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Development of Numerical Analysis on Seamless Tube and Pipe Process

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Abstract

High alloyed seamless tube and pipe production process may have some trouble because the process cause large shear strain, and workability of high alloy is usually not good. Numerical analysis is a strong tool to clarify the process, to prevent the trouble, and to design proper production process. As the seamless tube and pipe process with large shear deformation is difficult to simulate by numerical analysis, the various development has been made. This paper shows our current development of the numerical analysis on piercing mill and mandrel mill. It improves the accuracy by state of the art analysis model and specimen test on piercing mill, and make it possible to predict the key process on mandrel mill process producing high alloyed tube and pipe by a proper model of material property.

1. Introduction

Seamless pipe and tube are often used in severe environments and are required to have high strength and superior corrosion resistance. Some are therefore high-end products made from high alloy steels, such as 13%Cr steel, 18-8 stainless steel, and Ni-based alloy. Generally, however, such high alloy steels are inferior in hot workability. In addition, during the seamless pipe manufacturing process when the material is subjected to large shear deformation, as described later, high alloy steels are susceptible to strains exceeding their deformability and tend to cause various rolling defects.

To roll such a material having inferior hot workability into a flawless seamless pipe with the desired dimensional accuracy, a method is required to accurately predict the behavior of the deformation of the material being rolled. However, during the seamless pipe manufacturing process, the material is often subjected to large local deformations, so its deformation behavior can hardly be simulated numerically.

In this report, the author describes the problems in conventional method of predicting material deformation behavior, with a focus on the Mannesmann rolling process. This paper will also review recent developments in numerical simulation technology.

2. Object of Analysis; Conventional Simulation Techniques

2.1 Seamless pipe manufacturing process [1)]

The seamless pipe manufacturing process can basically be divided into the Mannesmann rolling process and the press forming process.

The typical Mannesmann rolling process is schematically shown in **Fig. 1**. This process uses a piercing mill, which is a skew rolling mill for piercing in cylindrical billets. While rotating the billet with a pair of skew rolls, the piercing mill presses the billet against a plug to pierce the billet, and then rolls the billet between rolls and the plug, forming it into a hollow tube of the prescribed outside diameter and wall thickness.

During this Mannesmann process, the hollow tube is elongated by a mandrel mill, a plug mill, or the like. The current mainstream is the mandrel mill. The mandrel mill is a continuous rolling mill in which a mandrel bar is inserted into the hole in the hollow tube, and the tube wall thickness is reduced by the mandrel bar and caliber rolls (**Fig. 2**). In the two-roll-type mandrel mill, which uses two rolls on each stand, the directions perpendicular to each other within the cross section of a tube are alternately rolled by the odd-numbered and even-numbered stands.

The Ugine–Sejournet process is a typical example of a press forming process where a billet provided with a hole by machining is

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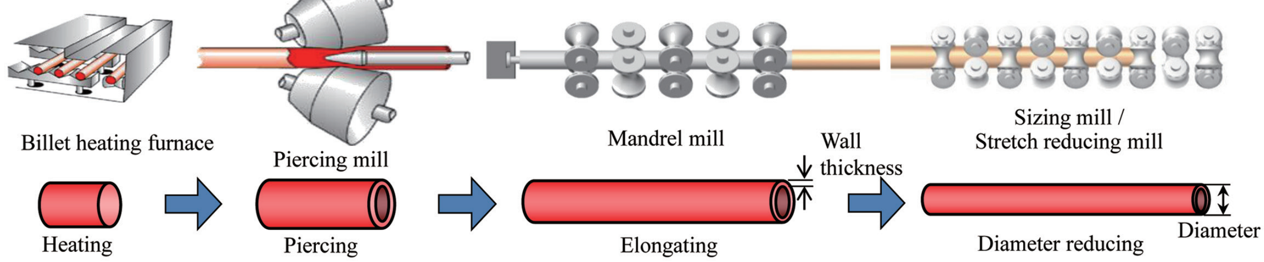


Fig. 1 Schematic of Mannesmann process

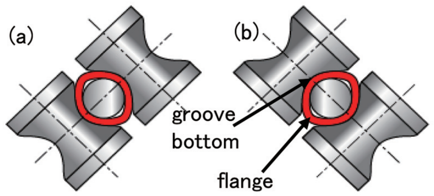


Fig. 2 Schematic of mandrel mill along cross-section view
(a) Odd numbered stand (b) Even numbered stand

elongated as it is extruded forward with a mandrel inserted into the hole.

