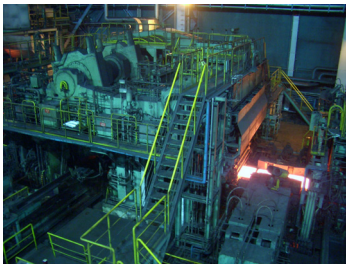
Development of a Bar-joining Apparatus for Endless Hot Rolling



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Endless hot rolling is a production process for finish rolling, that is carried out in a bath-less manner, while contributing to higher productivity and yield. Bar joining prior to finishing rolling is one of the key technologies for endless rolling. In contrast to the conventional method, in which the areas to be joined are heated and then joined together, Mitsubishi-Hitachi Metals Machinery (MH), Inc. and POSCO have recently developed a unique solid-state joining process capable of joining bars very quickly (in less than 0.5 seconds) and reliably without a special heating process. An apparatus using this new joining process has been incorporated into the No. 2 hot rolling mill at the POSCO Pohang Works, where full-scale endless hot rolling is already in operation.

1. Introduction

Completely continuous hot rolling, which can be regarded as the ultimate process for hot strip rolling, was first employed in commercial production in 1996. It is a technology for joining intermittently supplied rough bars and carrying out finish rolling in an endless manner. Endless rolling can prevent bar bending in the width direction at the head end and pinching at the tail end, which have been operational problems in intermittent rolling (batch rolling). This permits stable continuous rolling, resulting in uniform quality over the entire coil length. Endless rolling can also lead to increased productivity since it eliminates mill idle time. Moreover, the process makes it possible to produce extremely thin strips (1.0 mm thickness) via flying-gauge changing technology. **Figure 1** comparatively illustrates the equipment used for two types of hot strip rolling: batch rolling and endless rolling.

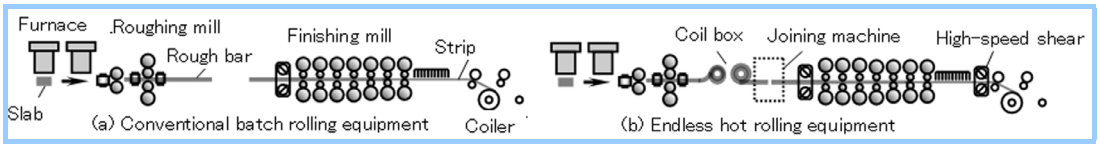

Figure 1 Comparison between two types of hot strip rolling equipment

Joining is one of the key technologies for endless rolling. A combination of induction heating and upset joining[1], and laser welding[2] are two of the joining technologies thus far adopted. Since these methods both require a relatively long joining time, the joining machine must travel a long distance with the rough bars, thus necessitating larger equipment. For wider application to endless hot rolling, MH has endeavored to provide a joining process capable of instantly joining bars via a simple joining machine while ensuring a joint strength comparable with that of the base metal. As a result of these endeavors, the company developed super-deformation joining (hereafter referred to as SDJ)[3,4]. SDJ is a solid-state joining process that requires only a short amount of time, and is accomplished by overlapping two rough bars, then bringing together a pair of knives to shear the joint position. SDJ is able to provide a joint strength that is high enough to withstand hot rolling without the formation of fractures. A joining machine based on SDJ technology was incorporated into the No. 2 hot rolling mill at the POSCO Pohang Works (hereafter referred to as P2H), where full-scale endless rolling has been in operation since January 2007[5]. Since that time, increased productivity, expanded production, quality improvements, and other benefits have been confirmed.

P2H now produces 100,000 tons of coils per month by endless rolling, and has set a record for continuously carrying out endless rolling for one hour, producing 45 bars (more than 1,000 tons). This paper presents a description of the SDJ technology developed by MH and POSCO, the results of a joint test and the results of applying SDJ to endless hot rolling into the existing line.

2. Outline and characteristics of the SDJ technology

2.1 SDJ process

Figure 2 depicts the SDJ process. In step 1, highly pressurized water is ejected onto the overlapping surfaces that are to become a joint area, and scale is removed. In step 2, the following bar is accelerated/decelerated so that the tail of the preceding bar and the head of the following bar overlap by the amount required for joining. In step 3, the bars are joined together by the shearing action of the knives. In step 4, crops generated during the joining process are cut off at their connections and removed.

