Long Service-life Cold-start Ladle Shroud

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Abstract

Cold-start ladle shrouds require very good thermal spalling resistance. Silica raw materials such as fused silica and zirconia mullite materials are widely used to them because of their low thermal expansion characteristics and improved thermal spalling resistance. However silica raw materials have poor wear resistance to tundish slag. We studied the application of non-silica alumina-carbon materials used in hot start practice that have superior wear resistance to cold-start ladle shrouds with carbon-free inner liners. Carbon-free material has low thermal conductivity and acts as a heat insulator to reduce the temperature difference between the inside and outside of the ladle shroud body. The result is reduction of thermal stress, especially at the start of casting. We confirmed the good effect by using FEM at actual casters with successful results.

1. Introduction

The most important roles of the ladle shroud are to prevent re-oxidation of the molten steel, steel flow turbulence in the tundish and tundish slag picking up. They contribute to improving steel quality. Cold-start ladle shrouds (without preheating before use) are widely used, and hot-start ladle shrouds (with preheating before use) are also used in long casting sequence.

The ladle shroud requires very good thermal spalling resistance because it receives huge thermal shock especially at the start of casting. Alumina-silica-carbon material (hereinafter AG material), which has good thermal spalling resistance, is generally used for both of cold and hot-start ladle shrouds. Silica raw materials such as fused silica and zirconia mullite materials are widely used notably for the cold-start ladle shroud, because their low thermal expansion characteristics improve thermal spalling resistance. However silica raw materials have poor wear resistance to tundish slag and manganese oxides in molten steel.

Hot-start practice for the ladle shroud reduces thermal shock at the start of casting, therefore, in order to achieve a longer sequence we can apply non-silica AG material with good wear resistance as hot-start material[1]. An investigation on the bonding binder system and grain size composition for non-silica AG material has been done to improve thermal shock resistance. The pre-heating practice of the hot-start ladle shroud has become a routine procedure prior to every cast and tundish[2]. Recently zirconia-carbon and alumina-magnesia-carbon materials have been also investigated as a hot-start ladle shroud material to achieve to more sequences[3].

We have studied the application of non-silica AG materials to the cold-start ladle shroud together with a carbon-free inner liner. Carbon-free material has significantly low thermal conductivity and its inner liner acts as a heat insulator to reduce thermal shock. In this paper, we will report on the finite element method (FEM) calculation results for new cold-start ladle shrouds and their successful trial results at actual casters.

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2. Typical Physical Properties and Chemical Compositions of AG Materials for Ladle Shroud

Table 1 shows the typical physical properties and chemical compositions of AG materials for the ladle shroud. AG-1, 2, 3 and 4 materials contain 27, 20, 10 and 0 weight % SiO_2. AG 1 and 2 materials are for cold-start practice and AG-3 and 4 materials are for hot-start practice. AG-4 is non-silica AG material.

The thermal spalling resistance index (r) below and wear resistance index are also shown in Table 1. The thermal spalling resistance coefficient (R) is calculated under the following equation (1). We assumed that all of the Poisson's ratios of the materials were the same in the range of this study and that we used the thermal expansion ratio at 1,500℃ as the thermal expansion coefficient because thermal expansion is rather linier as shown in Fig.2, and the bending strength as fracture strength. Here we defined the thermal spalling resistance index (r) evaluating thermal spalling resistance. The wear resistance index is based on the wear test results in our laboratory using a high frequency induction furnace. The

Table 1 Chemical compositions and physical properties of alumina carbon materials for ladle shroud

Material	AG-1	AG-2	AG-3	AG-4
Chemical composition (wt %)				
SiO_2	27	20	10	—
Al_2O_3	38	45	53	63
C	31	33	31	34
Others	2	1	1	2
Physical properties				
Apparent porosity (%)	15.0	14.0	13.5	13.5
Bulk density (g/cm^3)	2.25	2.30	2.45	2.55
Bending strength (MPa)	7.5	8.0	11.5	11.0
Modulus of elasticity (GPa)	8.5	8.5	12.0	10.0
Thermal expansion (% at 1000℃)	0.28	0.33	0.41	0.49
Property evaluation				
Thermal spalling resistance	3.15	2.85	2.34	2.24
Wear resistance	1.18	1.38	2.35	3.68