Another press forming process available, the Ehrhardt Push Bench process, extrudes the hollow billet backward.

2.2 Object of analysis

Ordinarily, seamless pipe and tube are required to have high strength and good corrosion resistance. High alloy steels are therefore often used for hollow tubes. Generally, the larger the alloy component, the higher is the hot yield stress of the material. When rolling such a material, it is necessary to heat it to a high temperature. However, as the alloy component is increased, the melting point of the material tends to drop. In this case, processing heat can cause flaws in the material due to grain boundary melting. Furthermore, dynamic recrystallization/dynamic recovery can cause work softening of the material during deformation, bringing about a marked decline in the uniform elongation of the material. As a result, the hot workability of the material shows a tendency to deteriorate.

Numerical analysis of the seamless pipe manufacturing process is used as a tool to design optimum manufacturing conditions, and to develop a new innovative process that fundamentally resolves various problems, for the purpose of manufacturing flawless pipes of prescribed dimensional accuracy from a steel material having inferior hot workability. Numerical analysis is also used as a tool to determine whether a newly developed steel product can be made into pipe, to clearly identify the causes of flaws and shape defects detected in test-manufactured pipe, and to design and verify new processes for solving those problems. To achieve these aims, it is indispensable to accurately predict pipe shape and size, processing heat, the distribution of strains accumulated in the material, and so on.

2.3 Problems in analysis

In the piercing mill, deformation of the material, especially at the front end of the plug is large, and as the rolling operation progresses, the material at the center of the plug front end is subject to an extremely large shear deformation along the plug surface. In the Ugine–Sejournet process, too, the material is subject to a large deformation at the outlet through which it is extruded out of the container. When finite element analysis (FEA) is applied to simulate such a large local shear deformation, the element of the deformed part collapses and the Jacobian used to calculate the stress-strain balance equation becomes minimal or negative. As a result, the calculation does not converge, or fails. This problem could not be solved with conventional numerical simulation models.

In addition, to quantitatively evaluate the factor in inferior hot workability of high alloy steel and the influence thereof on pipe rolling, it is necessary to create a mathematical model for expressing the phenomenon and perform material testing for deriving parameters for the model. However, there used to be no practical models and parameters that could be applied to such a large, complicated deformation process.

In the face of such restrictions, to solve various problems involving piercing mill or to design pipe manufacturing conditions, for example, experiments using a model mill were often performed. However, with experimentation using a model mill, it is difficult to estimate stress-strain distributions. Thus, it is difficult to predict from the deformation energy the pipe flaw induced by grain boundary melting caused by local processing heat or to quantitatively trace the process whereby a tool seizure or material defect occurs. Therefore, all that could be done was, rather than evaluate the process of the above phenomenon, to determine the presence or absence of defects, using a regression equation of defects threshold based on experimental data. Another problem was that model mills could not be used in experiments performed under difficult conditions, or experiments involving many variable factors.

2.4 Conventional analytical techniques

A number of research institutes in Japan and other countries have conducted R&D projects with the aim of solving problems in the numerical analysis of processes involving the large, local shear deformation mentioned above. With regard to numerical analyses of the piercing mill, in studies completed by around 2005, researchers proposed a combination of models, which separately handle qualitative Mannesmann fracture evaluations at the billet center using two-dimensional FEA, and the deformation of a hollow tube formed from a billet having passed the front end of the plug.[2-4] They also proposed a model in which a billet having a previously drilled hole is pierced through.[5] Incidentally, in order to accurately calculate stress-strain distribution, it is necessary to keep track of the deformation of the billet center by continuously analyzing the process in which the billet is made into a hollow tube and rolled between the rolls and plug. With the above models, however, the said process cannot be evaluated accurately, and as a result the shear strain at the plug surface cannot be handled properly.