2.2 SDJ mechanism

The SDJ apparatus joins bars by moving the top and bottom knives in the shearing direction. **Figure 3** schematically illustrates the joining process from start to finish, and shows the changes in state during the process. In the pressing step (a), air is eliminated at the overlapping surface to facilitate a vacuum condition. As indicated in the detailed drawing of Figure 3(a), the portion of the overlapping surfaces that does not come into contact with the knives is formed into a joint during the subsequent shearing step. In the shearing step (b), a portion of the overlapping surfaces is elongated by press and support forces, and scale is broken into segments to form scale-free surfaces. The scale-free surfaces are maintained since adhesion at the joint interface is simultaneously enhanced. At the end of the shearing step, a large upsetting force, which is the resultant of the support and press forces, is applied to complete the joining process. In addition, joining is presumably accelerated by the heat that is generated during the shearing step.

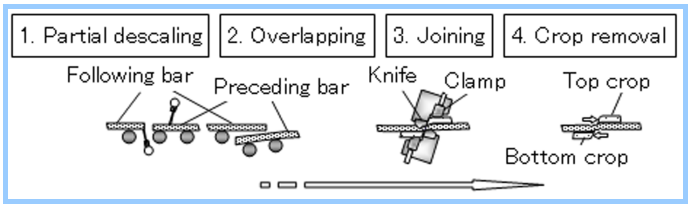

Figure 2 SDJ process

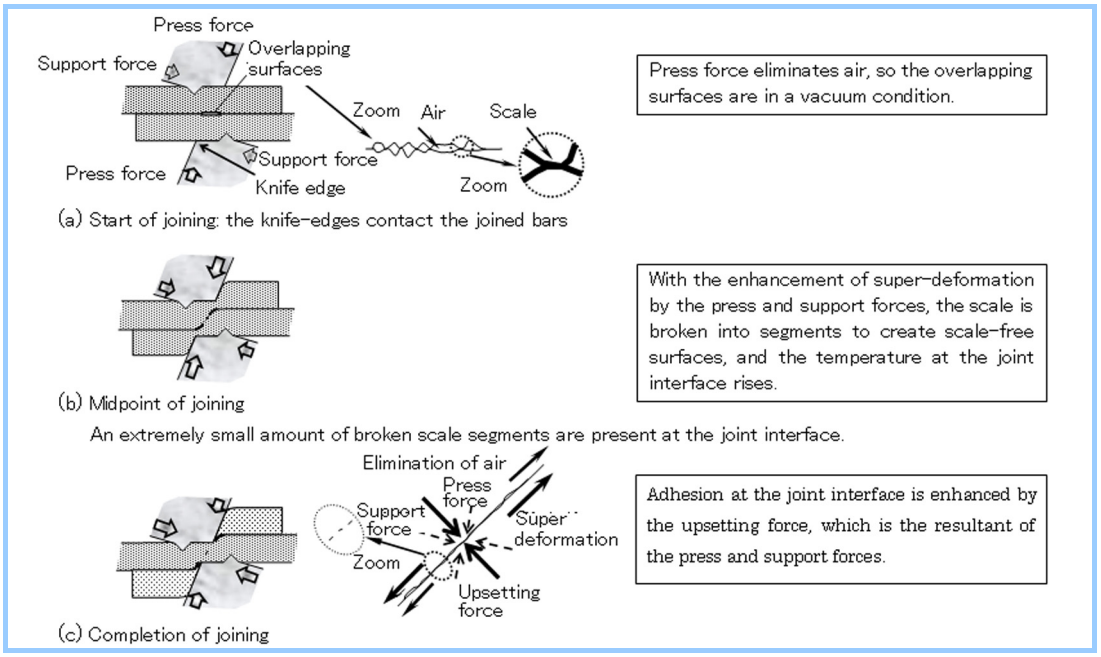

Figure 3 Schematic illustration of the joining process from start to finish, showing changes in state

As the above discussion indicates, the SDJ mechanism can be regarded as solid-state joining[6], in which bars are joined using super-deformation to create scale-free surfaces, and moving the atoms on both surfaces closer to each other so that metal bonding can be accomplished via the upsetting force.

