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Original Article

A Study on the Manufacture of High Carbon and High Chromium White Cast Iron Blade with Addition of Titanium

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Abstract - *In this study, we attempted to produce a blade having high hardness and high resistance with a precision casting method by adding a small amount of Ti, which is a carbide forming element, when producing a shot blasting machine impeller blade with high C-high Cr white cast iron. About 1.5~1.8wt.% of Ti, which is a strong carbide forming element, was alloyed so that TiC carbide could be formed on high C-high Cr white cast iron. For the heat treatment, after quenching at 990°C, tempering was carried out at 200°C so that the hardness and wear resistance could be improved greatly. Therefore, the goal of this study was to manufacture impeller blades for shot blasting machines with excellent hardness, wear resistance, and economic feasibility that satisfies the main evaluation indices for target achievement (blade replacement cycle of 1344 hours hardness value HRC58 or more). The failure factors and field test results according to the development performance of the Ti-added high C-high Cr cast iron blades are summarized and organized, respectively.*

Keywords *- Impeller blade, High C-high Cr white cast iron, Shot blast, TiC carbide.*

1. Introduction

1.1 The need to develop a high C-high Cr White Cast Iron Blade Added with the Carbide Forming Element Ti

The blade that is used in a shot blasting machine is a major part of an impeller, accounting for most of the life, maintenance, and repair costs of a shot machine, and the development of a blade with excellent durability will lead to major product competitiveness not only in the domestic market but also in the global market. The reason for this is that while many manufacturers are currently producing blades based on STD11 rolled materials by machining them, the price of the blades is similar worldwide due to the ease of access to the materials and the universalization of the heat treatment method. The reality is that there is no price difference or performance difference that can offset the logistics costs in accordance with exports and imports. However, alloy tool steel rolled material with high strength and hardness like STD11, which is currently used for blade material, is difficult to machine due to high hardness. It is not economical to produce. This is why blades made of white cast iron, which are known to have excellent service life since they are very economical and have excellent durability due to high wear resistance, are being used as substitutes for STD11 blade material and, in particular, they are being produced with precision casting methods for which productivity has been improved. White cast iron is a high C-high Cr alloy. In addition to the big advantage of possessing high economic efficiency compared to the STD11 rolled material, it has high hardness and excellent wear resistance since it contains a 2 to 3 times higher amount of carbide. However, in addition to the casting defects like cracks that have a high probability of occurring during casting, there is also a high probability that durability problems will occur when parts are used since impact toughness will be lowered noticeably due to high C content large amount of Cr carbide precipitation. From this point of view, an appropriate combination of wear resistance and impact toughness is important for high C-high Cr white cast iron. This can be solved by adjusting the chemical composition and suitable heat treatment after casting. In recent studies, some methods to improve hardness and wear resistance by adding an appropriate amount of carbide forming elements like V, W, Nb, and Ti to change the basic chemical composition of high C-high Cr white cast iron have been reported. Among these, V has been known as the strongest carbide forming element if W, which has a risk of brittleness, is removed. And it has been reported that wear resistance and impact toughness can be improved if an appropriate amount of V is added to high C-high Cr white cast iron. In particular, since Ti which is added to STD11 steel casting, has been noted to be a stronger carbide forming element than V recently, and since Ti is a stronger carbide forming element compared to V, it can impart high hardness and high wear resistance in addition to economic feasibility compared to STD11 steel rolled material and accelerates the formation of high hardness TiC carbide, it is necessary to develop long-lived impeller blades with high hardness and high wear resistance in this development technology by carrying out quenching and tempering heat treatment after producing a blade of high C-high Cr white cast iron material of ASTM Class II in which about 1.5~1.8wt.% of Ti was added, according to a precision casting method.

1.2 Characteristics of high C-high Cr white cast iron

Due to its excellent wear resistance characteristic, high C-high Cr white cast iron is widely used in various wear-resistant parts like ore separators, coal mine crushers, and ore crushers and supply devices used in mines and quarries. While wear resistance and toughness are demanded in some cases depending on the use conditions of these parts, wear resistance and toughness are generally incompatible characteristics in high Cr white cast iron. The characteristics must be adjusted by adjusting the alloy components. Cr content has the greatest effect on the wear resistance of wear-resistant white cast iron. White cast iron is classified into ASTM Class II-B, C (14-18%Cr), II-D, E (18-23%Cr), and III-A (23-28%Cr), depending on the Cr content. In general, while the most important phase for improving the wear resistance of white cast iron is a discontinuous M_7C_3 process carbide in Class III (23-28% Cr) alloy with a relatively high Cr content, it is a continuous M_3C process carbide in Class II (14-23%Cr) alloy with a relatively low Cr content. The high Cr-based white cast iron with these wear-resistant characteristics generally has a process or hypoeutectic composition. Wear resistance and impact resistance, which are the most important characteristics of high Cr-based wear-resistant cast iron, are determined by the carbides formed during solidification or heat treatment. The volume flux, size, orientation, and shape of these carbides are determined a decisive effect on wear resistance. High Cr-based wear-resistant cast iron obtains sufficient transformation and high hardness values by heat treatment [1)]. In particular, since pearlite formation on a white cast iron matrix may decrease hardness and a decrease in wear resistance, pearlite formation should be prevented by adjusting the alloy elements. For example, while the addition of Mo improves the hardenability of the alloy by suppressing pearlite formation by suppressing the formation of secondary carbide during cooling after casting, adding 3~4wt.% of Mo will not have much effect. High alloy white cast iron is mainly used by casting into components of machines that require wear resistance like this because it has a large amount of process carbide. Therefore, high alloy white cast iron must be produced to be used for tasks with repeated shocks by increasing the wear resistance and toughness. This can be done by adjusting the chemical composition and heat treatment by adjusting the metal matrix and carbide amount. All high alloy white cast iron contains many Cr to suppress graphite formation during solidification and maintain stability in the carbide phase. Ni, Mo, Cu, etc., suppress the formation of pearlite in the matrix when each is added separately or in combination.