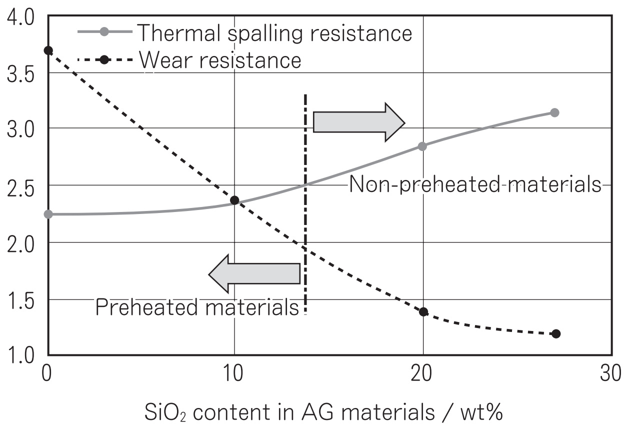

Fig.1 Relationship between SiO_2 content in AG materials and thermal spalling and wear resistances.

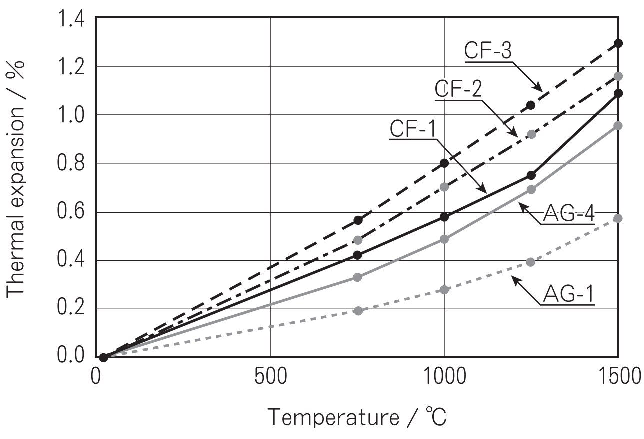

Fig.2 Thermal expansion coefficient of carbon-free materials.

larger values of thermal spalling resistance and wear resistance indexes are positive.

$$R = S \times (1 - \nu) / (E \times \alpha) \quad \cdots\cdots (1)$$

S : fracture strength, ν : Poisson's ratio,
E : modulus of elasticity, α : thermal expansion coefficient

$$r = S / (E \times \alpha_{1500}) \quad \cdots\cdots (2)$$

S : bending strength, E : modulus of elasticity,
α_{1500} : thermal expansion ratio at 1,500℃

Figure 1 shows the relationship between the silica content of the AG materials and the thermal spalling resistance and wear resistance indexes. The higher the silica content is, the higher the thermal spalling resistance index is, regardless of how low the wear resistance index is. That is to say, cold-start AG material has better thermal spalling resistance regardless of how poor the wear resistance is compared to hot-start AG material.

3. Carbon-free Material

It is known that AG material at the ladle shroud inside area is damaged by abrasion (steel attack) because it contains some 20–30% weight of graphite raw material, which is rather soft. Carbon-free material, which has good abrasion resistance, has been tried for reinforcing to the steel attack area[4], however the thermal expansion of carbon-free material is much larger than AG material. It often causes expansive cracking of the ladle shroud and peeling off of carbon-free material from the body[5].

On the other hand, a method of thermal shock reduction utilizing carbon-free material has been reported as carbon-free material has significantly low thermal conductivity and its inner liner acts as a heat insulator to reduce thermal shock[6]. We studied more about this and idea of applying non-silica AG material used in hot-start practice to cold-start ladle shroud with carbon-free inner liner.

For this study, the two following precautions were taken in order to avoid cracking and peeling off issues: 1) to apply similar thermal expansions of non-carbon and non-silica AG materials to the ladle shroud, 2) to use the same binder system for both of the non-carbon and non-silica AG materials.

