Long Life Copper Stave for Blast Furnace Developed by Nippon Steel Engineering

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Summary

Stave is the equipment for maintaining the furnace inside profile and protecting the furnace shell from the high temperature gas or molten material. Among them, Cu stave is installed to lower part of blast furnace in a high heat region. The water channel of conventional Cu stave is made by drilling to the copper plate. On the other hand, the water channel of the newly developed cast-in steel pipe Cu stave is made by casting the bent steel pipe in the copper body. The functions required for stave is classified in 3 points; 1) Long life and high reliability, 2) Appropriate cooling performance and 3)Heat insulation performance. Cast-in steel pipe Cu stave has excellent performance in these 3 functions than conventional one. In this paper, the advantages in technology of cast-in steel pipe Cu stave are described.

Key Words

Life-cycle cost reduction, Long life Cu stave, Stave cooler, Blast furnace

1. Introduction

Amid the growing international concerns for global warming, the demand for reducing greenhouse gas emissions, particularly the emission of CO2, is increasing. CO2 emissions from the steel industry are very high at 15% of the world's total CO2 emission, 70% or more of which is from the pig iron making process. Since a major part of CO2 emissions depends on the energy efficiency of the equipment, the steel industry is required to use BF with higher energy efficiency.

Nippon Steel Engineering have constructed and revamped more than 70 BF over the past 50 years. In each project, starting from the study of operational specifications, we handled the design, manufacture, and construction of the entire blast furnace equipment. Based on the experience obtained from working with such a wide range of processes, we have developed various types of energy-saving equipment.

BF provided by us and used in Japan's steel industry, which is one of the most advanced steel industries in terms of energy-saving, have achieved the world's lowest energy consumption for manufacturing of a ton of crude steel.

Since a BF is situated in the upstream in a steel plant, and it also operates throughout the year, those with longer life and higher reliability are desired. In this respect, we are using our wide-ranging expertise fostered through the extensive experience for the development and design of the equipment life extension.

This paper describes the cast-in steel pipe Cu stave that is one of the long-life, energy-saving equipment we have developed.

2. What is a Cu stave?

The Plant Machinery Division at Nippon Steel Corporation (which later became Nippon Steel Engineering) incorporated the technology of cast iron staves from the Soviet Union in 1969 for the first time. Since then, we have repeatedly improved the technology based on the results of the use under actual operation. As a result, we have succeeded in extending the average furnace life from 5 to 7 years to 15 to 16 years. We have delivered this cast iron stave to about 180 BF both in Japan and overseas, and contributed to the furnace life extension.

However, even longer furnace life, over 20 years, is now desired. The cast iron stave, due to its material characteristics, causes material deterioration at the lower part of the BF, which is exposed to high heat load. This has made it difficult to achieve stable furnace life of 20 years using the cast iron stave. As an alternative cooling means to the cast iron stave considering the high heat load, the rolled Cu stave was developed. This type of stave is made from a rolled copper plate on which holes are drilled and water supply and drain pipes are welded to form water channels. The use of rolled Cu staves was started in Germany in the mid-1990s, and has been spread to BF in many countries.

Other Cu staves developed to date include cast Cu staves with water channels formed using a core in the casting process, and cast-in monel pipe Cu staves with water channels formed using monel pipes bent into a channel shape and cast.

However, these Cu staves had the problems as described below. To solve these problems, we made the best use of our manufacturing and design expertise regarding cast-iron staves accumulated over 40 years to develop the cast-in steel pipe Cu stave, which has been used in actual BF since 2004.

3. What is a cast-In steel pipe Cu stave?

Currently, the most popular type of Cu stave is the rolled Cu stave, the manufacturing process of which involves drilling holes in a copper plate as described above. The water channel ends of this stave are plug-welded.

The cast-in steel pipe Cu stave developed by us is made by casting bent steel pipes into the copper, a completely different manufacturing process from that of the conventional rolled Cu stave. This unique manufacturing method has enabled achieving high energy efficiency and long life of BF, which cannot be achieved using the rolled Cu stave.

4. Properties required for a stave

To reduce and melt iron ore, high-temperature gas around 1,200°C is blown into a BF. A stave is a cooling facility installed on the inner surface of the shell to protect the shell from the high-temperature gas and molten burden material in the furnace, maintaining the profile inside the furnace. The following three properties are mainly required for a stave.

(1) Long life and reliability
Since it is impossible to repair a stave from outside of the BF due to its structure, extensive replacement work is required when the stave is damaged. Damaged staves have serious adverse effects on plant operations, causing a long blow-down, the temperature drop inside the furnace due to water leakage, or changing the profile which may result in operational failure. For this reason, stable long life is required for staves.

