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High Speed Production Technology for ERW Stainless Steel Pipes without Lubrication

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In order respond to the tendency of using stainless steel for automotive exhaust pipes, a technology of manufacturing high quality ERW stainless steel pipes has been needed. Roll marks and penetrator defects of welded seam due to formation of oxides easily occur during the manufacture of ERW stainless steel pipes because the physical properties of stainless steel are different from those of carbon steel. In the conventional forming process, lubrication is necessary to prevent roll marks. However lubricant is a cause of deterioration of welded seam quality. Kawasaki Steel developed a mill using a new forming process. It is the CBR (chance-free bulge roll) forming mill that can manufacture high quality ERW stainless steel exhaust pipes with excellent formability. It has achieved high quality of welded seam in welding with a speed as high as 110 m/min and the suppression of roll marks without lubrication.

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High Speed Production Technology for ERW Stainless Steel Pipes without Lubrication*



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1 Introduction

Electric resistance welded (ERW) pipes are produced by continuously feeding a steel strip and forming it into a cylindrical shape by means of forming rolls and then by welding the two edges of the open pipe by the high-frequency welding method. Because the process of manufacturing ERW stainless steel pipes is a continuous one in the same line, this is one of the highest productivity and high reliability pipe production methods. The usage of ERW pipes has become widespread and ERW pipes are being used in increasingly severe applications.

In the automobile industry, the worsening global environmental problem has promoted the trend toward cleaner exhaust gas, better fuel consumption. Therefore, lower weight materials for automotive exhaust systems and the use of stainless steel are being rapidly furthered[1–4]. Against this background, ERW stainless steel pipes are being used in parts such as exhaust manifolds and center pipes in an increasing number of cases. In particular, exhaust manifolds are subjected to severe working such as bending and pipe expanding because they are used in a narrow engine room. Therefore, superior workability of pipe including the quality of ERW seams becomes an important property in addition to strength at elevated temperatures and resistance to oxidation[5].

At Kawasaki Steel, a 2-inch chance-free bulge roll (CBR) forming mill was introduced in 1990 in the small-diameter ERW pipe plant in order to produce ERW stainless steel pipes for automotive exhaust systems[6–10]. The CBR forming mill was developed in order to improve productivity by the common use of forming rolls among various pipe sizes, and improve weld quality and the formability of pipes[11].

Because stainless steels contain elements that have a strong affinity for oxygen, such as Cr, oxides called penetrators are apt to remain in the seam during ERW, and so stainless steels are more difficult to weld than carbon steels. In order to improve the welded seam quality of stainless steel, the CBR forming mill features dry pipe production in addition to the use of the inert gas shielded welding method. In the dry pipe-making method, no lubricant is used for the forming rolls because it is considered to affect the welded seam quality by increasing the dew point of the atmosphere[12]. High-speed (mass) pipe production tests without lubrication were conducted during the start-up of the CBR forming mill and a high-speed tube production technology for stainless steel pipes without lubrication, which has been considered difficult in the conventional mill, was established by solving various forming problems.

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This enabled ERW stainless steel pipes of excellent welded seam quality to be manufactured.

This reports describes the high-speed tube production technology without lubrication using forming rolls in the CBR forming mill.

2 Outline of CBR Forming Mill

The CBR forming process is characterized by a new bulge roll forming method and a high-accuracy forming mill that includes cage rolls and flexibility of forming rolls.

2.1 Forming Flowers

Figure 1 shows the forming flowers of the CBR forming process as compared with those of the conventional forming process. In the CBR forming process, the two edges of a strip are formed beforehand by edge bend rolls and the center of the strip is then subjected to bend forming into a long and narrow oval-shaped pipe material using center bend rolls and cage rolls. The oval-shaped pipe material is then subjected to overbending at four points in the circumferential direction of the pipe using fin pass rolls, and the bulge roll forming of the side portion of the pipe and unbending of the overbent portion are then conducted by reducing the larger diameter of the oval, thereby finishing the oval pipe material into an open pipe. The CBR forming process thus differs from the conventional circular bend process that involves gradually bending the whole strip into a circular arc.