3. 1 Preparation of carbon-free material sample

We prepared the carbon-free samples in the same manner as the AG material. The blended raw materials were mixed in a mixer with phenolic resin as the binder. The mixture was formed with an isostatic-press. The green bodies were dried and fired at 1,000℃ in a reduced atmosphere. Fired bodies contained traces of residual carbon derived from phenolic resin. The carbon easily disappears when the material is exposed to molten steel.

Table 2 shows the physical properties and the chemical compositions of the carbon-free material samples. Samples 1, 2 and 3 are alumina-silica, alumina and spinel materials respectively.

3. 2 Evaluation

The carbon-free materials are evaluated by thermal expansion and thermal conductivity. The thermal expansion was measured by non-contact laser method (JIS R 2207-1) in a nitrogen atmosphere. The thermal

Table 2 Chemical compositions and physical properties of carbon-free materials

	CF-1	CF-2	CF-3
Chemical composition (wt %)			
SiO_2	27	–	–
Al_2O_3	66	96	70
MgO	–	–	26
Others	3	2	2
Physical properties			
Apparent porosity (%)	22.5	23.0	21.5
Bulk density (g/cm^3)	2.40	2.90	2.70
Thermal expansion (% at 1,000℃)	0.58	0.69	0.80
Thermal conductivity (W/m•k at 600℃)	0.98	1.29	2.25

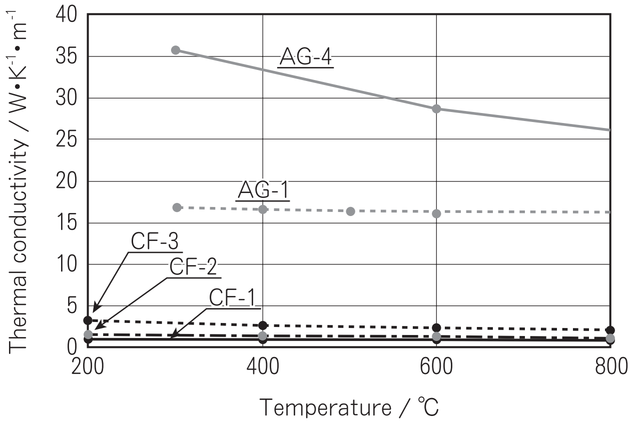

Fig.3 Thermal conductivity of carbon-free materials.

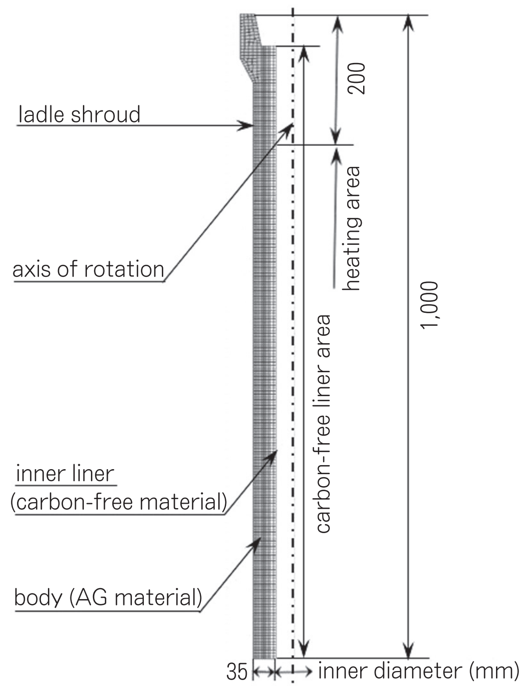

Fig.4 Mesh partition of finite element modeling.

conductivity ratio was measured by hot wire and heat flow methods (JIS R 2251).

Figure 2 shows the thermal expansion ratio of carbon-free materials and AG-1 and 4 materials. The thermal expansion ratio of the AG materials decreased with the increase of SiO_2 content. The thermal expansion ratio of AG-1 material at 1,000℃ was 57% of AG-4 material.

CF-1 had the lowest thermal expansion ratio of the three and was only 18% higher than AG-4 material. CF-2 had the second lowest thermal expansion ratio and CF-3 had the highest among the three.