However, due to progress in mathematical techniques for automatic meshing, by the beginning of the 2000s the analytical technique utilizing adaptive meshing attained a practical level. The author and collaborators developed a new analytical method using the above function, and around 2006, made it applicable to solve problems and design new processes in the piercing mill and Ugine–Sejournet processes. With regard to the piercing mill, the new method made it possible to analyze tool surface pressure distribution. As a result, it has become possible, for example, to predict tool wear and seizure, and to design suitable measures to prevent them. With regard to the Ugine–Sejournet process, the new method allows for an unsteady state analysis of extrusion, making it possible to understand various phenomena and plan solutions to manufacturing problems, through such measures as simulations of the front end to back end of pipe.

The above analytical techniques have contributed to the development of various new technologies relating to seamless pipe and tube at Nippon Steel & Sumitomo Metal Corporation, such as the mass production of long, high-alloy pipe and tube which won this year's Okochi Memorial Production Prize.

3. Present Condition of NSSC's Numerical Simulation Technology

3.1 Piercing mill

As mentioned above, the author and collaborators developed analytical models that permit continuous simulation of the deformation of various parts of a material (billet) in the entire process, where a billet is made into a hollow tube and rolled between rolls and a plug. However, as developed so far, the models cannot always be applied to determine the possibility of rolling specific steel grades into pipe, or design optimum pipe manufacturing conditions as it cannot always satisfy the accuracy. Therefore, efforts have been made to further improve the accuracy of existing models.

The elements used in conventional simulation models were tetrahedrons because of limitations in the application of adaptive remeshing. Recently, however, it has become possible to apply adaptive remeshing to hexahedrons as well under certain conditions. It was eventually confirmed that simulation accuracy could be improved using hexahedral elements and modifying the model. Specifically, by using hexahedral elements, it made possible to arrange the hexahedral elements parallel with the direction of motion of the nodes, and stress analysis accuracy improved. Accordingly, it became possible to more accurately calculate the frictional force of the rolls, thus it became possible to simulate the process consistently (**Fig. 3**). In addition, by performing parallel calculation operations, including the remeshing, calculation time could be shortened. As a result, it became possible to implement simulations larger in scale and more realistic. All in all, the accuracy of simulation in a given time improved markedly, as shown in **Fig. 4**.

With the aim of improving the accuracy of estimation of processing heat in order to predict flaw due to grain boundary melting in the process of manufacturing high alloy steel pipe, the author and collaborators not only improved the accuracy of deformation prediction mentioned earlier but also performed a hot compression test to validate the model for calculating the processing heat of high alloy steel. First, as shown in **Fig. 5**, the compression test was carried out at a constant strain rate to maintain a uniform stress distribution without causing a barrel-shaped deformation in order to permit accurate measurement of processing heat of the high alloy steel. The correct material properties obtained by the compression test were used to analyze processing heat. It was confirmed that the measured and calculated material temperatures agreed very well (see **Fig. 6**). Thus, it became possible to directly determine critical grain boundary melting by a numerical simulation based on the results of material testing. Therefore, it should be possible to quantitatively predict the possibility of rolling a specific high alloy steel grade into a pipe without conducting experiments using a model mill.

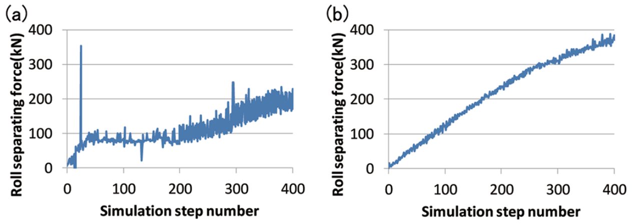


Fig. 3 Separating force computation comparison on roll biting of piercing (a) 2006 model (b) 2012 model