(2) Appropriate cooling ability
To protect the shell from high-temperature gas around 1,200°C and molten material, appropriate cooling ability is required for staves. Since high cooling ability is required for cooling the furnace part between the bosh and lower part of the shaft, which is exposed to high temperature, a Cu stave is used for this part in many cases.

(3) Thermal insulation ability
A BF in which iron oxide is reduced and melted at high temperature is desired to have a heat insulation structure not to waste thermal energy. On the other hand, as described above, a stave is cooled to maintain the profile inside the BF and to protect the shell. Therefore, it removes thermal energy from the high-temperature gas and material. Removing heat by a stave involves the equivalent fuel (coke) consumption, directly causing an increase in the reducing agent rate (RAR). An increase in the RAR may in turn lead to an increase in CO_2 emissions and rise of the unit price of molten pig iron. For this reason, a stave must have appropriate heat insulation (heat removal restriction) ability to minimize heat energy taken from inside the furnace, as well as appropriate cooling ability.

Conventionally, bricks with low thermal conductivity are embedded at the front of a cast iron stave to obtain both cooling ability and heat insulation ability.

Meanwhile, a Cu stave is used to form a heat insulation layer from semi-molten material located in front of the stave by cooling such material with the high cooling ability to make it adhere to the inner surface of the stave.

In the following chapter, we discuss the differences and advantages of the cast-in steel pipe Cu stave compared with the rolled Cu stave regarding these properties.

5. Technical advantages of the cast-In steel pipe Cu stave

5.1 Long life and reliability

Rolled Cu staves sometimes have the following three problems.

(1) Deformation
Rolled Cu staves are warped due to the difference in thermal expansion between the stave inner surface, which is exposed to high temperature gas, and the stave outer surface, which is cooled. They are seriously deformed when a stave is too long or when the positions of fixing bolts are not appropriate.

Such deformation may cause wearing of a protruding portion and breakage of a weld due to high temperature gas flowing to stave joints and back surfaces.

(2) Weld cracking due to thermal fatigue
Welds of rolled Cu staves are subjected to repeated thermal stresses due to the temperature fluctuation, resulting in cracking and breakage.

(3) Wear
Iron ore, sintered steel, and coke, have higher hardness than that of copper, abrade Cu staves when they contact the stave surface and descend. In

general, the wear rate of a Cu stave depends on the contact force and descending speed of the material in contact with the stave surface, hardness of the copper and material, and the shape of the material.

To solve these problems, we started the development of a new Cu stave that has three advantages.

5.1.1 Deformation resistance

For the prevention of deformation, appropriate design of the stave length and bolt constrained points is important. The use of the cast-in steel pipe Cu stave with its own design is beneficial for effectively reducing the risk of deformation.
Figure 1 shows the constrained points of a rolled Cu stave and the cast-in steel pipe Cu stave.

(1) Rolled Cu stave
A rolled Cu stave is constrained to the shell by mounting bolts and pins. To prevent the weld at the base of a rising pipe from being damaged by stresses, rising piping is connected to the shell by an expansion joint. Due to this structure, the upper and lower ends of the stave are freely displaced, causing the stave to be easily deformed. The large thermal load that is repeatedly applied to the Cu stave in the course of the fluctuation in BF operations, etc., causes plastic strain to be gradually accumulated, and results in large deformation. There are cases in which the deformation at the upper end reached 50 mm or more and a weld was broken, under the condition of an overly long stave, an inappropriate bolt position, or high heat load exceeding the design condition.

(2) Cast-in steel pipe Cu stave
The cast-in steel pipe Cu stave has the following three deformation-resistant features.

1) Constraint of protective pipe
As shown in Figure 1, for the cast-in steel pipe Cu stave, gas seal boxes in addition to bolts are used to fix the protective pipes at the ends of the stave. This applies the displacement constraint to the upper and lower ends of the stave. Furthermore, as shown in Figure 2, since the protective pipe is casted in the body of the Cu stave, there are no welds with a breakage risk.

2) Frame structure with cast-in pipes
As shown in Figure 1, the cast-in steel pipe Cu stave uses steel pipes, which are stiffer than copper and serve as the framework. The use of steel pipes provides a structure that is more deformation-resistant than conventional Cu staves.