With the edges butted in an I-type form as shown in Fig. 1, it is possible to increase the edge opening width W_F after fin pass roll forming, i.e., the edge opening width (V-convergence angle) just before welding owing to the adoption of this characteristic bulge roll forming flowers using fin pass rolls. Thus this forming process enables high-frequency welding with stable weld seam quality to be conducted[11-13].

2.2 Forming Equipment

The line configuration of the CBR forming mill is

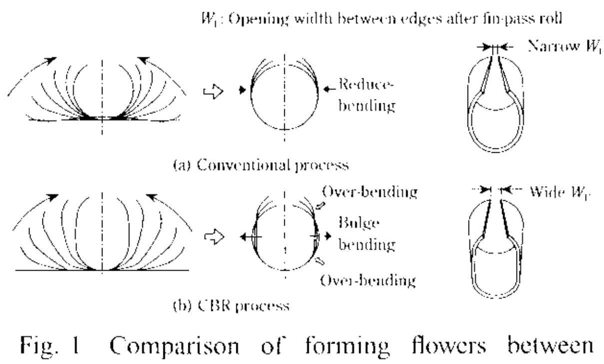


Fig. 1 Comparison of forming flowers between conventional forming process and CBR forming process

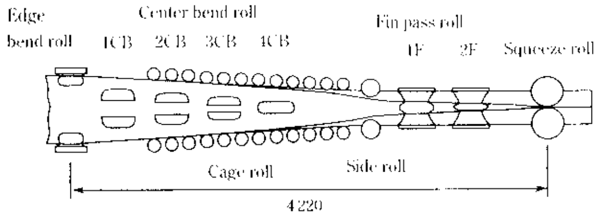


Fig. 2 Layout of 2" CBR forming mill for manufacturing ERW stainless steel pipes

shown in **Fig. 2**. The arrangement of forming stands in sequence from the upstream forming side is as follows: edge bend rolls (EB), 4 pairs of center bend rolls (1CB to 4CB), 2 pairs of fin pass rolls (1F and 2F), rotary seam guide rolls (RSG) and squeeze rolls (SQ). The range from the exit side of 1CB to the entry side of 1F is the cage roll forming range (CR). Driving rolls are used in the 4 pairs of rolls EB, 1CB, 1F and 2F. In this forming process, the upstream forming rolls used before fin pass roll forming are shared among various pipe sizes and it is possible to form ERW stainless steel pipes of various sizes without roll changing by changing only the position settings of these rolls, thus greatly improving the productivity[14,15]. The CBR forming mill can produce ERW stainless steel pipes of 22.2–60.5 mm in outside diameter and 0.6–3.0 mm in wall thickness.

3 Forming Technology in Pipe Production without Lubrication

3.1 Control of Roll Marks

Figure 3 schematically shows the cross-sectional contour of the formed strip at the center bend (CB) rolls of the CBR forming mill as compared with that of the conventional breakdown (BD) mill. In the CBR forming mill, the edges are constrained by the cage rolls and, therefore, the contact of the center bend rolls with only the center of the strip will suffice for forming by bending. Therefore, the width of CB rolls can be made narrow and the difference in the roll peripheral speed between the throat portion and the flange portion is small, suppressing the formation of roll marks. With the conventional BD rolls, even the edges of the strip are

