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## 1 Introduction

In recent years, demand for stainless steel seamless pipe has increased sharply in response to the increasing number of oil wells in highly corrosive environment. In particular, it has been reported[1] that, if the running cost is considered, 13% martensitic stainless steel tubing for oil wells is more economical than the combination of carbon steel OCTG and inhibiters which is used in corrosive environment, and consequently, demand for stainless tubing has shown a remarkable increase. However, the hot workability of stainless steel and other high alloy steels is low, and as a result, these materials show high rates of internal and external surface defects in seamless pipe rolling by the conventional Mannesmann process.[2-4] Moreover, because of the many problems associated with the Mannesmann process, including the extremely short life of the piercing plugs and shoes used in rolling[5-7] and low productivity, high alloy steel seamless pipes have conventionally been manufactured by the hot extrusion process.

Kawasaki Steel began the 13% Cr pipe production by the Mannesmann process in 1982, and has been working on the development of manufacturing technologies aimed at improving the quality and productivity of high alloy steel seamless pipe and increasing the life of piercing plugs and shoes.[8-20] This report shows an outline of the technologies developed.

## 2 Problems in Rolling High Alloy Steel Stainless Pipe

**Figure 1** shows the seamless pipe rolling process at Kawasaki Steel's Chita Works. Round billets rolled at the Mizushima Works Billet Mill are cut to the specified length, heated in a rotary hearth furnace, and then pierced with a Mannesmann piercer. In the case of small-diameter seamless pipe, the hollow blooms which are obtained in this manner are elongated by the mandrel mill, reheated, and sized to the specified outer diameter by the hot stretch reducer. For medium-diameter seamless pipe, the rolling process consists of an elongator, plug mill, and reeler. After reheating, the material is sized by the sizer.

**Figure 2** shows the nonconforming ratio of internal and external surface defects in high alloy steel seamless pipe produced by the conventional technology, in com-

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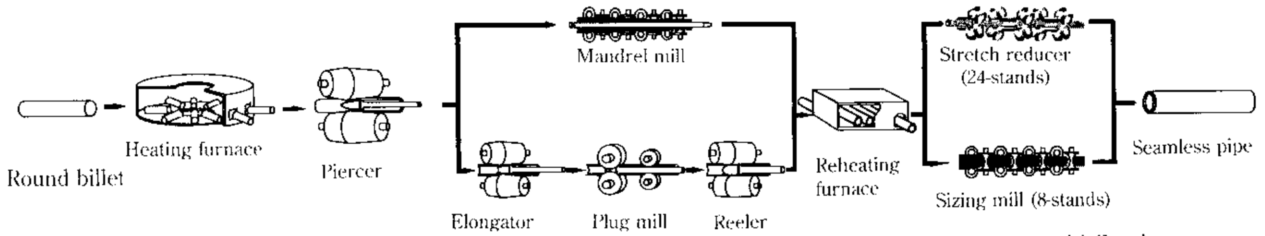



Fig. 1 Schematic flow diagram of manufacturing process of seamless pipe in Kawasaki Steel

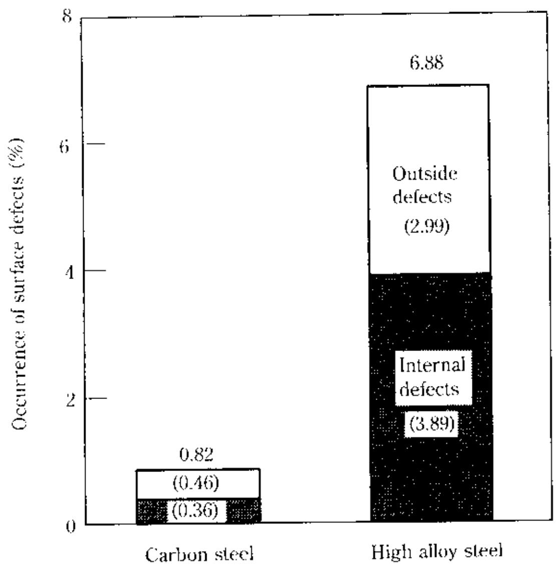



Fig. 2 Comparison with occurrence of surface defects between carbon steel and high alloy steel seamless pipe