Figure 3 shows the thermal conductivity ratio of carbon-free materials and AG-1 and 4 materials. All of the thermal conductivity ratios of the carbon-free materials were 1/10 lower than those of the AG materials. They should work well as heat insulators to reduce thermal shock.

4. FEM Evaluation of Thermal Stress on Carbon-free Inner Liner Ladle Shroud

4. 1 FEM model

We used FEM and calculated the thermal stress on the cold-start ladle shroud at the start of casting with a two-dimensional revolution model. The dimensions were 1,000mm in length and 35mm in thickness. It consisted of an AG material body and carbon-free inner liner.

It was assumed that the ladle shroud inside from 200mm below the top to the lower edge was immediately subject to severe thermal shock from 20℃ to a molten steel temperature of 1,570℃ without pre-heating. The atmospheric temperature was equal to 300℃ (Fig.4). The AG-4 and CF-1 materials were applied to the body and the inner liner respectively. Tables 1 and 2 show the physical properties of the AG-4 and CF-1 materials. The modulus of elasticity was assumed at a constant value in the calculated temperature range. Some thermal conductivity data came from extrapolation. The specific heat was estimated by chemical compositions. The Poisson's ratio was assumed at a constant value.

We evaluated three items : 1) The effect of a carbon-free inner liner on thermal stress, i.e. a thermal stress comparison of ladle shrouds with an 8mm thick carbon-free inner liner and 0mm, the later corresponds to a ladle shroud with only AG material. 2) The effect of carbon-free inner liner thickness on thermal stress. 3) The effect of the ladle shroud inner diameter (bore) on thermal stress.

We traced the circumferential direction element of thermal stress at the outer edge of ladle shroud as the evaluation index.

4. 2 Effect of carbon-free inner liner on thermal stress

At first we evaluated the effect of a carbon-free inner liner on thermal stress. We compared a ladle shroud with an 8mm thick carbon-free inner liner (C-free liner shroud) and without a carbon-free liner (AG shroud). The two models had 35mm body thicknesses and 60mm bores. We applied AG-4 material to the body and CF-1 material to the inner liner. The AG shroud had a 35mm thick AG-4 body and the C-free liner shroud had a 27mm thick AG-4 and 8mm thick CF-1 body.

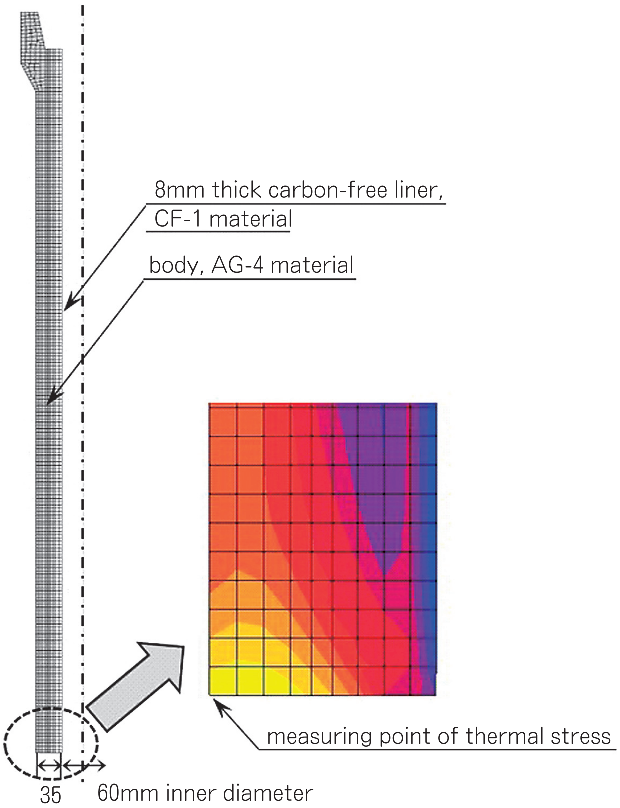

Fig.5 Contour map and measuring point of thermal stress.