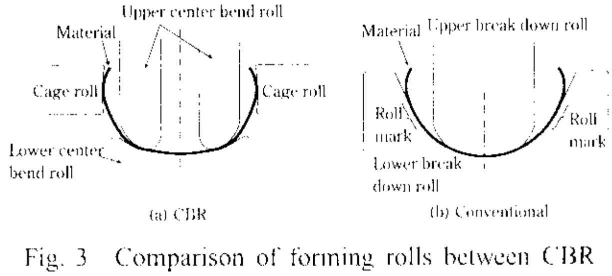


Fig. 3 Comparison of forming rolls between CBR and conventional forming

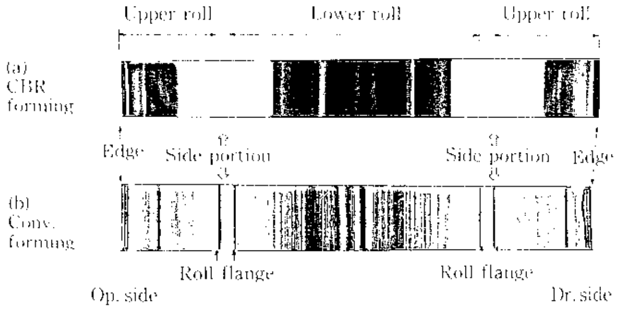


Fig. 4 Contacting state of formed sheet with No. 1 F roll

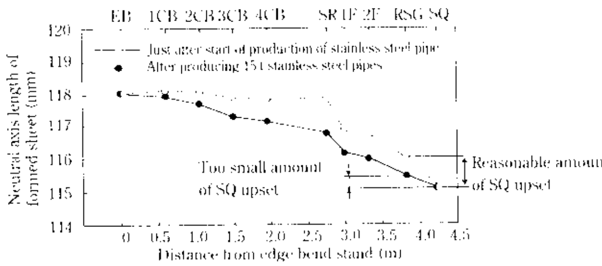


Fig. 5 Variation of neutral axis length of formed sheet in CBR mill zone (SUS436J1L, ϕ 38.1 mm $\times$ t 2.0 mm)

constrained and, as a result, the difference in the roll peripheral speed is great and roll marks are apt to occur.

When the CBR forming process is adopted, fewer roll marks occur even in fin pass roll forming for the following reason. In the conventional forming process, the maximum bending moment acts to the side portion of the pipe and, at the same time, the edge narrowing by the rolls at the side portion of the pipe maximizes the contact pressure of the side portion of the pipe with the rolls at this portion. In the CBR forming process, however, the maximum bending moment acts on the over-bent portion rather than on the side portion of the pipe and the lateral width of the side portion of the pipe is narrower than that of the roll caliber. Therefore, forming is such that the side portion of the pipe is bulged within the roll bite and the pressure of contact with the strip at the roll flange is low, hence the formation of roll marks is suppressed[16]. **Figure 4** shows the results of measurement of the contact of the material with the rolls at 1F using pressure measuring film. In the CBR forming process, the contact pressure between the material and the rolls in the portion corresponding to the roll flange of two-roll type fin pass is small. Therefore, it is possible to suppress roll marks formed in this portion in the conventional forming process. In actual production, the prevention of roll marks at the fin pass rolls without lubrication was achieved by adopting the bulge roll caliber and divided roll construction.

3.2 Suppression of Decrease in Neutral Axis Length of Formed Material

A continuous pipe production test without lubrication was conducted in the high-speed range of pipe production of 110 m/min and the forming characteristics were investigated. As a result, the neutral axis length of formed material on the exit side of fin pass was found to decrease. This phenomenon could not be reproduced in model mill experiments in which small quantities of pipe were made. The characteristics of this phenomenon, its cause, and preventive measures are described below.

3.2.1 Characteristics of decrease in neutral axis length of formed material

In a continuous (mass) pipe production test without lubrication, the line was stopped twice, i.e., just after the start of operation and after producing about 15 t of pipes to take samples. Then, changes in the neutral axis length of material formed during the forming process were measured and compared. The results are shown in **Fig. 5**. In the sample of formed material taken after the production of about 15 t of pipes, the neutral axis length of formed material on the exit side of the fin pass is small compared with that of the sample of formed material taken just after the start of operation and, therefore, the amount of upset is decreased. This decrease in the neutral axis length of formed material was observed in the upstream forming stage on the entry side of the fin pass and the neutral axis length on the exit side of the final cage zone was about 1 mm smaller than the neutral axis length just after the start of production. This suggests that the amount of welding upset is decreased due to a decrease in the neutral axis length of formed material. When the amount of welding upset is insufficient, the amount of molten metal discharged to the internal and external surfaces decreases and penetrator defects are apt to occur. Therefore, it is difficult to assure the quality of welded seams.

The amount of upset during the mass production of pipes may be obtained by increasing the strip width. In this method, however, the problem of great work hardening of material was considered owing to the addition of an excessive upset and great circumferential reduction of the pipe at the beginning of production. Therefore, it was necessary to use another approach.