3. Results of the SDJ joint tests

3.1 Test method

We constructed a basic SDJ test apparatus capable of joining bars up to a maximum width of 100 mm, as well as a wide-width SDJ test apparatus capable of joining bars up to 450 mm in width, and conducted an SDJ test using this equipment[4]. **Figure 4** shows the joint test procedure carried out using the test apparatus. To simulate the temperature of the joined material and the overlapping surface conditions in actual hot rolling, the bars were piled on top of one another in an electric furnace, and heated to 1,200–1,300°C. After being taken out of the furnace, the bars were exposed to the atmosphere to form scale on the overlapping surfaces. Partial descaling was performed on the joining area of the two bars using highly pressurized water. The bars were again overlapped before being placed on the test apparatus to initiate the joining process. After the two bars were joined, crops were removed by manually bending the crop connections several times. Tensile test specimens were collected from the joined material and subjected to analysis. The material was carbon steel (hereafter referred to as CS) with a tensile strength of 394-436 MPa.

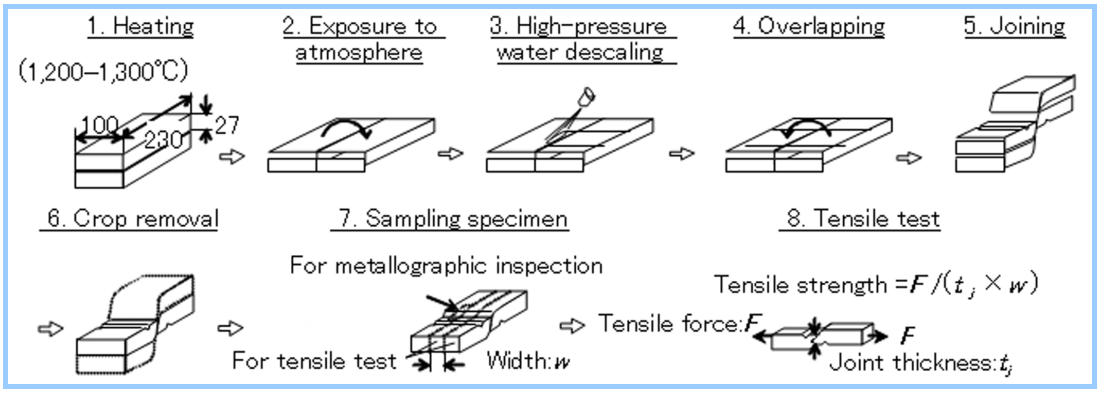

Figure 4 Test apparatus joining procedure

3.2 Test results and discussion

(1) Joint strength: **Figure 5** shows the relationship between location relative to the bar width direction and the strength ratio β_j of the joint to the base metal. The ratio β_j is obtained by dividing the tensile strength of the joint (hereafter referred to as joint strength) by the tensile strength of the base metal (394 MPa). The joint strength was fairly uniform in the width direction, except near the bar edges, and the ratio β_j varied approximately from 0.70 to 0.85. An observation of tensile fracture surfaces revealed that there were poorly joined areas within several millimeters of the bar edges. This indicates that the reason why bar edges have a lower joint strength is that they are affected by these poorly joined areas. The joint strength had a tendency to be higher for increased descaling pressure p_d, and this is assumed to be due to the fact that higher pressure descaling results in less scale.

(2) Metallographic joint analysis: **Figures 6**(a) and (b) show a macrograph and a microstructure of a CS joint cross-section, respectively, while Figure 6(c) shows a microstructure of the base metal cross-section. Figure 6(b) is an enlarged view of the joint center in the thickness direction that is circled in Figure 6(a). The structure was composed of ferrite and pearlite in the vicinity of the joining line. Compared with the unjoined area of the base metal, finer crystal grains were present along the joint interface, and were merged with the base metal grains. As a result, the joining line could not be clearly identified. Additionally, minute scale segments (which are presumed to have been broken up and formed during the joining process) were observed in the crystal grains. The presence of these fine crystal grains indicates that they were formed by super-deformation and recrystallization that took place when the bars were joined. Hence it can be concluded that super-deformation during the joining process is instrumental to the rapid joining and integrating of bars.