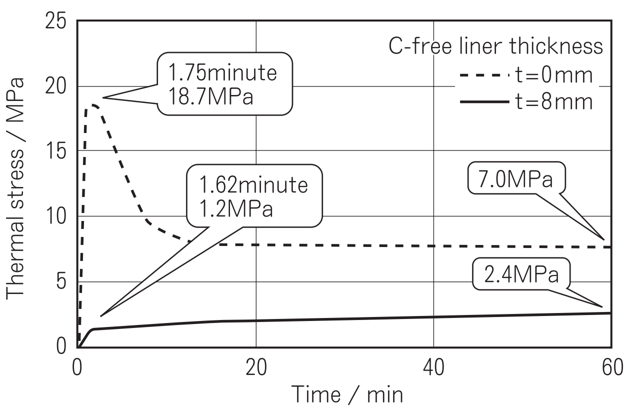

Fig.6 Influence of carbon-free inner liner on thermal stress at tip of ladle shroud.

Figure 5 shows the contour map of thermal stress at the lower edge of the C-free liner shroud. The yellow, red and blue colors show magnitude of thermal stress in a decreasing order. As a cylindrical body such as a ladle shroud is heated from the inside, the largest tensional stress occurs at the outer edge. We traced circumferential direction element of thermal stress at the outer edge of the ladle shroud as the evaluating index.

Figure 6 shows the thermal stress change against heating time. Under actual casting conditions, a ladle shroud is heated from the inside by molten steel just after casting start. Its immersed part was heated from both outside and inside by molten steel as the tundish is filled with molten steel. These were not practical conditions, however we calculated for the case of a ladle shroud being heated for 60 minutes, only from the inside, in order to examine the effect of a carbon-free inner liner on thermal stress.

The largest thermal stress occurred 2 minutes after heating the AG shroud and then thermal stress decreased and became constant after 15 minutes. Thermal stress on C-free liner shroud increased rapidly just after heating and increased gradually until 45 minute and then became constant.

Thermal stress is generated by the temperature difference between outside and inside of the ladle shroud. Thermal expansion of carbon-free material is larger than AG material. It seems that the carbon-free liner was inferior from the view of expansive cracking. However, the thermal insulating effect of a carbon-free liner is considered to be much greater than the thermal expansion effect and reduced the thermal stress at the start of heating significantly. The C-free liner shroud decreased thermal stress to 6% 2 minutes after heating and to 34% 60 minutes after heating.

4. 3 Effect of carbon-free inner liner thickness on thermal stress

We evaluated the effect of carbon-free liner thickness on thermal stress with AG-4 body material and CF-1 carbon-free liner. We compared the thermal stress of four models of AG shrouds. They had 0, 4, 8 and 16mm thick carbon-free liners (Fig.7). We calculated them for 5 minutes according to 4.1 procedure.

The 4mm thick carbon-free inner liner was effective for reducing thermal stress at the start of heating. The result shows that it took some 0.3 minute from heating start for the generation of thermal stress. The 8mm thick carbon-free inner liner was more effective for reducing thermal stress than 4mm. There was not a large difference between the 8mm and 16mm thick carbon-free inner liners.

Figure 8 shows the relationship between carbon-free inner liner thickness and thermal stress 5 minutes after heating. The 4mm thick carbon-free inner liner reduced thermal stress by 20% compared to the AG shroud. The 8mm thick carbon-free inner liner further reduced by about 50% of thermal stress. There were less than 10% difference between 8mm and 16mm thick carbon-free inner liners.

4. 4 Effect of inner diameter (bore) of ladle shroud on thermal stress

A larger bore ladle shroud is thermally stressed more than a smaller bore ladle shroud under the same heating conditions. Larger bore ladle shrouds are considered to have less difference between outer and inner circumferences so that the thermal expansion of the inside acts more on the outside.