3.2.2 Clarification of cause

(1) Method of Experiment

A hypothesis of the occurrence mechanism of the decrease in the neutral axis length is illustrated in **Fig. 6**. In ERW stainless pipe mills including the CBR forming mill, the ratio of roll peripheral speed is raised gradually for each drive stand in order to prevent the rolling movement of strip, and pipes are pro-

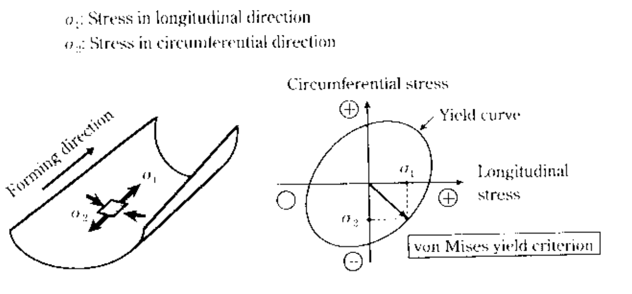


Fig. 6 Mechanism of decrease in strip width in cage roll forming zone

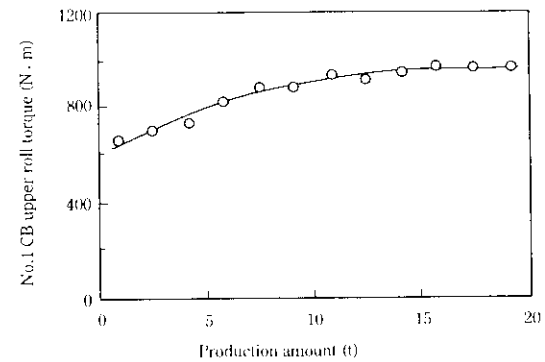


Fig. 7 Effect of pipe production amount on roll torque of No. 1 CB roll

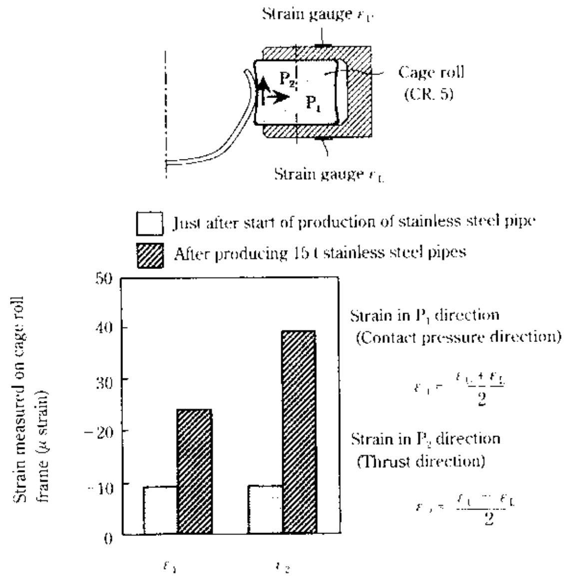


Fig. 8 Variation of forces acted in cage roll

duced by providing interstand tension. In the CBR forming mill, pipes are produced by increasing the ratio of throat-diameter-converted roll peripheral speed of the first fin pass roll (1F) relative to the first center bend roll (1CB) by 1%. For this reason, longitudinal tension acts on the strip. However, this force alone may be insufficient to cause the plastic deformation of the material, so that higher tension may be necessary. If a compressive force in the transverse direction acts in addition to that in the longitudinal direction during forming, a state of biaxial stress is produced and as shown by the von Mises yield condition, plastic deformation occurs under the action of a longitudinal stress below the yield stress in a state of longitudinal uniaxial stress, with the result that the neutral axis length decreases. Therefore, the pipe-making characteristics were investigated by considering the longitudinal and transverse stresses.

Because it is difficult to directly measure the tension in the mill, changes in torque were measured using strain gauges attached to the roll shafts of 1CB. Furthermore, strain gauges were attached to yokes of the cage rolls at the outer of 3CB and changes in the force acting on the cage rolls were measured. Next, the roll temperature may rise due to the generation of friction heat during pipe production without lubrication. Therefore, the temperature rise in each roll was measured and the temperature dependence of the coefficient of friction was also investigated.