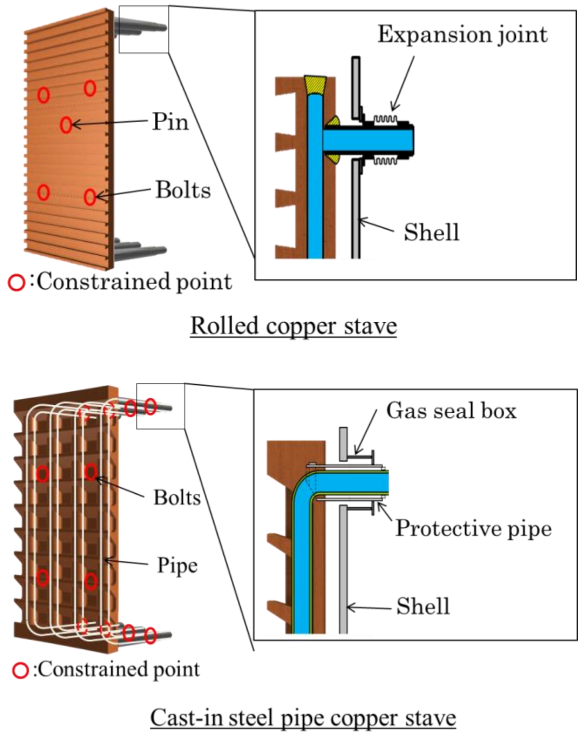

Figure 1: Difference of positions of constrained points

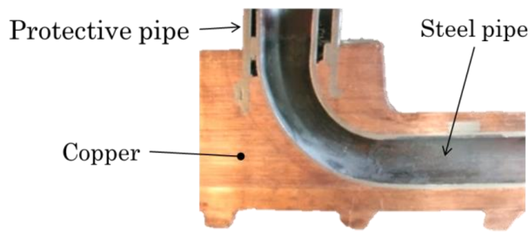

Figure 2: Structure of protective pipe

3) Cooling and stress mitigation using a bumpy stave inner surface
The inner surface of the cast-in steel pipe Cu stave is made bumpy. Figure 3 shows the cross-sectional shapes of a rolled Cu stave and the cast-in steel pipe Cu stave. Since rolled Cu staves have a rectangular cross-sectional shape, the temperature increases at locations on the stave inner surface far from water channels. In contrast, the cast-in steel pipe Cu stave uses a bumpy surface to render the equivalent distance between the stave inner surface and each water channel. This allows the stave inner surface to be uniformly cooled. Such uniform cooling in turn reduces the temperature difference between the stave inner and outer surfaces, and suppresses thermal stresses and deformation.

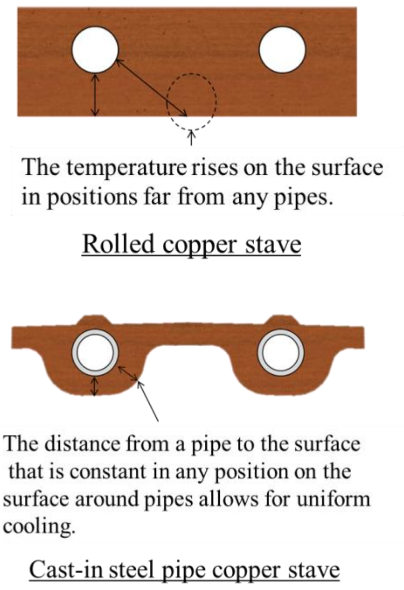

Figure 3: Uniform cooling by bumpy shape

Furthermore, as shown in Figure 4, under large thermal load, compression plastic strain is caused on the stave inner surface of a rolled Cu stave by the temperature difference between the stave inner and outer surfaces, which may lead to stave deformation. In contrast, the inner surface of the cast-in steel pipe Cu stave is isolated at each bump, thereby making compression stresses less likely to act on the stave and suppressing plastic strain.

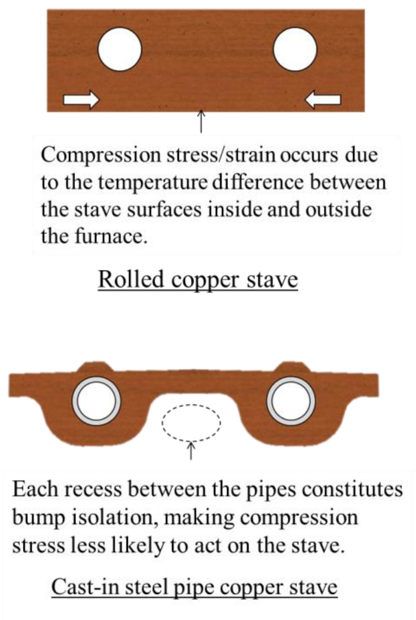

Figure4: Stress reduction by bumpy shape

As described above, the bumpy surface of the cast-in steel pipe Cu stave reduces stresses and strains that act on the stave, and suppresses deformation.