(3) Joint state changes after rolling: **Figure 7** shows a cross-sectional view of the joint after rolling. After one rolling pass, the steps at the joint were flattened, and the joint angle θ_j was also reduced. Top and bottom crop removal edges still existed on the extension of the joining line, but they were not serious enough to cause strip breakage.

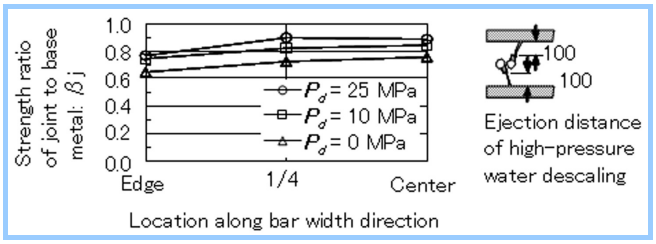

Figure 5 Relationship along bar width direction and strength ratio β_j of the joint to base metal
Material joined: CS. Size: 28 mm thickness × 200 mm width. Tensile strength of base metal: 394 MPa.

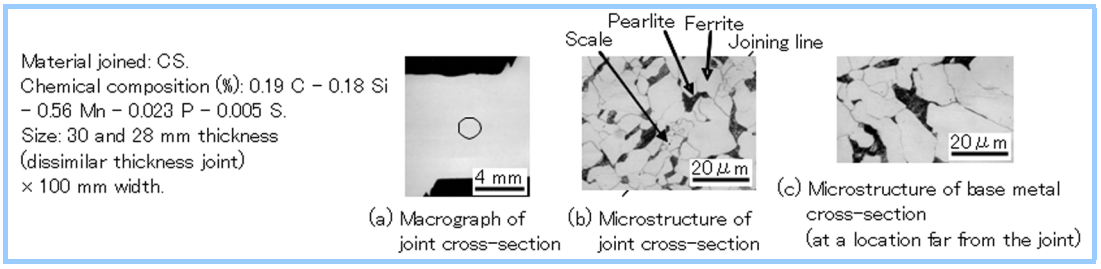

Figure 6 Cross-sectional photos of the CS joint. Tensile strength of base metal: 436 MPa.

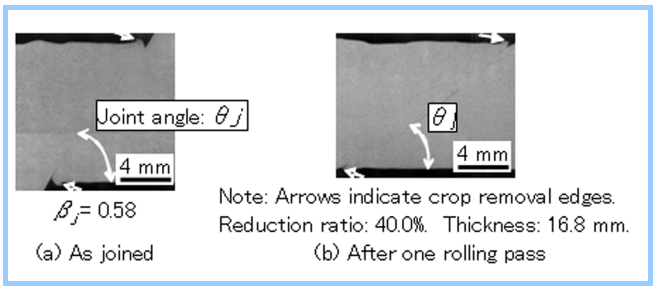

Figure 7 Joint cross-sectional shape before and after rolling
Material joined: CS. Size: 28 mm thickness × 450 mm width. Tensile strength of base metal: 436 MPa.

4. Results of applying SDJ to endless hot rolling into the existing line

4.1 Layout of the endless rolling line

Figure 8 illustrates the layout of the endless rolling line. The primary equipment between the roughing and finishing mills (from right to left) are the coil box, crop shear, leveler, partial descaling device, overlapping device, joining machine and crop-removing device. The coil box dispenses the rough bars after rough rolling, serving as heat-retention and to adjust the join timing. The crop shear cuts off abruptly deformed portions created at the head and tail ends of the bars by rough rolling. The joining apparatus is made up of the remaining components, from the partial descaling device to the crop-removing device. The partial descaling device ejects highly pressurized water onto the rough bar surfaces to remove scale immediately prior to joining. The overlapping device overlaps the preceding and following bars by utilizing the deflection at the tail end of the preceding bar. The crop-removing device is installed close to the joining machine, and removes crops directly after joining for immediate disposal from the rolling line.