(2) Experiment Results and Considerations

The results of measurement of the top roll torque of 1CB are shown in **Fig. 7**. The torque shows values of direction in which the motor is on the generating side and the torque value tends to increase with increasing production amount. Therefore, the longitudinal tension in the mill increases with increasing production amount.

The results of measurement of changes in the force acting on the cage roll are shown in **Fig. 8**. As with the longitudinal tension (1CB torque), the forces in the contact pressure direction and in the thrust direction (P_1 and P_2) increase with increasing production amount. It was found that the force in the thrust direction P_2 acts in the direction in which the roll is lifted up. This means that conversely, a compressive force in the transverse direction acts on the material side due to the action of P_2.

Therefore, the forces acting on the cage roll in the contact pressure direction and in the thrust direction were considered as follows. The mechanism by which the transverse compressive force is produced by the cage roll is shown in **Fig. 9**. In the cage zone in which the flat sheet is formed into a cylinder, this formation occurs during the rising movement of the edges. In contrast to this, because the direction of the cage roll axis is perpendicular to the direction of the mill line, the direction of roll rotation is different form the passing direction of material. The material is formed during an upward slide over the roll surface when it passes each roll, with the formation of a thrust force (friction force) P_2 in the direction in which it raises the roll. The reason why this force in the thrust direction increases with longitudinal tension may be that

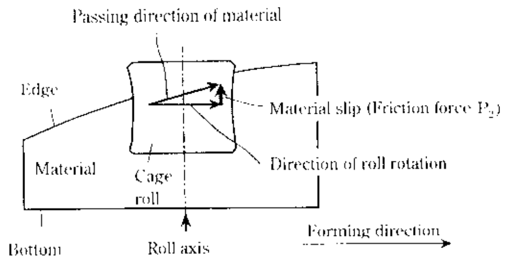


Fig. 9 Formation mechanism of friction force acting on cage roll

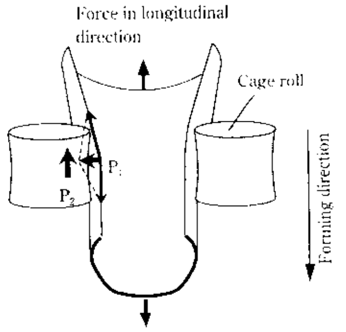


Fig. 10 Relation between longitudinal force and forces acting on cage roll

the force in the contact pressure direction P_1 increases as the strip tension increases, with the result that P_2, which is a component of μP_1 (μ denotes the coefficient of friction), also increases as shown in **Fig. 10**.

This would suggest that a decrease in the neutral axis length of sheet material occurs because the action of the longitudinal tension and that of the transverse compressive force by the cage roll produce a state of biaxial stress.

The reason why the neutral axis length decreased during the continuous production of a large amount of pipe may be the rise in the roll temperature, since the temperature of the fin pass roll (1F) rose to about 150°C after the continuous production of about 15 t of pipes. It seems that the tension acting on the strip is correlated with the friction force μP between the roll and the material. Because the coefficient of friction μ has temperature dependence as shown in **Fig. 11**, μP is related to the roll temperature which is raised by the heat of friction. In other words, because the roll temperature rises during the mass production of pipes and μ increases, the longitudinal tension increases.

3.2.3 Preventive measures

Because it was estimated that the decrease in the neutral axis length is caused by the action of longitudinal tension and that of a transverse compressive force by the cage roll, measures were taken to reduce these actions.

The measure to reduce the transverse compressive

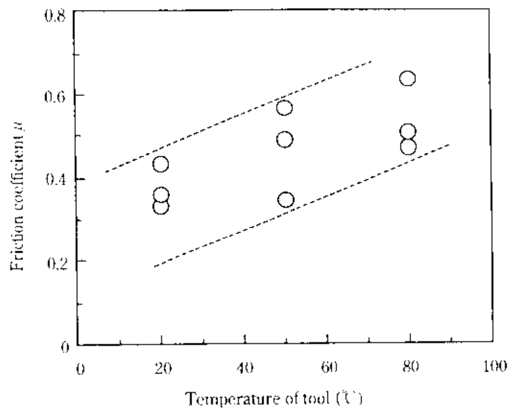


Fig. 11 Relation between temperature of tool and friction coefficient (Tool: sintered hard alloy, Material: SUS436J1)