According to the analysis results of thermal stress on the cast-in steel pipe Cu stave under large thermal load as shown in Figure 5, the warped amount is approx. 1.2 mm. This level of protrusion of the stave is considered sufficiently small to prevent any problems.

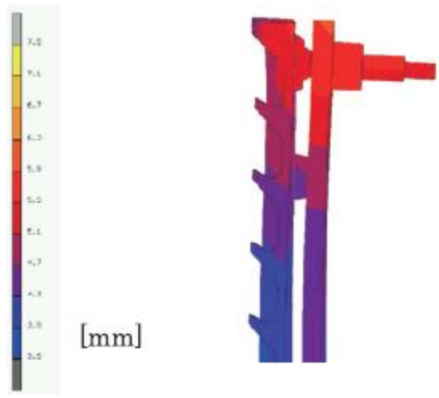

Figure 5: Deformation quantity

5.1.2 Eliminating the risk for weld breakage using a weldless structure

Since the cast-in steel pipe Cu stave forms water channels using steel pipes, plug welding or pipe connection welding, which are indispensable for making rolled Cu staves, are not necessary. By avoiding the use of welding, which is structurally weak parts, the risk for breakage of welds can be eliminated. (See Figure 6)

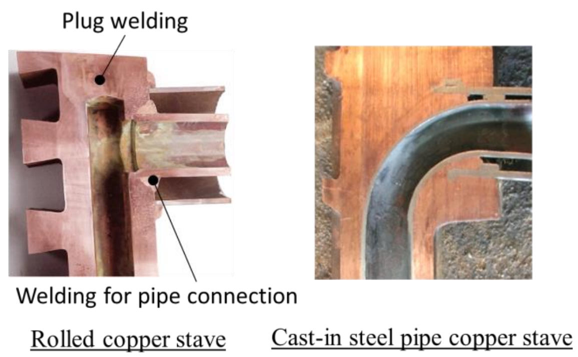

Figure 6: Difference of channel forming method

5.1.3 Wear resistance

Cu staves prevent wear by the scabs formed by using its high cooling ability, thereby avoiding direct contact with the descending material in front of the stave.

However, such accretion often falls off due to fluctuations during furnace operations. Without accretion, the wear of a Cu stave depends on the contact force and descending speed of the material in front of the stave, hardness of copper and the material, and shape of the material.

Given this, countermeasures against wear feasible for a stave include reducing the contact force and descending speed of the material when there is no accretion, in addition to stably retaining accretion, as well as not allowing the hardness of copper to be reduced.

While grooves for rolled Cu staves is formed by machining, the cast-in steel pipe Cu stave forms ribs by integrally casting, allowing for forming as-desired rib shapes. Based on this feature, we have developed an upward rib structure with wear resistance. (See Figure 7.) The hardness of copper depends on the cooling ability that will be described in 5.2.

(1) Self-linings made from accretion

The cast-in steel pipe Cu stave has high material retention force due to the use of upward & large ribs. The scab formed in front of the upward ribs remains and suitably prevents wear of the staves.

(2) Reduction of the contact force and descending speed of material

If there is no accretion inside-furnace surface of a rolled Cu stave, material once entered between ribs hardly moves because the ribs are small. Therefore, material in front of the stave descends without being influenced by the ribs. In contrast, since the ribs of the cast-in steel pipe Cu stave face upward and are large, material that has entered between the ribs is discharged back into the furnace, creating a flow (load transfer). At this time, the material is discharged upward. This upward flow pushes the material in front of the stave back to the furnace, causing the contact force and descending speed of the material to be reduced at the rib tips.

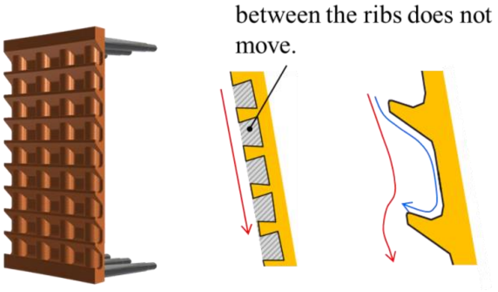

Figure 7: Upward ribs (Cross section)

Figure 8 shows the results of a DEM (discrete element method) analysis in which material is modeled using particles to simulate the material descending behavior.