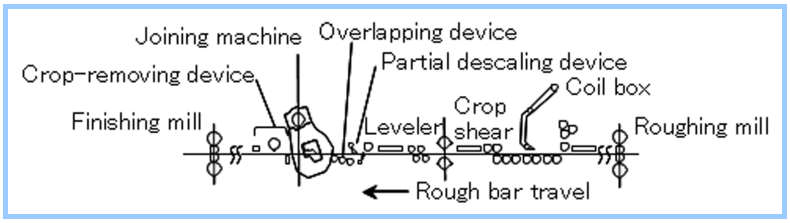

Figure 8 Layout of the endless rolling line

4.2 Structure of the joining machine

Figure 9 illustrates the action of the joining machine applied to the existing line. It has a mechanism similar to that of a pendulum flying shear[7]. The crankshaft has two eccentricities, with eccentricity 1 connected to the top knife and top clamp, and eccentricity 2 connected to the bottom knife and bottom clamp. Rotation of the crankshaft moves the top and bottom knives closer together or farther apart. The crankshaft is also connected to the pendulum shaft via a lever so that rotation of the crankshaft is converted to a back-and-forth motion of the pendulum housing, parallel to the direction of motion of the rough bars. When overlapping rough bars enter the joining machine, the crankshaft is rotated counterclockwise. The top and bottom knives then come into

contact with the rough bars at a speed approximately equal to the speed of the bars. As the knives approach each other, the bars are sheared to complete the joining process. The knives move apart when the crankshaft undergoes further counterclockwise rotation from the position shown in Figure 9(b). Since they are subject to a combination of up/down movement and pendulum motion, the knives follow a quasi-elliptic trajectory.

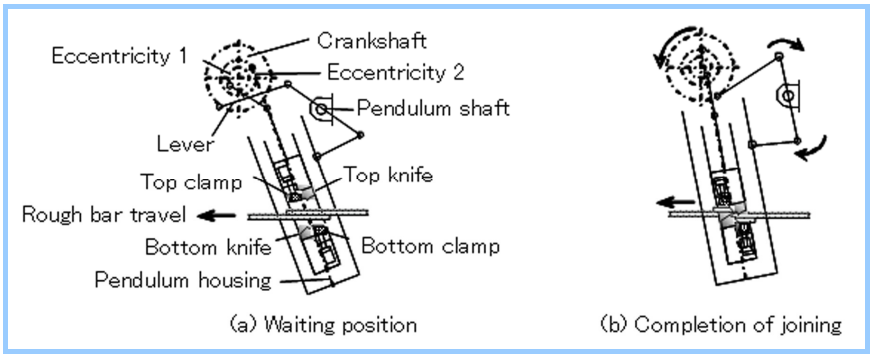

Figure 9 Joining action of a pendulum type joining machine

In the conventional method, which is a combination of induction heating and the upset joining process, the faces of the joining edges are heated for 3–5 seconds to reach the desired joining temperature before being upset. Thus the joining machine must travel a long distance with the rough bars[1]. By contrast, the SDJ technology completes the joining process in less than 0.5 seconds. It is therefore possible to implement speed synchronization with the rough bars, even with a pendulum machine, which is fixed to a foundation. Accordingly, the length of the joining machine, from the descaling device to the crop-removing device, can be reduced to approximately 15 m so that the machine can be compactly installed in comparison to a method that requires the joining machine to move along the line.

4.3 Joining and rolling at P2H

Figure 10 shows the strength ratio β_j of the joint to the base metal, measured relative to the bar width direction, for material joined at P2H. The ratio β_j was about 0.70 when no partial descaling was performed prior to joining, and reached 0.85–1.00 with partial descaling, resulting in an average ratio of 0.90 or higher. When β_j equaled 1.00, fractures developed in the base metal rather than at the joint interface[5]. Partial descaling was performed with a descaling pressure p_d of 25 MPa and a water ejection distance of 100 mm. The material joined was low-carbon steel, which has a lower tensile strength than the CS used with the test apparatus. Nevertheless, the measured β_j values were comparable to those obtained with the test apparatus.