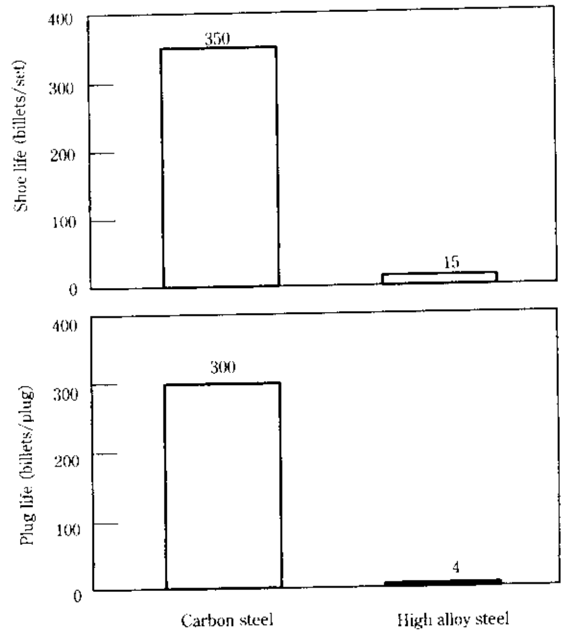



Fig. 3 Comparison with plug and shoe life for piercing between carbon steel and high alloy steel billets

parison with the rates for carbon steel pipe. When rolling high alloy steel, internal and external surface defects occur at a rate of approximately 7%, which is more than 8 times the rate of carbon steel. Internal and external surface defects tend to occur more easily in high alloy steel because the hot workability of the material is low. Further, as will be discussed later, because the life of the piercing plugs and shoes is extremely short, a large number of defects are also caused by metal adhesion and wear of the rolling tools.

**Figure 3** shows the life of the piercer plug and shoes in the piercing of the high alloy billets in comparison with the carbon steel. Plug life is extraordinarily short for high alloy steel, for approximately four billet rolling, which is about 1/80 the plug life for carbon steel. Similarly, the life of the fixed guide shoes in high alloy rolling is approximately 15 billet rolling, or less than 1/20 the shoe life in carbon steel rolling. These result in the increase of the rolling tool unit cost and deterioration of productivity due to the high frequency of tool exchanges.

## 3 Development of Rolling Technology for High Alloy Steels

### 3.1 Billet Heating Control

The results of a Gleeble test of typical high alloy steels used as material for seamless pipe are shown in **Fig. 4**, together with the values for carbon steel. At temperatures above the piercing temperature, which is 1 200°C or higher, the deformation resistance of high alloy steels is 60 MPa or more, or approximately 1.5 times the value of carbon steel. Because deformation resistance (and tensile strength) decrease as temperature increases, higher billet temperature seems advantageous to stable piercing.

However, the diameter reduction ratio of 13% Cr steel shows a sharp drop in the Gleeble test at temperatures over 1 280°C, and SUS 304 and 316L show a similar drop at temperature over 1 300°C. In the case of 13% Cr

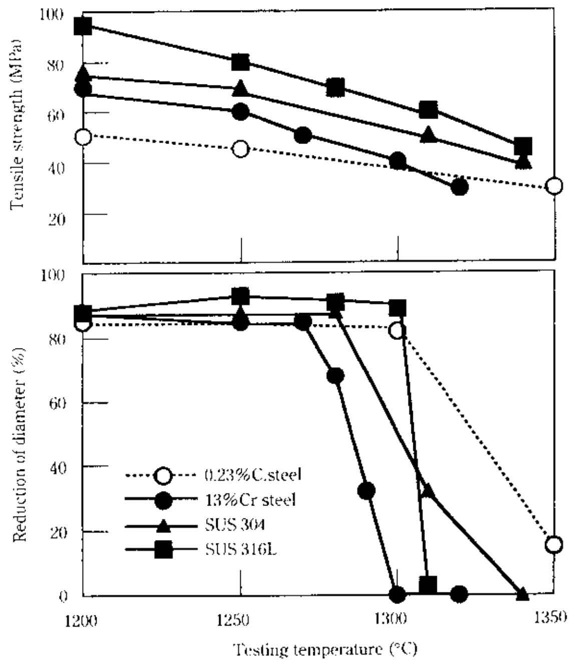



Fig. 4 Influence of testing temperature on reduction of diameter and tensile strength (on heating Gleeble test)

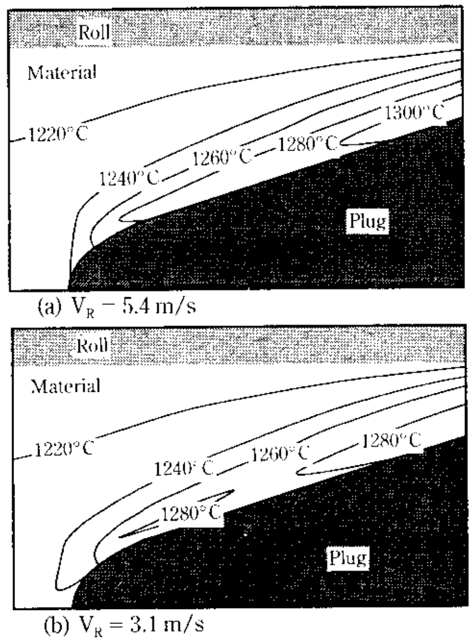



Fig. 5 Temperature distribution of SUS316L in piercing heating temperature of billet: 1 230°C, roll peripheral speed ($V_R$): (a) 5.4 m/s, (b) 3.1 m/s

steel, hot workability decreases markedly due to the precipitation of $\delta$ ferrite.[8,9] In SUS 304 and 316L, this decrease is caused by the grain boundary melting.[10,11] Thus, it is necessary for high alloy rolling to decide the rolling conditions to avoid the precipitation of $\delta$ ferrite and grain boundary melting when the billets are being heated and pierced.