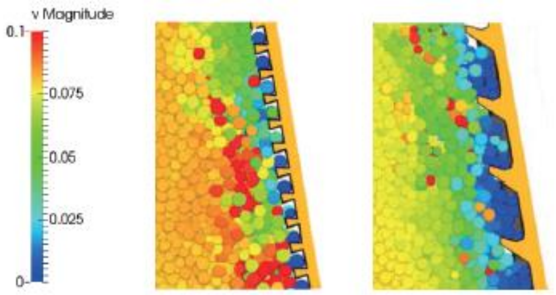

Figure 8: Simulation for burden descending behavior by DEM analysis

Figure 8 shows that a stagnation layer consists of slowly descending material formed on the stave surface due to the effect of the upward ribs described above. According to the results of the DEM analysis, the contact force acting on the rib tips was reduced by approx. 40%, and the descending speed of the material was reduced by 60 to 70%.

Assuming that the wearing rate is in proportion to the product obtained by multiplying the contact force by descending speed, reductions in the contact force and descending speed cause the wearing rate to be approx. 0.25 times. Thus, the stave life is expected to extend nearly 4 times.

For new BF, we have achieved a longer Cu stave life by designing the optimum profile in the furnace and stave rib shape. For existing BF with Cu staves rapidly worn by contact force and descending speed increased due to an inadequate profile, or worn by material with increased descending speed during operations at the high pig iron tapping ratio, both the contact force and descending speed of the material can be reduced by replacing existing rolled Cu staves with our staves. If the life of an existing stave is 5–6 years, it can be extended 4 times to approx. 20 years.

5.2 Appropriate cooling ability

To prevent a stave shell from being damaged and also prevent a Cu stave from deformation and wearing due to a decrease in the copper hardness, it is required to maintain the appropriate cooling ability throughout the furnace life. Although regarding the cast-in steel pipe Cu stave there are concerns about insufficient cooling ability due to steel pipes with low heat conductivity located on thermal conductive pathways and about the separation of steel pipes from copper impairing the cooling ability, these problems have already been solved by the following technologies.

(1) Cooling ability

Table 1 shows the purity and thermal conductivity of the copper used for rolled Cu staves, cast Cu staves, and the cast-in steel pipe Cu stave. Although the cast-in steel pipe Cu stave has low cooling ability when compared with rolled Cu staves made of high-purity copper only, the cooling ability of the cast-in steel pipe Cu stave, which uses 99.9% high-purity copper, supersedes that of cast Cu staves with a proven track record.

Table 1: Thermal conductivity for each Cu staves

Type of Cu stave		Material	Purity of Copper	Thermal Conductivity [kcal/m-h-°C]
Rolled & Drilled Type		Rolled copper	≥ 99.9%	315
Cast Type		Cast Copper (CAC101)	≥ 99.5%	173
Cast-in Steel Pipe Type	Copper	Cast Copper (CAC103)	≥ 99.9%	260
	Pipe	Steel Pipe	—	40

Figure 9 shows the results of 3D thermal conductivity analysis for each Cu stave. The surface temperature of the cast-in steel pipe Cu stave inside the furnace is lower than that of cast Cu staves with a proven track record, thus indicating impeccable cooling ability.

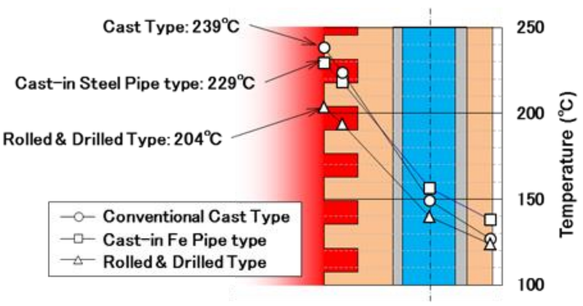

Figure 9: Results of 3D thermal conductivity analysis

(2) Adhesion between copper and steel pipes

To maintain the cooling ability of the cast-in steel pipe Cu stave, joint surfaces of the copper base metal and a steel pipe adhering to each other are required to not separate, withstanding repeated stresses from thermal fluctuation inside the furnace. If the joint surfaces are separated, the heat transfer ability of the stave between the copper base metal and steel pipe is impaired, increasing the risk of base metal temperature rise resulting in problems. For removing such a risk, we have developed unique manufacturing technologies to obtain high adhesion between the copper and steel pipes.