We evaluated the effect of the bore on thermal stress with materials AG-4 and CF-1. The thickness of the ladle

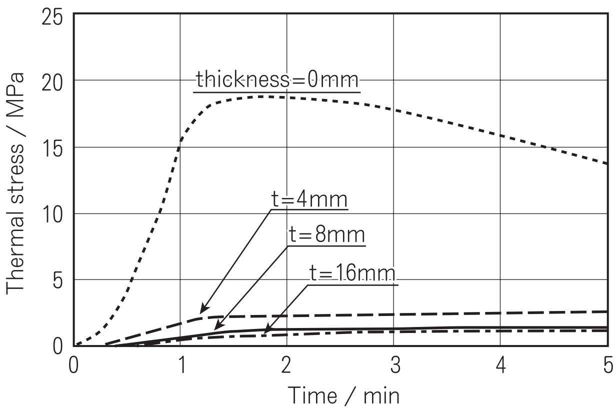

Fig.7 Influence of carbon-free inner liner thickness on thermal stress.

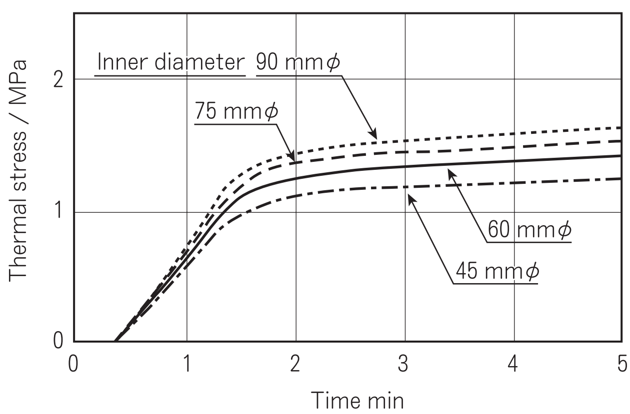

Fig.9 Influence of inner diameter of ladle shroud on thermal stress.

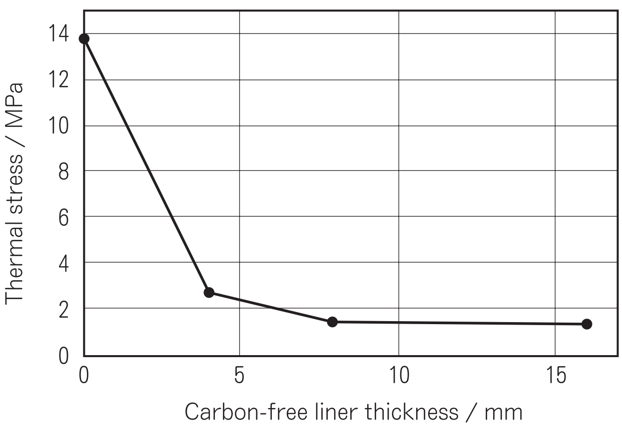

Fig.8 Influence of carbon-free inner liner thickness on thermal stress.

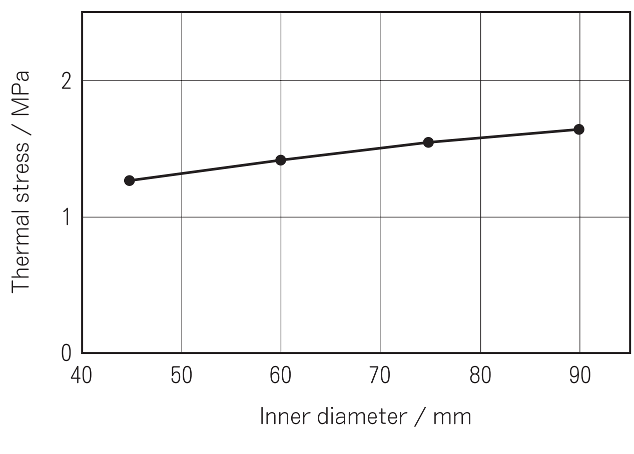

Fig.10 Influence of inner diameter of ladle shroud on thermal stress.

shroud body was 35mm and it had 8mm thick carbon-free liner. We compared the thermal stress of the four models with 45, 60, 75 and 90mm bore according to the procedure in 4.1.

Figures 9 and 10 show that the larger bore ladle shroud received more thermal stress under the same heating conditions. The 90mm bore ladle shroud was thermally stressed 30% more than the 45mm bore.