A temperature simulation was, therefore, carried out by a heat transport analysis model considering the heat generation by working of the material and friction in order to estimate the trend of the temperature in the rolled material while the high alloy steel billet is pierced.[10] The temperature analysis was performed with the slab method in 2 dimensional cylindrical model considering the heat transfer between the pulg, rolled material, and rolls. The fundamental hypotheses are as follows.

(1) The rectangular rolled material at the entry remains rectangular at the exit (Additional shear strain is not considered).
(2) The effect of additional shear strain is considered in work-generated heat.
(3) The heat flow in the circumferential direction is ignored.
(4) The rolled material maintains round in the roll bite.
(5) There is no temperature distribution in the longitudinal direction of the billet at the entry side of rolling.

Because the amount of applied shear strain is large when a billet of high alloy steel is pierced, the billet is heated by work-generated and friction-generated heat to a higher temperature than the original reheating temperature. **Figure 5** shows the temperature distribution of the rolled material when billets of SUS 316L which had been heated to 1 230°C were pierced at roll circumferencial speed of 5.4 m/s and 3.1 m/s. When the billet was pierced at a circumferencial speed of 5.4 m/s, the material reached a temperature of more than 1 300°C, which is significantly higher than the original reheating temperature. On the other hand, the maximum temperature reached in rolling at a circumferencial speed of 3.1 m/s was approximately 1 280°C. Thus, it indicates that the deformation speed of the rolled material increased as the circumferencial speed of the rolls increased, and as a result, the amount of work-generated heat also increased. This shows that the temperature of the rolled material can be controled by changing the rolling speed. Conversely, when a billet of high alloy steel is pierced with a piercer, it is important to control the rolling speed, that is, the piercing deformation speed, in order to suppress work-generated heat in the rolled material, and thereby prevent internal defects.

**Figure 6** shows the appropriate range of the billet heating temperature and piercing deformation speed for 13% Cr steel in small-diameter seamless pipe. Internal cracks occur as the heating temperature and/or the deformation speed increase. It implies that $\delta$ ferrite tends to precipitate during piercing because the amount of work-generated heat increases at the higher deformation speed, and as a result, internal scab occurs. On the other hand, when the heating temperature is lower, inter-

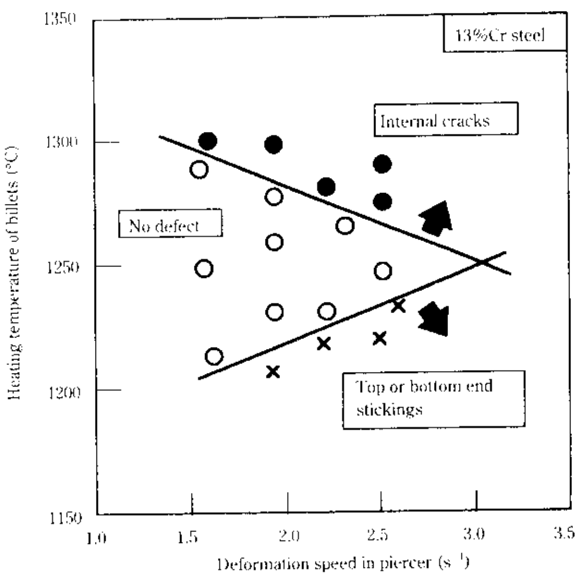



Fig. 6 Influence of heating temperature of billets and deformation speed in piercer on internal cracks and top or bottom end stickings

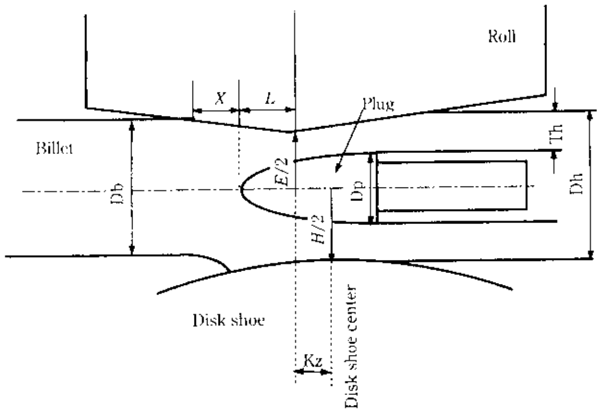
ruption of piercing at the top and botton end tend to occur more easily.