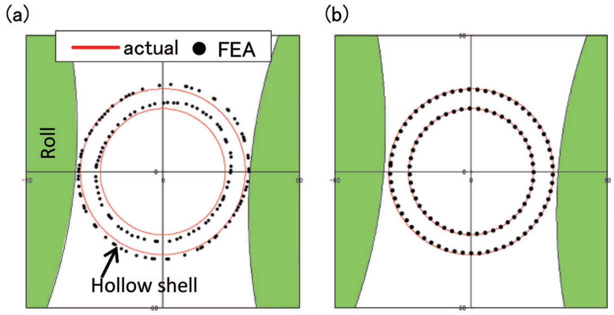


Fig. 4 Deformation shape accuracy comparison of piercing (a) 2006 model (b) 2012 model

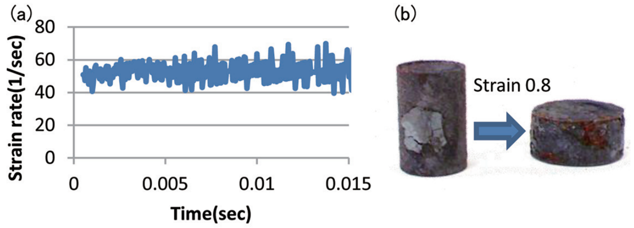


Fig. 5 Compressive velocity and compressed specimen shape of hot compression test (a) Compressive velocity (b) Compressed specimen shape

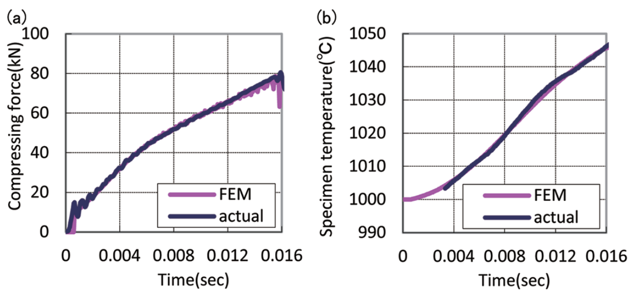


Fig. 6 Verification of processing heat computation (a) Compressing force (b) Specimen temparature

3.2 Mandrel mill

3.2.1 Technical problems in rolling pipe on mandrel mill

With a single-stand in a mandrel mill, it is impossible to uniformly reduce the wall thickness of the pipe all around. Indeed, the reduction is greatest immediately under the bottom of the roll groove and less near the flanges. In the flange direction, the hollow tube does not make contact with the mandrel bar and is not reduced in wall thickness. The groove bottom is constrained by the rolls and the mandrel bar, and is elongated by the reduction between those tools, whereas the flange is not directly subjected to reduction. Instead, as the groove bottom is elongated, the circumferential length of the material is reduced by the axial tension, and the material wall thickness decreases accordingly. If this deformation is excessively large, 'necking' can occur in the flange, causing unwanted perforations in the material (**Fig. 7**). This phenomenon is especially conspicuous with thin-walled materials. Thus, stainless steel and other materials having poor hot workability are difficult to roll on a mandrel mill, especially when their wall thickness is small.

It is known that when the alloy component is increased, the circumferential length of the hollow tube being rolled decreases and the bulge width also decreases (this phenomenon is called "underfill"). This causes the material to shrink-fit to the mandrel bar inserted into the pipe after rolling. If this occurs, it becomes difficult to extract the mandrel bar from the hollow tube (**Fig. 8**). It is considered that underfill occurs when an excessively large axial tension acts upon the flange, causing the circumferential length of the hollow tube being rolled to decrease and the tube width to narrow down. This phenomenon tends to occur more easily with alloy steel or stainless steel than with carbon steel.

In order to predict such unwanted phenomena, it is important to accurately calculate the shape of the pipe rolled. When using FEA to predict, with regard to the hot workability of a given material, it is necessary to not only handle the dynamic recovery/dynamic recrystallization that influences stress-strain curve and uniform elongation but also to analyze the inter-pass change in material properties. Therefore, the author and collaborators developed a new deformation analysis technique that also takes into account static recovery and static recrystallization. The developed technique is described below.

3.2.2 Prediction of underfill using FEA[6)]

The author and collaborators attempted to clarify the mechanism that causes the phenomenon whereby underfill becomes conspicuous as the alloy component is increased. An evaluation of the effect of work hardening on the phenomenon revealed that the degree of underfill of a given material varies according to the stress-strain curve of the material. However, an examination of the difference in the work hardening observed from the stress-strain curve in medium carbon steel and that in 18-8 stainless steel, for example, the difference in the degree of underfill was negligibly small. This did not coincide with the actual phenomenon.