5. Trial Results

5. 1 Manufacturing test

We manufactured the actual ladle shroud with AG-4 and CF-1 materials. We selected middle size (56mm bore) ladle shroud design and applied an 8mm thick carbon-free inner liner according to the FEM calculation results above. We cut it out and observed it visually. Both materials were bonded tightly and there was no cracking (Fig.11).

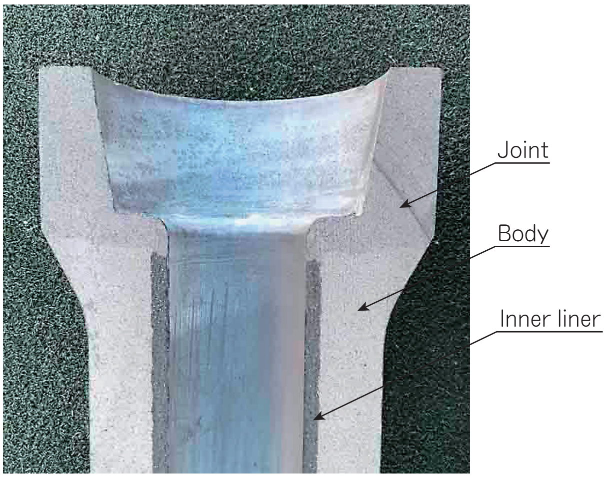

Fig.11 Cut section of original ladle shroud product.

5. 2 Casting test

The ladle shroud with AG-4 and CF-1 materials mentioned above was tried at caster A in an electronic mill. The conventional ladle shroud was cast for 1 sequence of 8 heats and had to be replaced. The new ladle shroud was cast for 3 sequences of 22 heats with the tundish being changed 3 times. Figure 12 shows the trial results and photograph of the cut section after use.

When the tundish is changed, the temperature of the ladle shroud lowers. The ladle shroud might not have enough thermal spalling resistance at tundish change if the carbon-free inner liner has already worn out and not enough thickness remains. Carbon-free inner liner wear is determined by casting conditions and steel grade. To obtain good performance of the C-free shroud it is important to select carbon-free material and the inner liner thickness.

Table 3 sums up the C-free liner shroud performances in progress. All of them performed satisfactorily.

Table 3 Ladle shroud performances at actual casters

Caster	Heats	Bore / mm	Thickness / mm	Usage
A	20 - 25	56	32	Intermittent
B	11 - 21	58	36	Intermittent
C	7 - 12	55	31	Intermittent
D	12 - 22	75	33	Continuous

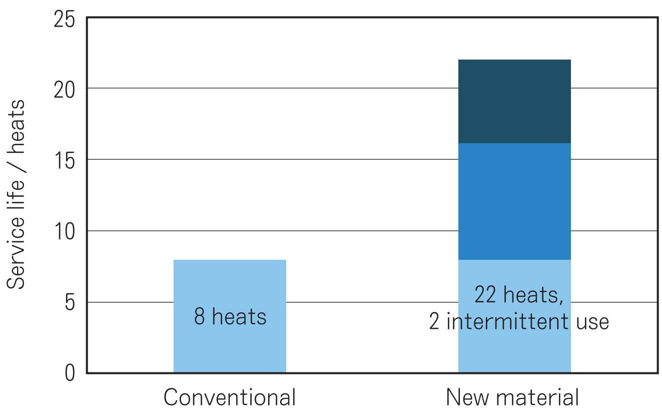

Fig.12 Ladle shroud performance at Caster A and the cut section after use.

6. Summary and Challenges of the Future

We applied non-silica AG material that has superior wear resistance to cold-start ladle shroud with a carbon-free inner liner. The carbon-free inner liner has significantly low thermal conductivity and acts as a heat insulator to reduce the temperature difference between inside and outside of the ladle shroud. This results in the reduction of thermal stress especially at the start of casting.

We tested a C-free shroud at an actual caster. The conventional ladle shroud had cast for 1 sequence of 8 heats, and the new ladle shroud cast for 3 sequences of 22 heats with 2 tundish changes.

To obtain good performance of the C-free shroud it is very important to select the carbon-free material and thickness according to steel grade, casting and the wear conditions. We will challenge using the C-free shroud with larger dimensions in the future.

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