As discussed above, a billet temperature control technology, that is, a method of controlling the heating temperature and piecing speed, is important for stable piercing of high alloy steel and for preventing the internal defects. Therefore, the billet heating temperature and piercing deformation speed of 13% Cr steel, SUS 304, and other high alloy steels at the small-diameter and medium-diameter seamless pipe mills were optimized respectively, making it possible to manufacture high-quality seamless pipe stably.

### 3.2 Optimum Piercer Setting

In recent years, the rotary disk shoe (disk shoe) has been adopted in cross helical rolling mills for the purposes of increasing the life of the guide shoes and improving product quality. Kawasaki Steel also revamped the piercer at its small-diameter seamless pipe mill from fixed type guide shoes to disk shoes in 1988.

**Figure 7** is a conceptual diagram of a piercer using the disk shoe method. The piercer has a large degree of flexibility in the settings for obtaining hollow blooms of a target outer diameter (Dh) and wall thickness (Th). In other words, it is possible to obtain blooms of the same dimensions using various combinations of gorge ($E$), lead ($L$), shoe interval ($H$), and plug diameter (Dp). However, internal and external surface defects, wall thickness eccentricity, and interruption of piercing at the top and bottom end tend to occur easily with certain settings. Because this tendency is greater particularly in high alloy steel piercing, the optimization of all piercer settings is more important both for improving quality




Db: Diameter of billet
Dh: Outer diameter of hollow bloom
Th: Wall thickness of hollow bloom
$E$: Distance between rolls (Gorge)
Dp: Diameter of plug
$L$: Plug advance (Lead)
$X$: Distance from the first contact position of billet with roll to the top of plug
$H$: Distance between disk shoes
Kz: Longitudinal position of disk shoes

Fig. 7 Concept and notations of piercer with disk shoe

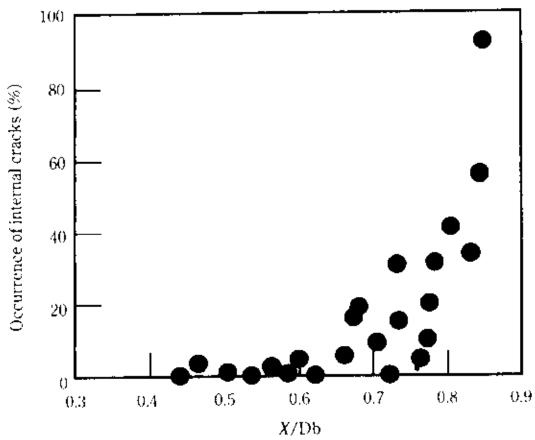



Fig. 8 Relation between $X$/Db and occurrence of internal cracks

and for stabilizing piercing when rolling high alloy steels.

**Figure 8** shows the relationship between the nonconforming ratio of internal scab and the ratio of the distance between the billet bite position in the piercer and the plug end to the billet diameter ($X$/Db). It indicates that the nonconforming ratio of internal scab increases sharply when $X$/Db exceeds 0.6. As the distance $X$ increases, the number of idle rotations from the time when the billet is bit by the rolls until the plug begins to piece the billet also increases. Therefore, it seems that mannesmann effect occurs more easily before the billet is pierced by the plug and nonconforming ratio of inter-

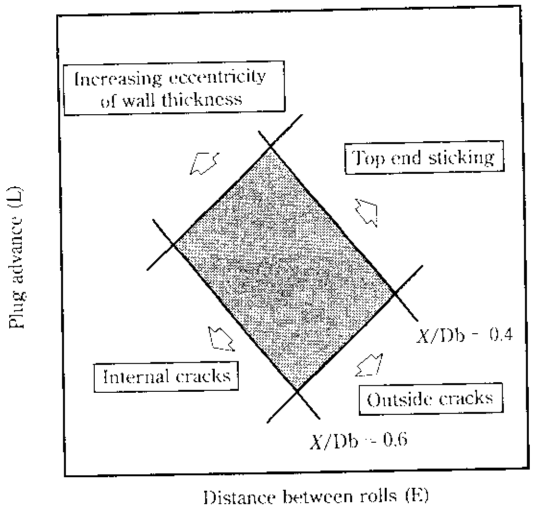



Fig. 9(a) Influence of distance between rolls and plug advance in piercer on internal and external cracks, top and bottom end stickings, eccentricity of wall thickness