Therefore, the deformation behavior that caused an underfill (see Fig. 8) was examined. It was found that underfill behavior varied markedly when there was difference in strain recovery. In multi-pass continuous rolling, the part of the material significantly reduced in thickness at the groove bottom hits against the flange in the next pass. Since that flange has been work-hardened on the immediately preceding stand, its deformation resistance becomes greater than at the groove bottom. As the strain is recovered by static recovery/static recrystallization, work hardening is relaxed with the lapse of time. In this case, the difference in strain recovery determines the difference in deformation resistance between the groove bottom and flange, and this difference significantly influences deformation behavior. In particular, in high-alloy steels containing large proportions of alloying elements, the recovery of strain is impeded. In addition, since they are rolled at a low temperature to prevent a flaw due to grain boundary melting, recovery of strain is further delayed (**Fig. 9**). During an FEA that focused on the above characteristic, it was found that when a high alloy steel material is rolled into pipe at

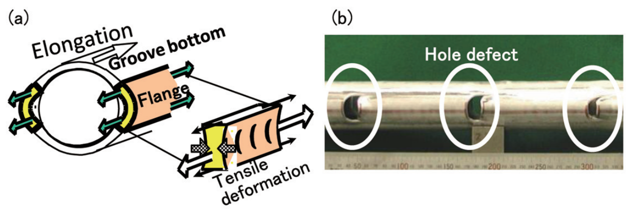


Fig. 7 Hole defect by necking on flange
(a) Deformation on flange (b) Hole defect

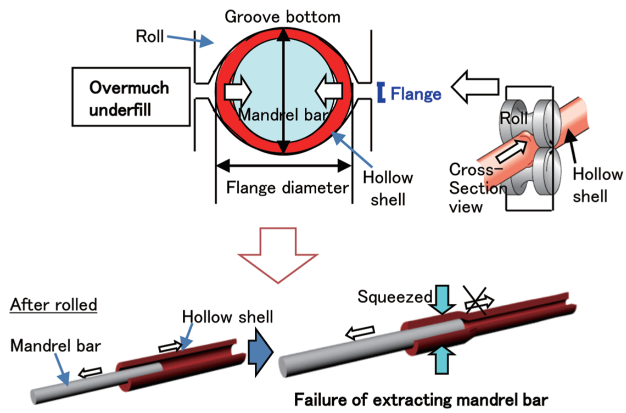


Fig. 8 Failure of extracting mandrel bar

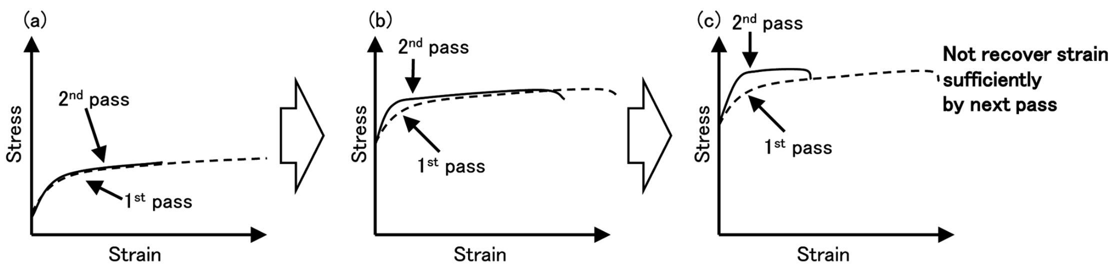


Fig. 9 Stress strain curve differences among steel grade and rolling temperature
(a) Carbon steel 1,100°C (b) High alloyed steel 1,100°C (c) High alloyed steel 1,000°C

a low temperature, the flange is subject to a large tensile stress (**Fig. 10**).