4.4 Benefits of endless hot rolling

The following are typical benefits obtained from endless hot rolling using the equipment described above.

(1) Increase in productivity: **Figure 11** presents an example of the amount of time saved by endless hot rolling compared to batch rolling. In batch rolling, idle time accumulates from the instant the tail end of a bar goes beyond the final stand to the instant the line starts rolling the next bar. In addition, the batch rolling speed is lower at the head end of a bar, and increases after the head end has passed through the final stand. Moreover, in thin-gauge batch rolling, the rolling speed decreases before the tail end passes through the final stand. On the other hand, endless rolling involves no idle time, and bars can be rolled at maximum speed from the second bar to the second-from-last bar, even in thin-gauge rolling. Thus, endless rolling can significantly reduce processing time.

Figure 12 shows the rate of productivity of endless rolling compared to batch rolling. Under the conditions indicated in Figures 11 and 12, the productivity of endless rolling is 25–30% higher than that of batch rolling, allowing the finishing mill to be utilized to its maximum capability.

(2) Quality stabilization: **Figure 13** shows an example of the product quality obtained from endless rolling at P2H. The coiling temperature, which affects the mechanical strength and metallurgical structure of the coil, is uniform while the strip thickness and crown are controlled to fit the desired specifications. In other words, the quality is well stabilized.

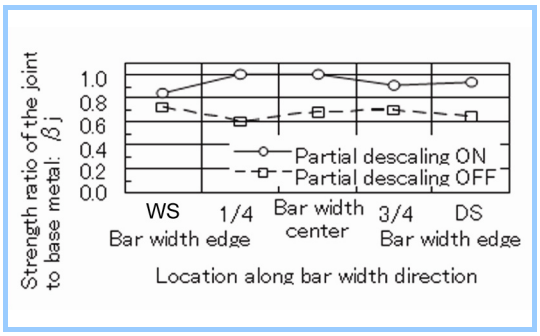

Figure 10 Strength ratio β_j of the joint to base metal relative to the bar width direction for material joined by production version

Material joined: low-carbon steel. Size: 31 mm thickness × 1,200 mm width. Tensile strength of base metal: 308–319 MPa.

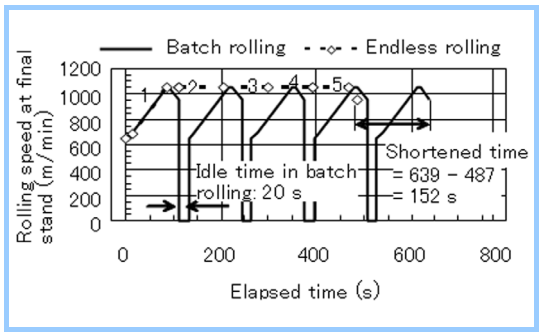

Figure 11 Example of time saved by endless hot rolling compared to batch rolling

Strip size: 1.40 mm thickness × 1,219 mm width. Number of bars: 5. Weight per bar unit width: 18.0 kg/mm. Bar weight: 22.0 tons.

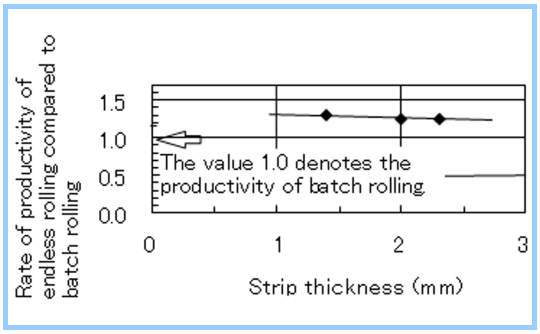

Figure 12 Rate of productivity by endless rolling compared to batch rolling

Number of bars: 5. Weight per bar unit width: 18.0 kg/mm. Bar weight: 22.0 tons. Idle time between two consecutive bars during batch rolling: 20 s.