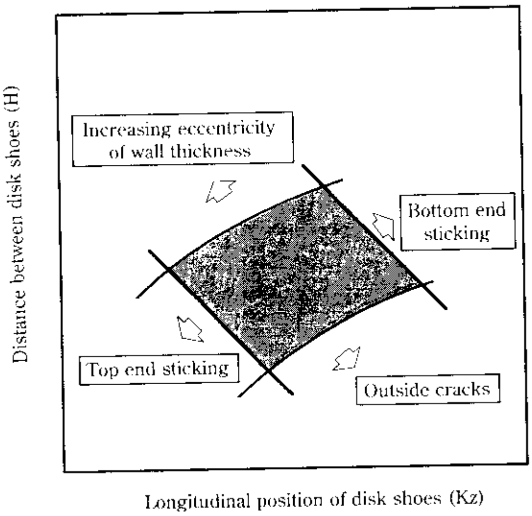



Fig. 9(b) Influence of distance and longitudinal position of disk shoes in piercer on internal and external cracks, top and bottom end stickings, eccentricity of wall thickness

nal scab increases as a result.

The relationship between the piercer setting and the nonconforming ratio of internal and external surface defects, ratio of wall thickness eccentricity, and interruption rate of piecring at the top and bottom end in high alloy steel was investigated in order to obtain the optimum ranges of piercer settings. The results are shown in **Figs. 9** (a) and (b). As seen in Fig. 8, when $X$/Db becomes greater than 0.6, the nonconforming ratio of internal scab increases. Conversely, when $X$/Db is smaller than 0.4, that is, when $E$ and $L$ become excessively large, the interruption rate of piercing at the top end increases. On the other hand, if $L$ and $H$ are increased while $E$ is decreased, the rate of wall thickness eccentricity in hollow blooms after piercing becomes worse. Considering the reverse case, if $E$ is increased and $L$ and $H$ are decreased, the disk shoes tend to adhere the metal and wear more easily, and as a result, the nonconforming ratio of external surface defects increases. Further, increasing the pipe longitudinal position of the disk shoes (Kz) and $H$ excessively increases the tendency of bottom end sticking, while reducing these two factors excessively increases the top end sticking.

Accordingly, in order to pierce high alloy steels without causing internal and external surface defects and interruption of piercing it is necessary to control each of the piercer settings, $E$, $L$, $H$ and Kz, within the appropriate range shown in Fig. 9. Conversely, it indicates optimizing the piercer settings makes it possible to pierce billets of high alloy steels such as 13% Cr, SUS 304, and others stably, without causing internal and external surface defects and failure of piercing.

### 3.3 Mandrel Mill Rolling

The hollow blooms obtained by piercing billets with the piercer are elongated at the mandrel mill. **Figure 10** shows a conceptual diagram of the cross-section of the mandrel mill rolling. At the mandrel mill, a hollow bloom is rolled using pairs of top and bottom caliber rolls and a mandrel bar, after that, the mandrel bar is extracted. However, failure of bar extraction sticking happens depending on the shape and dimensions of the shell after rolling. The rate of failure of rolling is high with thin-walled shells and high alloy steels in particular.

The pass schedule, setting of the roll gap and rotational speed, and roll groove design are important in mandrel mill rolling. Therefore, the design system for the pass schedule and groove of the mandrel mill rolling (MAP system) was developed.[12,13] This resulted in the stable rolling of both high alloy steel and thin-walled carbon steel materials.

At the mandrel mill, as shown in Fig. 10, the swell of

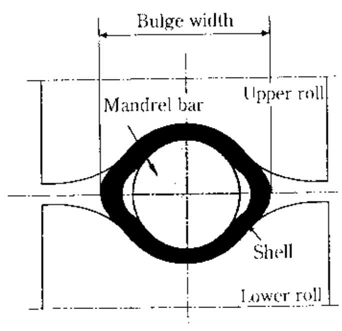



Fig. 10 Cross section profile of shell in rolling at mandrel mill

the rolled material at the flange known as bulge occurs. When the width of the bulge is excessive, internal defects (bulge defect) occur, while conversely, the mandrel bar tends to stick when the bulge width is insufficient. The high alloy steel has a higher tendency to generate the bulge defect and to stick to the bar compared with carbon steel. Moreover, even with a bulge width that is just a little bit large enough to avoid mandrel bar sticking, the mandrel bar can cause scratches on the inner surface of the shell, resulting in internal defects.

Therefore, a bulge gauge capable of measuring the bulge width during rolling was developed.[14] **Figure 11** shows the relationship between the bulge width at No. 4 stand and the nonconforming ratio of internal defects for 13% Cr steel. It should be noted that the bulge width is shown in non-dimensional value calculated with the groove configuration and roll gap. When the bulge width increases to more the 1.15, the bulge defect occurs. On the other hand, when the bulge width decreases to under 1.05, the shell is scratched by the bar. In other words, internal defects can be prevented by controlling the bulge width at No. 4 stand within the range of 1.05 and 1.15.