Various examinations as described below were conducted through which the adhesion between the copper and steel pipes was verified, and the reliability was checked.

i) Metal structure observation by EPMA

Figure 10 shows the results of metal structure observation using an EPMA (electron probe micro analyzer) at the boundary between the copper and a steel pipe. The left side in the two images shows the Fe distribution, and the right side shows the Cu distribution. At the joint, Fe and Cu mutually diffuse, showing that a strong joint surface is formed.

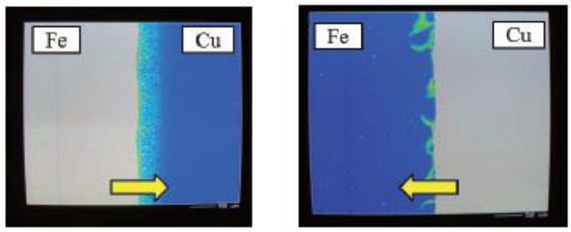

Figure 10: Observation of metal structure by EPMA

ii) Tensile test and shear strength test

To evaluate the mechanical adhesive strength between the copper and steel pipes, we conducted a tensile test and shear strength test under a high temperature at 400°C. Figure 11 shows the result of the tensile test. Figure 13 shows the result of the shear strength test. During both tests, while no fracture occurred on the surface on which copper and steel adhere to each other, the copper side fractured. Thus, the part at which copper and steel adhere to each other has sufficient strength exceeding the mechanical strength of the copper base metal.

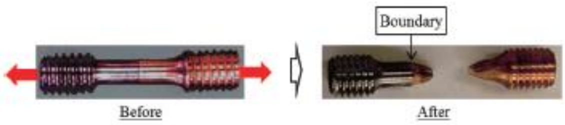

Figure 11: Tensile strength test of adhesion part

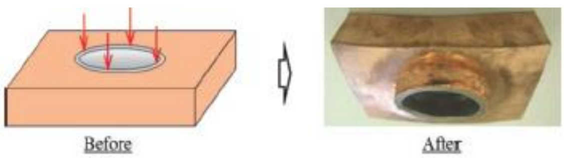

Figure 12: Shear strength test of adhesion part

iii) Heat shock test

To confirm the adhesion and thermal conductivity between the copper and steel pipes after undergoing repeated thermal load, we conducted a heat shock test as shown in Figure 13. For the examination, we applied heat shocks to the specimen by heating the top surface of the specimen using a burner until the temperature in the position approx. 10 mm above the steel pipe was elevated to 400°C, and then cooled the specimen by running cooling water through the pipe (Figure 14). This process was repeated 20 times. Since the surface temperature of Cu staves 50 mm or more away from the pipe is usually controlled to not exceed the level of 200–250°C, the thermal load in this test was more severe than during actual furnace operations.

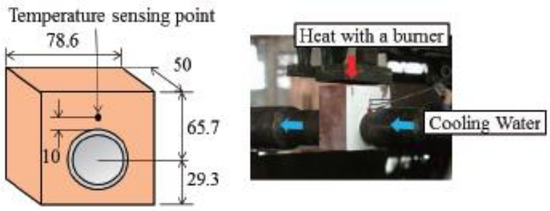

Figure 13: Examination of heat shock

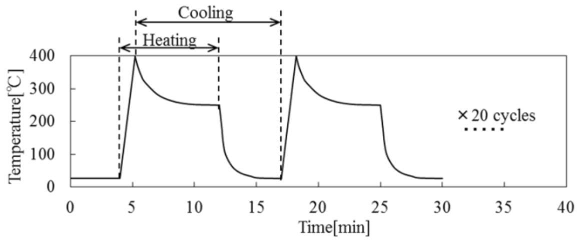

Figure 14: Condition of heat load

As a result, after sustained repeated heat shocks of the specimen, neither the separation of the pipe from the base metal at the joint surface nor deterioration of thermal conductivity was observed. In view of the result of this examination, no separation at the joint surface or reduction of the thermal conductivity is expected under the conditions of the furnace operations.

As discussed above, there is no concern such as insufficient cooling ability or separation of the steel pipes from the copper in the practical use of the cast-in steel pipe Cu stave.

5.3 Thermal insulation ability

The upward ribs of the cast-in steel pipe Cu stave allow for stable formation of a self-lining layer that prevents the stave from wearing and serves as a heat insulation layer on the inner surface.
Figure 15 graphically illustrates the temperature measured for a week at the rib tip of a rolled Cu stave and the cast-in steel pipe Cu stave those are installed at the shaft level.