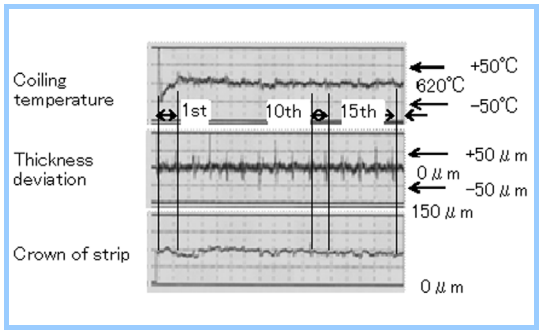

Figure 13 Example of the product quality obtained from endless rolling

Material rolled: SAE1022. Number of endlessly rolled coils: 15

4.5 Equipment-related advantages of SDJ over the conventional method

Figure 14 depicts the layouts of endless rolling equipment for different bar-joining processes. The layouts were compared with each other by setting the maximum bar speed during joining at 70 m/min, and setting the distance L_a, between the joining machine and position F1, and the distance L_b, between the coil box and the joining machine, to be the same. For the method that combines induction heating and upset joining, the equipment length was established as the bar moves a distance of 20 m when the maximum bar speed is 60 m/min[8]. Considering the bar length in the two rolling passes prior to the final rough rolling, the distance between the roughing mill and the coil box must be at least 45 m. Hence the distance shown in Figure 14(a) between the roughing mill and position F1 is 119 m, since 45 + 74 = 119. On the other hand, the required distance for the SDJ process, shown in Figure 14(b), can be reduced to 100 m, since 45 + 55 = 100. Thus the SDJ technology allows for more compact equipment than the conventional method. As a result, endless rolling can be incorporated into a wider range of existing lines where line space is limited.

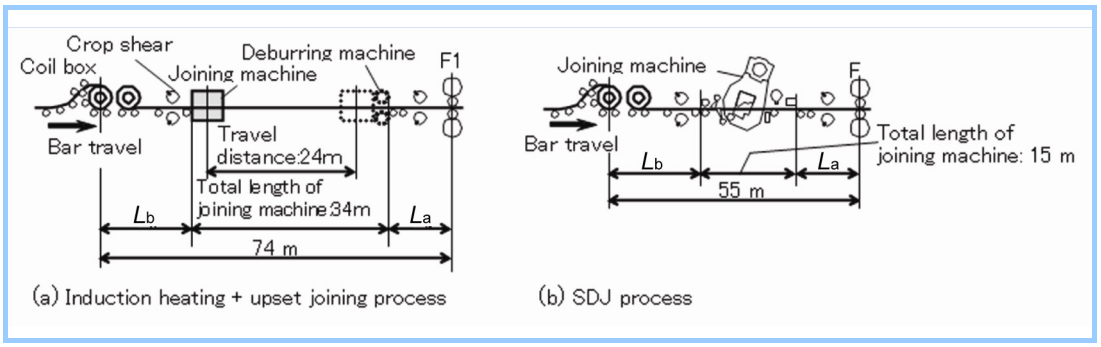

Figure 14 Layouts of endless rolling equipment for different bar-joining processes

Maximum bar moving speed during joining: 70 m/min

5. Conclusions

(1) SDJ, a highly reliable, fast joining technology, eminently suited to the bar-joining process for endless hot rolling, has been developed, tested, and incorporated into an existing line.

(2) With the adoption of SDJ, it is possible to install a joining machine to the foundation while reducing the overall length of the endless rolling equipment, including the coil box. As a result, the feasibility of endless rolling is enhanced in many cases, including at a large number of existing facilities.

Acknowledgments

The present research was initiated by Hitachi, Ltd., prior to the establishment of Mitsubishi-Hitachi Metals Machinery, Inc. It was therefore promoted in collaboration with POSCO. The authors would like to thank Dr. Takao Funamoto of Hitachi Kyowa Engineering Co., Ltd., and Dr. Jongsub Lee of POSCO, as well as many others, for their contributions over the years.

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