As described above the development of the MAP system and bulge gauge optimization of the roll groove design and bulge width, and other improvements for the mandrel mill at the small-diameter seamless pipe mill,

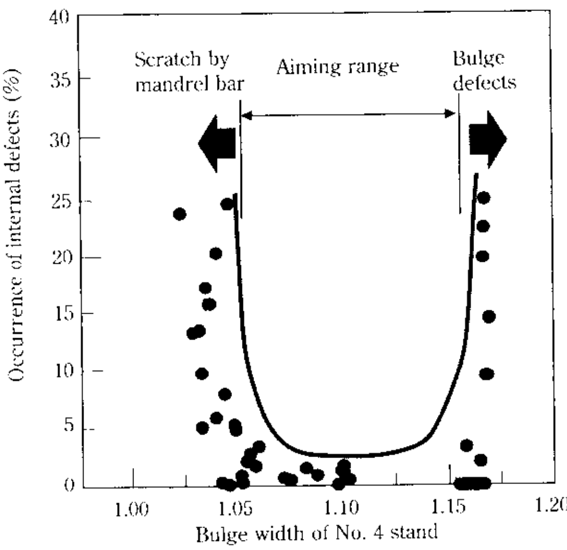



Fig. 11 Relation between bulge width on No. 4 stand and occurence of internal defects

have made it possible to roll 13% Cr steel and other high alloy steels seamless pipes with high quality and stability.

## 4 Development of Long Life Rolling Tools

At Kawasaki Steel, life extension techniques have been developed respectively for the plug, shoes, rolls, and other rolling tools.[15] The following will discuss outlines of these techniques. As mentioned previously, the lives of these rolling tools are very short when rolling 13% Cr steel and other high alloy steels compared with rolling carbon steel. In particular, the life of the piercer plug is extremely short. Therefore, a piercer plug for high alloy steels was newly developed.[16] **Table 1** shows the chemical composition, tensile strength at high temperature, thickness of the surface scale, and life of the newly developed plug compared with the conventional one. In comparison with the conventional material, which is a 3%Cr-1%Ni steel, the composition of the new plug, in which the Cr content was reduced to 0.5% and Nb, Mo, W, and Co were added, provide improved high-temperature tensile strength and thicker scale on the plug surface. As a result, the life of the plug has increased to more than three times.

A technology for extending shoe life will be described next. As mentioned in the previous section, disk shoes have been introduced at the small-diameter seamless pipe mill. With this disk-shaped shoe rotating in the bloom longitudinal direction the increase in the temperature of the shoe is reduced, because the contact surface between the rolled material and the shoe is constantly changing. Therefore, the shoe life rises dramatically in comparison with fixed type guide shoes. However, the slipping in the bloom circumferential direction between the rolled material and shoe which is larger than axial slipping and still remains in the rolling with the disk shoes causes the adhesion between the rolled material and shoes when high alloy steels are rolled. For this reason, a disk shoe lubricating system was also developed at the small-diameter seamless pipe mill.[17]

On the other hand, the drive roller shoe was developed at the medium-diameter seamless pipe mill, as illustrated in **Fig. 12**.[16] Because the drive roller shoe rotates in the circumferential direction, the slipping between the material and shoe is extremely slight. Therefore, adhesion have been completely eliminated not only in carbon steel, but also in high alloy steel. Because shoe wear is

Table 1 Comparison with chemical compositions, tensile strength, thickness of surface oxide and plug life between the conventional plug and improved one

| Plug | Chemical composition (wt%) | | | | | | | | Tensile strength at 1 200°C (MPa) | Thickness of surface oxide (mm) | Plug life (billets/plug) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ni | Nb | Mo | W | Co | Fe | | | |
| Conventional | 0.3 | 3.0 | 1.0 | — | — | — | — | bal. | 49 | 0.35 | 4 |
| Improved | 0.3 | 0.5 | 1.0 | 0.5 | 1.5 | 3.0 | 1.0 | bal. | 127 | 0.55 | 13 |

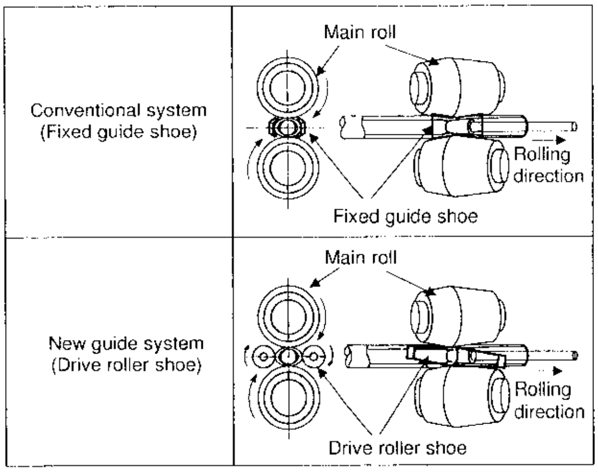



Fig. 12 Schematic diagrams of conventional fixed guide shoe and new guide, "drive roller shoe", in elongator mill