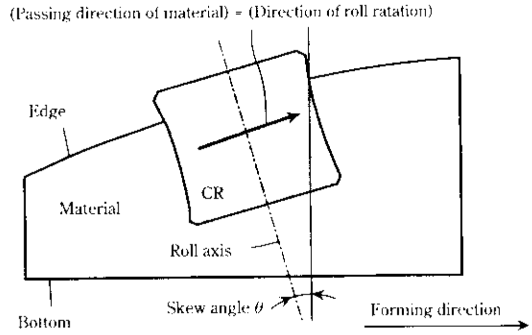


Fig. 12 Skew of cage roll axis

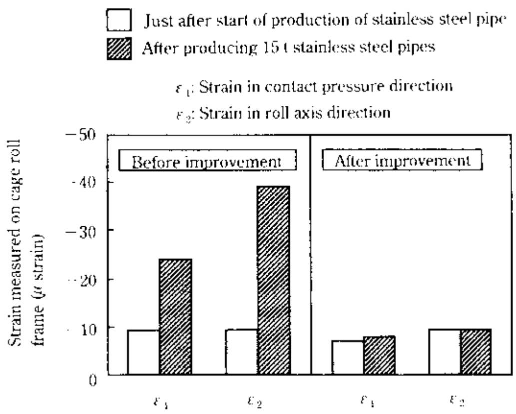


Fig. 13 Comparison of strain measured on cage roll between before and after improvement

force by the cage roll is shown in **Fig. 12**. An increase in the force in the thrust direction was suppressed as shown in **Fig. 13** even during continuous pipe production by skewing the cage roll axis so as to reduce the difference between the direction of roll rotation and the passing direction of material. The level of this stress was about 1/4 the observed before the improvement.

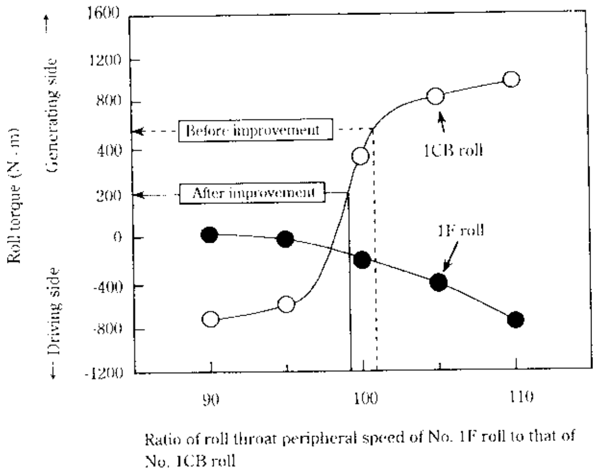


Fig. 14 Relation between ratio of roll throat peripheral speed of 1F roll to that of 1CB roll and roll torque

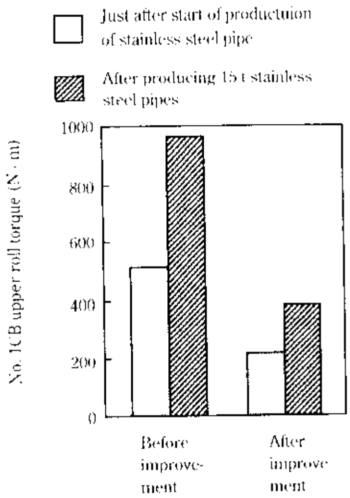


Fig. 15 Comparison of No. 1 CB upper roll torque between before and after improvement

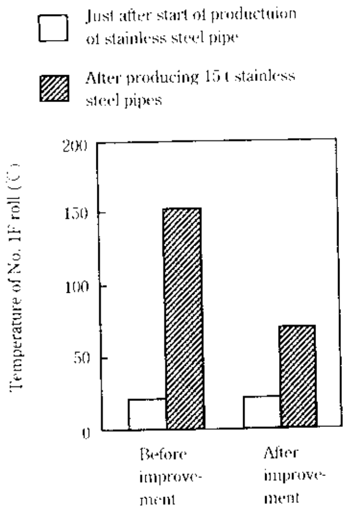


Fig. 16 Comparison of temperature of No. 1 F roll between before and after improvement