Comparing the two staves, we can see that the cast-in steel pipe Cu stave has smaller temperature fluctuation than that of the rolled Cu stave. It appears that this is caused by a stable accretion or stagnation layer thanks to the upward ribs. This can be seen from the DEM analysis results shown in Figure 8. Since the accretion and stagnation layer have lower heat conductivity than that of copper, they work as a thermal insulation layer.

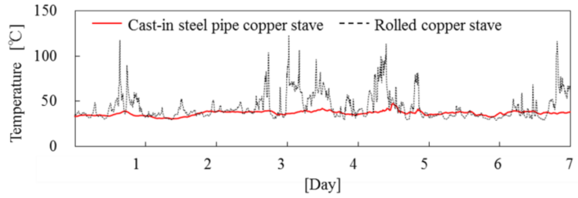

Figure 15: Temperature data of Cu stave

Figure 16 shows the results of heat conductivity analysis when the stave inner surface is heated for each rolled Cu stave and cast-in steel pipe Cu stave assuming that material is adhered between the ribs of both staves. Comparing the two staves, the average temperature of the cast-in steel pipe Cu stave's inner surface was higher by approx. 70°C than that of the rolled Cu stave. Possible causes of this difference are considered below.

- **Larger pitch of the ribs**

Copper has high thermal conductivity and low temperature is maintained at the rib tips. Since the cast-in steel pipe Cu stave has large pitch of the ribs, it can reduce the area of each rib tip that is in contact with gas in the furnace.

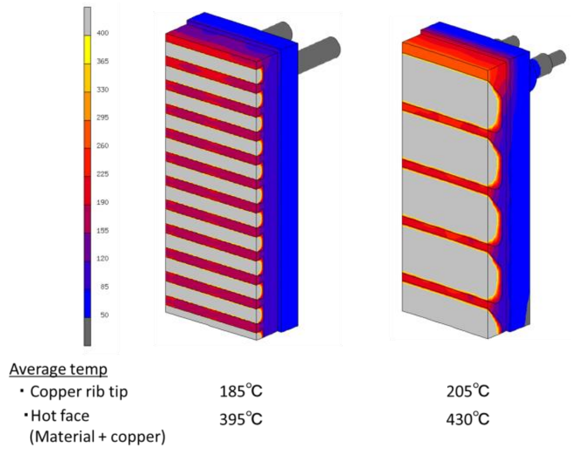

Figure 16: Results of 3D thermal conductivity analysis

- **Deeper ribs**

The cast-in steel pipe Cu stave, as shown in Figure 7, is enabled to have deeper ribs than those of rolled Cu staves by the bumpy inner surface. This allows the material adhering to the stave between the ribs to be thick.

Since the heat transfer coefficient is determined by dividing the thermal conductivity by thickness, the thicker the accretion is, the lower the heat transfer coefficient becomes and the higher the surface temperature of the adhering material becomes as well. Therefore, the average temperature on the surface of the accretion inside the furnace of the cast-in steel pipe Cu stave is higher than that of rolled Cu stave.

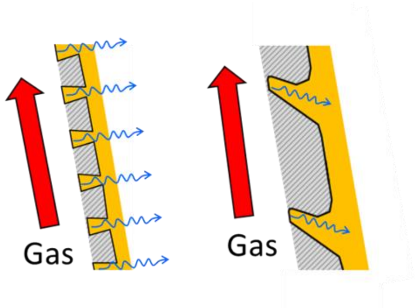

Figure 17: Difference of the extraction of heat

As the surface temperature becomes high, the temperature difference between the working surface and gas inside the furnace becomes smaller. This reduces the removed amount of heat. The amount of heat removed by the gas inside the furnace can be expressed using the following equation.

$$q=Q/A=h\times\Delta T$$

From a calculation using the equation, the difference of removed heat caused by the temperature difference by 35°C is approx. 0.01 MW/m2.

By suppressing heat removal from the furnace, the consumption of coke equivalent to the removed amount of heat can be reduced as well. In the case of a 5,000 m3-class BF for instance, this means a coke consumption reduction of nearly 7,000 tons per year.

6 Other Characteristics of the Cast-In Steel Pipe Cu stave

In addition to the technical advantages in extending life and saving energy, the cast-in steel pipe Cu stave has also the characteristic of the high design flexibility.

When a cast iron stave or cooling plate that a BF uses is broken and something needs to be done in order to extend the life, the replacement with a Cu stave using the existing shell opening may be required.