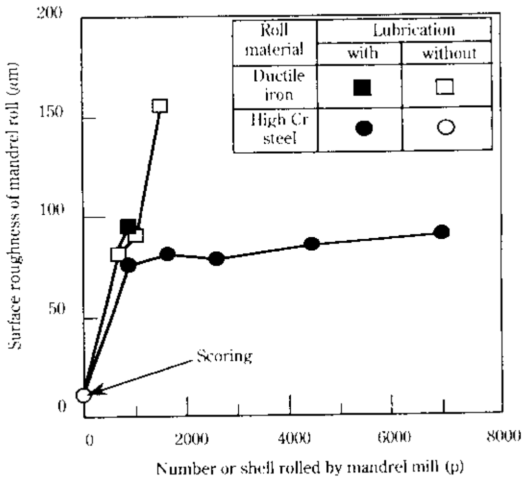



Fig. 13 Effect of roll material and lubrication on surface roughness of mandrel roll

also slight, the life of the shoe exceeds 30 000 billet rolling, which is approximately 100 times the life of the fixed type shoe. Furthermore, because the guide roller shoe has the effect of improving rolling efficiency and reducing the heat generated by friction, it is possible to improve productivity and also to reduce internal defects. As a result, it has become possible to produce high-quality high alloy steel seamless pipe with high productivity at the medium-diameter seamless pipe mill.

Finally, the techniques to extend roll life are discussed. Recently, high speed steel and high Cr cast steel have been adopted for hot rolling of steel strips in order to improve the roll life. However, mandrel mill, sizer, and similar equipment are tend to be sticked between the rolls and shell because the circumferencial speeds of the caliber bottom and flange are different. In particular, metal sticking at the flange causes a problem when large tonnages of 13% Cr and other high alloy steels are rolled using high speed steel or high Cr cast steel roll.

Therefore, a roll lubricating system was developed.[19] **Figure 13** shows the effect of lubrication on the roughness of the roll surface when using ductile cast iron and high Cr cast steel rolls for the mandrel mill. In case of the ductile cast iron rolls, the surface roughness increases sharply with the increase of the number of rolling, and it is necessary to exchange the rolls after approximately 2 000 rollings. On the other hand, in the rolling with high Cr steel rolls, adhesion occurrs immediately after rolling the high alloy steels without lubrication. However, it does not occur when roll lubrication is used. Moreover, the surface roughness of the rolls is stabilized at approximately 100 μm, more than 7 000 shells can be rolled with one set of rolls. Recent experiments shows more than 12 000 shells can be rolled by using high speed steel in combination with lubrication.

Similarly, lubricating systems were also developed for the hot stretch reducer and sizer mill.[20] These systems have provided long roll life without roll sticking even when rolling large tonnages of high alloy steel.

## 5 Improvement of Quality and Productivity of High Alloy Steel Seamless Pipe

As described above, rolling technology for high alloy steels and life extension technology for rolling tools were developed at the small-diameter and the medium-diameter seamless pipe mills. The nonconformance ratios of internal and external surface defects of 13% Cr steel, SUS 304, and other high alloy steel seamless pipes before and after the development of these technologies are shown in **Fig. 14**. The development of the technology for rolling high alloy steels and the life extension technology for rolling tools has made it possible to

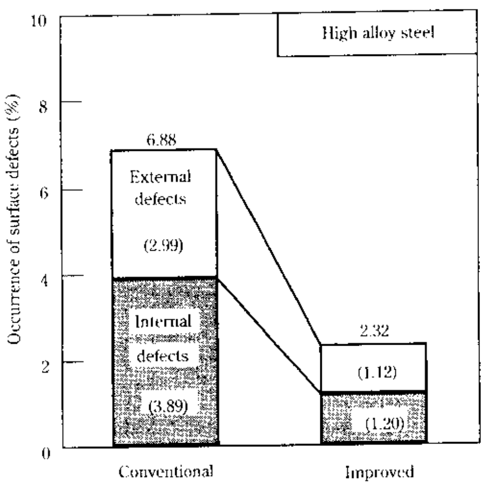



Fig. 14 Comparison with occurrence of surface defects of high alloy steel seamless pipe