Next, the longitudinal tension in the forming region of the cage roll was reduced by reviewing the ratio of roll throat peripheral speed of 1F to that of 1CB. **Figure 14** shows the relationship between the roll throat peripheral speed of 1F to that of 1CB and roll torque. It is apparent that the 1CB torque is on the drive side at the ratio of peripheral speed of not more than about 98% and on the generating side at the ratio of peripheral speed of 98% or more. When the ratio of peripheral speed is 97%, the strip is strongly pushed in by 1CB and the strip vibrates vertically between 1CB and 2CB, making forming unstable. Furthermore, because tension tends to be loose at the leading and trailing ends of the strip and comes to the compressive side when the ratio of peripheral speed is set at a lower level, a ratio of peripheral speed of 99% at which about 200 N·m of generating side torque (1CB) is generated was selected so that tension remains on the tension side in the longitudinal direction of the strip.

Figure 15 compares the results of measurement of 1CB torque during continuous pipe production before and after the review of the ratio of peripheral speed. An increase in the 1CB torque was suppressed even during continuous pipe production because the ratio of peripheral speed was set at 99% and the level of this torque was about 1/2 that observed before the improvement. Furthermore, because the ratio of peripheral speed was reviewed, a rise in the fin pass roll temperature decreased as shown in **Fig. 16**. Thus, this temperature was held to 70°C or under. The force in the contact pressure direction was also reduced as shown in Fig. 13 because the ratio of roll throat peripheral speed was reviewed.

Owing to these measures, the neutral axis length of formed material did not decrease and stable forming was achieved even when the maximum mill speed was increased to 110 m/min without lubrication of forming rolls. Commercial production was started after the establishment of this high-speed pipe production technology without lubrication. Although it was initially considered that this variation could be suppressed by lubricating rolls with soluble oil, etc., the above measures were taken to improve the welded seam quality of stainless steel.

4 Quality Characteristics of ERW Stainless Steel Pipes for Exhaust Gases

4.1 Quality of Welded Seams

Sharpy impact test pieces were prepared by flattening pipe and the effect of forming roll lubrication on the toughness of welded seams was investigated. The results

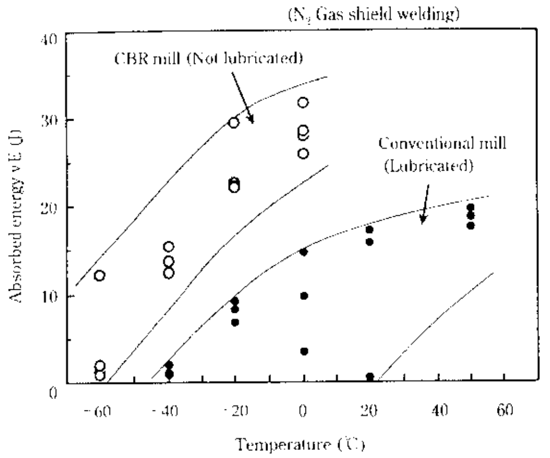
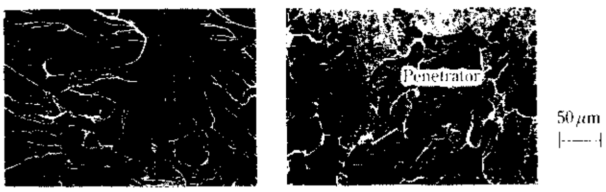


Fig. 17 Welded seam toughness of ERW stainless steel exhaust pipes produced by CBR and conventional mills (SUS436J1, 38.1 mmϕ × 2.0 mm$t$)



(a) CBR mill (Not lubricated) (b) Conventional mill (Lubricated)

Photo 1 Fracture appearance of Charpy impact test specimens of ERW stainless steel exhaust pipes produced by CBR and conventional mills (SUS436J1, ϕ38.1 mm × t2.0 mm)

of the investigation are shown in **Fig. 17**. The lubricated samples were produced in Kawasaki Steel's conventional mill and water-soluble oil was used as the lubricant. It is apparent from Fig. 17 that the nonlubricated sample is superior to the lubricated one in the toughness of welded seams. **Photo 1** shows the SEM images of the fractured surface of the Sharpy impact test piece. Many penetrators are observed on the fractured surface of the lubricated sample, probably due to the bonding of the oxygen in the lubricant to Cr. In the nonlubricated sample, there is no penetrator and a sound welded seam is obtained. The new high-speed stable forming technology without lubrication greatly improved the quality of welded seams of ERW stainless steel pipes after inert gas sealed welding.