In the case of rolled Cu staves, since water channels are formed by drilling, the water channel layout is restricted, making it difficult to freely form water channels in a manner tailored to the existing shell opening. In contrast, water channels of the cast-in steel pipe Cu stave, which are formed using bent steel pipes, allow for flexible layout adopting steel pipes for the existing opening of the shell (Figure 19).

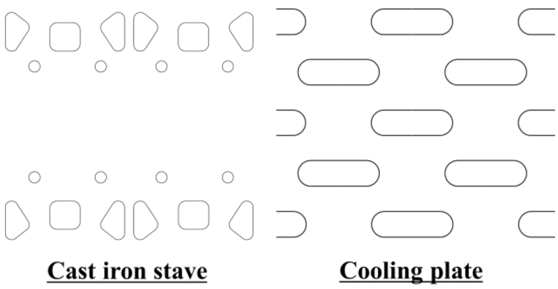

Figure 18: Shell openings for cast iron stave and cooling plate

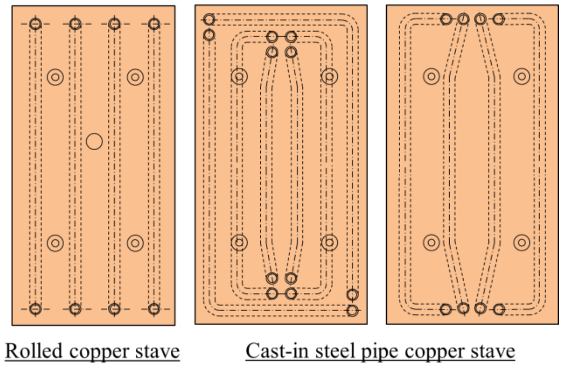

Figure 19: High flexibility of cooling channel layout

7 Track Record of Use at Actual Plants

Multiple furnaces in operation have already adopted the cast-in steel pipe Cu stave (615 pcs of staves have been delivered and 140 pcs under construction), and these furnaces have been stably operated since.

SSAB Raahe steel BF No.2
One of those is a SSAB Raahe steel (former name: Rautaruukki) BF No. 2, to which the cast-in steel pipe Cu stave with the upward ribs had been set in the part between the bosh and lower stack as shown in Figure 20.

In the case of Raahe BF No. 2, the maximum amount of wear on the Cu stave surface was 0.3 mm/year. This indicates that the stave life likely be more than 20 years.

USIMINAS Ipatinga BF No.3
From 2015, cast-in Cu staves for belly to lower shaft were installed and now being operated without any wear and other trouble.

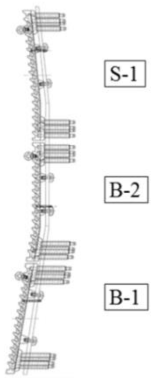

Figure 20: Raahe No. 2BF

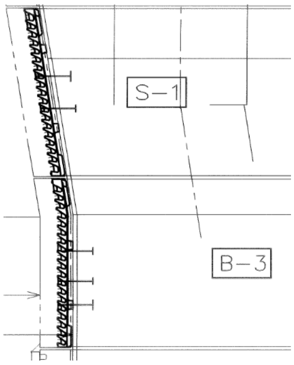

Figure 21: Ipatinga No. 3BF

8 Conclusion

The cast-in steel pipe Cu stave has the following technical advantages over rolled Cu staves.

(1) Longer life
The main problems of Cu staves are (1) deformation; (2) damage of welds; and (3) wear. For the cast-in steel pipe Cu stave, unique countermeasures against these issues have been taken, greatly reducing or even eliminating the risks of the problems.

(2) Appropriate cooling ability
The unique manufacturing method we have developed has allowed for strong adhesion of steel pipes to copper, enabling the stave to have sufficient cooling ability that can be sustained throughout the furnace life.

(3) Thermal insulation ability
The upward ribs of the cast-in steel pipe Cu stave allow burden material to stably adhere to the stave surface between these ribs. Since this accretion has low heat conductivity and works as a thermal insulation layer, the amount of heat removed from the furnace is smaller by about 0.01 MW/m2 than that in the case of a rolled Cu stave. Such energy-saving effect from the heat removal restriction is equivalent to the coke consumption reduction of nearly 7,000 tons per year for a 5,000 m3-class BF.

(4) Increased design flexibility
Casting steel pipes into a Cu stave has increased the flexible design of water channels. A cast iron stave and cooling plate can be easily replaced with a Cu stave using cast steel pipes.

The cast-in steel pipe Cu stave of Nippon Steel Engineering can thus contribute to life extension and energy efficiency improvement of BF.

Abbreviations

BF: Blast furnaces