Thus, when the strain recovery is delayed, a large tensile stress is applied to the flange, causing an underfill. The reason for this is as follows. First, when the material is rolled on the second and succeeding stands, the part at the groove bottom has low deformation resistance, whereas the flange that has been rolled at the preceding groove bottom has high deformation resistance because of the effect of work hardening. In the case of carbon steel, even the part that has been rolled at the immediately preceding groove bottom becomes soft when it is rolled on the next stand, since the strain is recovered. In other words, it is only at the groove bottom immediately after the rolling that the material hardens. On the other hand, when a high alloy steel material is rolled into pipe at a low temperature, the flange that has been rolled at the preceding groove bottom remains hard because of a slow strain recovery. Furthermore, the flange becomes harder as it is subjected to a large reduction at the groove bottom of the succeeding stand. However, even when the steel grade and rolling temperature are different, the flange elongation is the same as the groove bottom elongation as long as the reduction rate at the groove bottom and the groove bottom elongation in the rolling direction are kept unchanged. Therefore, when the flange has hardened, it is subjected to a larger tensile stress.

Generally, when a large axial tensile stress is applied to a material being deformed, the flange outside diameter is reduced. **Table 1** compares the results of analysis of the circumferential strain among ordinary steel and high alloy steel and that during low temperature, rolling on and after the second stand, with consideration given to the characteristic of strain recovery. With carbon steel, the flange immediately under the rolled section decreases slightly in circumferential length when the hard section is elongated after rolling at the groove bottom. With high alloy steel, on the other hand, the work-hardened flange is forcefully pulled as shown in Fig. 10 at the same time that the hard section after rolling at the groove bottom is elongated. As a result, the flange is pulled with a larger force over a wider area, causing the flange, especially the part immediately under the rolled section, to markedly decrease in circumferential length as the rolling operation progresses.

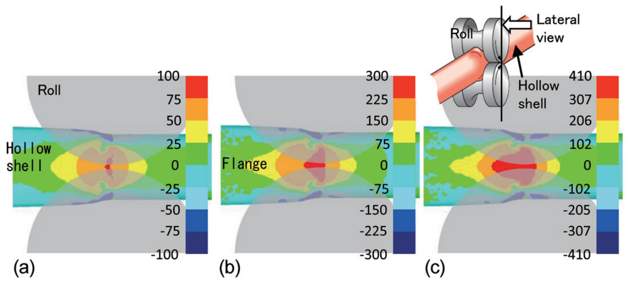


Fig. 10 Rolling direction stress comparison among steel grade and rolling temperature
(a) Carbon steel 1,100°C (b) High alloyed steel 1,100°C
(c) High alloyed steel 1,000°C

Thus, it was found that when a high alloy steel material is rolled into pipe at a low temperature, a large circumferential shrinkage deformation occurs over a wide area. This confirmed that the underfill of high alloy steel is larger than that of ordinary steel because of the difference in deformation resistance between the groove bottom and flange due to a delay in strain recovery.

Table 2 shows examples of FEA prediction accuracy. FEA prediction results agree well with measurement results on the cross-section shape, and the flange outside diameters indicating the degree of underfill show minimal differences.

As has been described above, the author and collaborators found that in multi-pass continuous rolling, the delay in strain recovery in each pass is the governing factor in the occurrence of an underfill. Eventually, they were able to establish techniques to accurately estimate pipe circumferential length from material properties according to steel grades and rolling conditions, and to predict the occurrence of various rolling defects.

3.2.3 Results of technical developments for high quality elongation and rolling of high alloy steel

Figure 11 shows how the design of pipe manufacturing conditions using the above-mentioned FEA technology has helped reduce the degree of underfill. Under the development conditions, the flange diameter after rolling can be made much larger than the groove bottom because of the absence of underfill. As a result, the bar extracting force has been reduced sufficiently, as shown in **Fig. 12**. This helps prevent bar extraction troubles.