4.2 Production of Ultra-Thin-Walled Pipes

In the CBR forming mill, the stable forming or thin-walled pipes in which the formation of edge waves is suppressed can be achieved for the following two reasons. First, the cross-sectional contour is smoothly changed and redundant strain in the strip is minimized by the cage roll forming process, which allows the edges

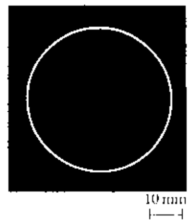


Photo 2 Cross section of ultra thin wall-thickness ERW stainless steel exhaust pipe produced by CBR mill (SUS436J1, ϕ38.1 mm × t0.6 mm)

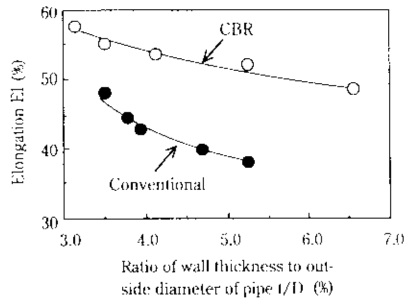


Fig. 18 Comparison of elongation of ERW stainless steel exhaust pipe by tensile test between CBR and conventional forming (SUH409L)

of strip to be continuously constrained at short intervals. Second, the diameter in the vertical direction of the open pipe is compressed during the bulge roll forming at the fin pass rolls and, therefore, the bottom portion of the open pipe is easily elongated in the longitudinal direction. In the conventional breakdown mill, forming is conducted in a stepped manner and the cross-sectional contour changes abruptly. Therefore, excessive elongation called edge stretch occurs and edge waves are apt to be formed, making it difficult to form ultra-thin-walled pipes 0.6 to 0.8 mm in thickness. In the CBR forming mill, however, such ultra-thin-walled pipes can be produced as shown in **Photo 2** and commercial production of these pipes has already been started.

4.3 Elongation Property of Product Pipes

The elongation property of product pipes in the tensile test of pipes (JIS No. 11 test piece) is shown in **Fig. 18**. Because the work hardening of material during the forming process is small in the CBR forming mill[17], it is possible to produce ERW stainless steel pipes that have a high elongation property compared with the conventional mill.

5 Conclusions

In order to improve the quality of welded seams of ERW stainless steel pipes for automotive exhaust systems that must provide high formability, a high-speed stable tube production technology without the lubrication of forming rolls was established, and the quality characteristics of product pipes were investigated. The following results were obtained:

(1) The formation of roll marks was suppressed by cage roll forming and bulge roll forming and the prevention of roll marks during rolling without lubrication was achieved.

(2) The forming problem of a decrease in the neutral axis length of formed material, which occurred in the continuous pipe production test without lubrication, was solved by optimizing the interstand tension and skewing the cage roll axis. Stabilization of forming and welding was thus achieved in the rolling without lubrication and commercial production has been started.

(3) Because of the successful establishment of a high-speed stable forming technology without lubrication, a completely nonoxidizing atmosphere was produced and the quality of welded seams of ERW stainless steel pipes after inert gas shielded welding was improved substantially.

(4) The formation of edge was suppressed by the bulge roll forming at the fin pass rolls and stable production of ultra-thin-walled pipes 0.6 to 0.8 mm in thickness became possible.

(5) The work hardening of material during the forming process was suppressed, allowing ERW stainless steel pipes with a high elongation property to be produced.

Kawasaki Steel has established a high-speed tube production technology for ERW stainless steel pipes for automotive exhaust systems by the CBR forming mill that has various excellent characteristics as mentioned above.

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