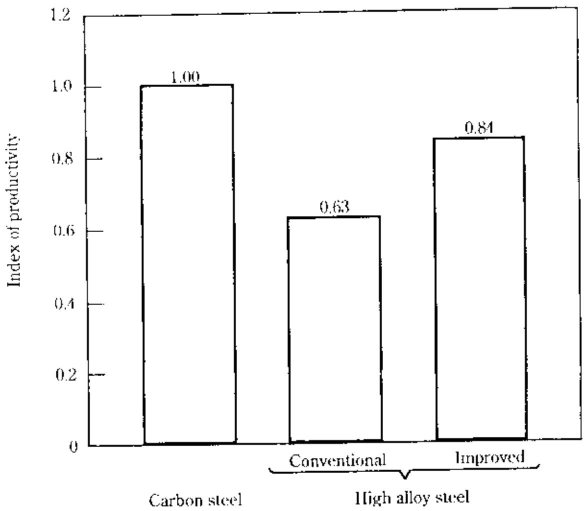



Fig. 15 Comparison with productivity of carbon steel and high alloy steel seamless pipe rolled by Mannesmann process

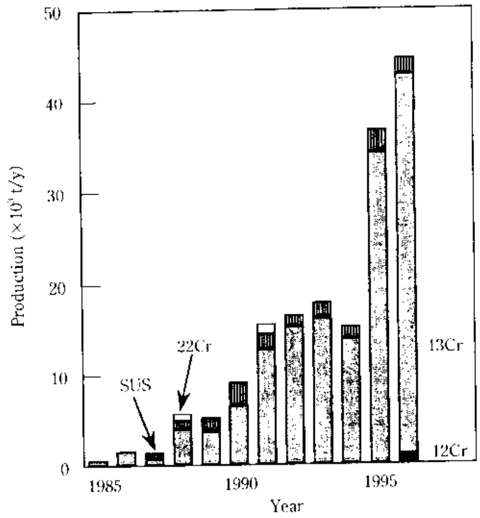



Fig. 16 Production of high alloy steel seamless pipes by Kawasaki Steel

reduce both internal and external surface defects to approximately 1/3 time the previous levels.

**Figure 15** shows the productivity of high alloy steel rolling before and after the development of these technologies in comparison with the productivity of carbon steel. With the conventional technology, the productivity of high alloy steels was approximately 63% that of carbon steel. The development of life extension technology for rolling tools and other measures has improved the productivity of high alloy steels by approximately 20%.

More specifically, the rate of occurrence of internal and external surface defects of high alloy steel seamless pipe has been reduced to approximately 1/3 the former level, and productivity has risen by approximately 20%. Furthermore, the life of rolling tools has been improved to roughly 3–100 times. As a result of these improvements, the production of high alloy steel seamless pipe has increased dramatically. **Figure 16** shows the trend in the annual output of high alloy steel seamless pipe at Kawasaki Steel. The company began the 13% Cr steel pipe production in 1982, SUS 304 and other austenitic stainless steel pipes in 1987, and 22% Cr steel pipe in 1988. Annual production exceeded 10 000 t for the first time in 1991, and has subsequently shown marked increases, reaching more than 40 000 t in 1996. The increase in the production of 13% Cr steel tubes for OCTG has been remarkable. In addition, a weldable 12% Cr steel pipe for line pipes was developed in 1996.

As described above, the development of a rolling technology for high alloy steel and a life extension technology for rolling tools has made it possible to produce seamless pipe of 13% Cr steel, SUS 304, and other high alloy steels with high quality and high productivity. As a result, it has become possible to produce high alloy steel seamless pipe in quantities of more than 40 000 t annually at Kawasaki Steel.

## 6 Conclusion

At Kawasaki Steel production technologies were developed for high alloy steel seamless pipe of 13% Cr steel, SUS 304, and others, with the following results.

(1) AS a rolling technology for high alloy steels, a billet temperature controlling technology by controlling the billet heating temperature and piercer deformation speed was developed.

(2) A piercer setting optimization technology was developed, making it possible to reduce the internal and external surface defects, interruption of rolling at the top and bottom end, and so on even when rolling high alloy steel billets.

(3) A mandrel mill rolling technology was established by developing the MAP system and bulge gauge, and by optimizing the roll caliber configuration and bulge width.

(4) As a technology for improving the tool life when rolling high alloy steels, a piercer plug for high alloy steels, disk shoe lubricating system, drive roller shoe, and roll lubricating systems for the mandrel mill and other equipment were developed.

(5) The technical development described above has reduced the nonconforming ratio of internal and external surface defects in high alloy steel seamless pipe to 1/3 the previous level and has improved productivity by approximately 20%. Further, the life of tools when rolling high alloy steels has improved to 3–100 times or more.

(6) As a result, it has become possible to manufacture 13% Cr steel, SUS 304, and other high alloy steel seamless pipe with high quality and high productivity. Thus, the production of high alloy steel seamless pipe

has increased dramatically, making it possible to produce more than 40 000 t annually.

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