The application of FEA, based on material properties, has led to

Table 1 Comparison of deformation at 2nd stand among steel grades and rolling temperature

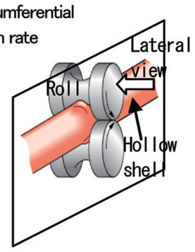
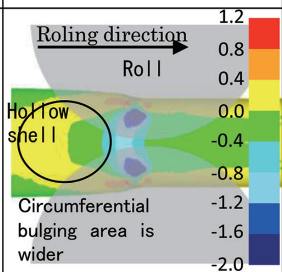
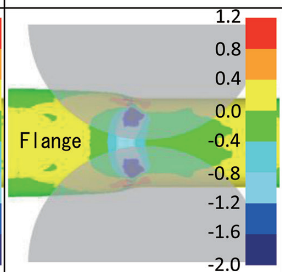
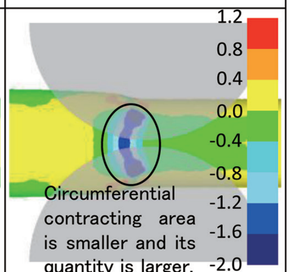
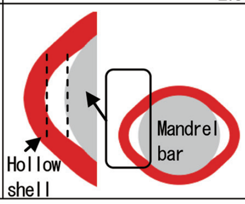
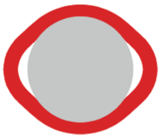
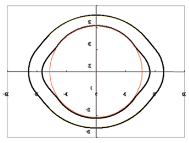
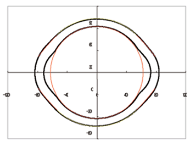
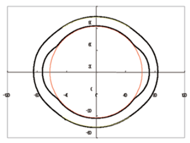
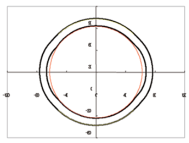
	Carbon steel 1100°C	High alloyed steel 1100°C	High alloyed steel 1000°C
Circumferential strain rate 			
Rolled hollow shell shape along cross-section view at 2nd stand			

Table 2 Accuracy verification of FEA

	1st stand	2nd stand	3rd stand	4th stand
FEA				
actual				

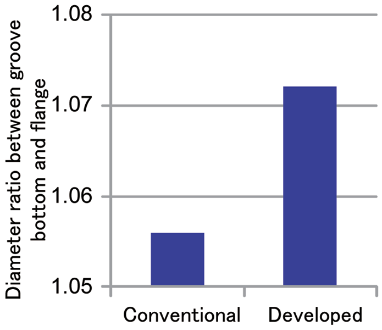


Fig. 11 Achievement of underfill prevention

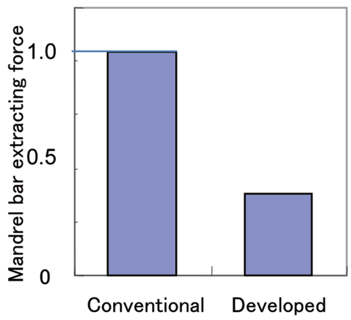


Fig. 12 Achievement of mandrel bar extracting force reduction

the development of techniques for high quality elongation and rolling of high alloy steel that permits predicting and avoiding quality defects and rolling troubles. The technology has made it possible to mass-produce long seamless pipes of high alloy steel and deliver them in a short time.

3.3 Understanding material properties

The author and collaborators created a database of properties of various steel grades by, for example, using techniques that permitted the accurate measurement of material properties (as described in 3.1 and Fig. 5) in order to obtain stress-strain curves from the results of compressive/tensile tests and from an understanding of the static recovery/static recrystallization behavior described in 3.2.2. The database now serves as a base for FEA in the company's seamless pipe manufacturing process.

4. Conclusion

This report describes problems in conventional numerical simulation techniques and the background to technological developments, with a focus on the piercing mill and mandrel mill used in the Mannesmann rolling process, and reviews current technological conditions at Nippon Steel & Sumitomo Metal. For the piercing mill, it has become possible to make more accurate simulations. Thanks to the development of a new method for testing materials, it has become possible to accurately calculate processing heat to predict material flaw due to grain boundary melting. For the mandrel mill, it is now possible to accurately predict the degree of pipe underfill by means of a simulation, precisely reflecting the appropriate material properties. All of this contributes greatly to the stable rolling of high alloy steel materials.

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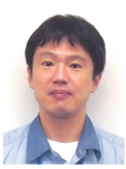

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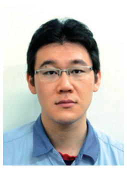

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