1.3 Matrix structure, carbide, as cast and heat treatment structure, and Solidification Behavior of High Cr cast iron[1)]

If the matrix structure, carbide, as cast and heat treatment structure, and solidification behavior of a general high Cr cast iron in which alloy elements have been added are summarized, they are as follows.

1.3.1 Matrix Structure

Like steel material, an overall martensite structure is needed to have the best wear resistance characteristic in white cast iron. Under repeated impact conditions, martensite-based white cast iron must minimize residual austenite by tempering to have maximum spalling resistivity. The white cast iron of the pearlite matrix is generally not used because wear resistance and toughness are not that good.

1.3.2 Carbide

In high Cr cast iron, while carbide is very hard and has wear resistance, it is fragile. In general, wear resistance improves as the carbide content increases (the C content is increased), and toughness improves as the amount of matrix structure increases (the C content is decreased). Primary crystal carbide is extruded from eutectic reaction molten metal and is very susceptible to impact. The amount of process C is inversely proportional to the content of Cr. Therefore, Cr has the greatest effect on the formation of process carbide. If the Cr content is increased from 10wt.% to 12wt.%, the process carbide is changed from M_3C to M_7C_3. If Cr is increased for all carbides, the Cr content of the alloy is increased, the ratio of the metal elements in the carbides is increased, and the hardness of the carbides is also increased.

1.3.3 Austenite structure as cast

Solidification proceeds by forming the primary crystal austenite dendritic phase for the hypoeutectic alloy. Later, the process reaction of the Cr carbide of the austenite-M_7C_3 occurs. During cooling under the equilibrium solidification condition, additional carbide is precipitated from the austenite matrix at a critical temperature of about 760°C. With continued cooling, the austenite is transformed into ferrite and carbide. Austenite is supersaturated with C, and a nonequilibrium state condition exists in a general production process. Due to the high content of C and Cr, it generally becomes metastable austenite cast iron, and pearlite and bainite transform are suppressed.

1.3.4 Martensite structure as cast

Martensite structure appears after casting in the thick part of the cast where cooling is slow. The residual austenite and martensite are mixed in actual casting since transformation into partial martensite occur because the austenite is unstable during slow cooling. Therefore, the hardness is relatively low after the heat treatment. Such an alloy requires sufficient alloy to suppress pearlite transform, and appropriate annealing may be carried out to reduce the residual austenite and increase the hardness and toughness.

1.3.5 Solidification of behavior and structure

Most of the high Cr white cast irons have a composition range of 11~30wt.%Cr and 2~3.3wt.%C. The austenite dendritic phase starts to be generated from the liquidus according to the solidification of the hypoeutectic material, and it is continued up to a temperature at which the process reaction occurs. At this time, the $\text{liquid} \rightarrow \gamma + M_7C_3$ reaction occurs. On the other hand, in the hyper eutectic high Cr white cast iron, solidification generally proceeds preferentially in the M_7C_3 domain. A large primary crystal carbide is formed, and a process reaction occurs subsequently. As the Cr content increases, the C content for the process is decreased.

1.3.6 Heat Treatment Structure

The most important purpose of the high Cr white cast iron heat treatment is to transform an austenite matrix containing many alloy elements into martensite to obtain excellent mechanical characteristics. In addition, it is important to stabilize the metastable residual austenite through heat treatment and sub-zero treatment. The heat treatment of the high Cr white cast iron includes various methods like stress removal heat treatment, quenching and tempering heat treatment, etc. The most important is the destabilization heat treatment which has the same meaning as the quenching heat treatment. The destabilization heat treatment reduces the content of the alloy elements (especially the C content) in the matrix by precipitating the secondary carbide in the matrix by maintaining the temperature at 920-1060°C for 1 to 6 hours as the number of alloy elements in the austenite matrix decreases, the Ms temperature increases. Therefore, the matrix can be transformed into martensite while cooling to room temperature. Although it differs according to the composition of the matrix and the destabilization temperature, secondary carbides like M_3C, M_7C_3, $M_{23}C_6$, etc., may be generated. Also, the amount of residual austenite varies depending on the destabilization condition and the composition of the matrix.

1.4 High Cr white cast iron alloy composites for manufacturing shot blasting machine blades2~4)

In addition to recent studies on changes to the structural and mechanical characteristics caused by dendritic phase formation in high-Cr white cast iron1), Kyungdong Shot Machinery Co., Ltd. 2) invented an alloy composite for the production of shot blasting machine blades and the alloy composite of the shot blasting machine blades that were produced using this in 2016. A blade with a work-life that has been extended 20 times compared to the 27%Cr cast iron blade that had been used in the past was developed. This alloy composite is the high Cr white cast iron based on Class III (Cr-Mo white cast iron) mentioned previously. Each alloy element that greatly increased the wear resistance of the high Cr white cast iron blade, its role, and the amount added are explained below. This alloy composite2) is composed of 2.45~2.65wt.% of carbon (C), 1.00~1.20wt.% of silicon (Si), 0.05~0.80wt.% of manganese (Mn), 15.00~16.50wt.% of chromium (Cr), 1.50 to 1.75 wt.% of molybdenum (Mo), 1.50~1.80wt.% of vanadium (V), 0~0.05wt.% of phosphorus (P), and 0~0.05wt.% of sulfur (S). After designing a shot blasting machine blade using this alloy composite, precision casting and appropriate quenching and tempering were carried out. The hardness after the quenching and tempering heat treatment was measured to be HRC63~64, satisfying the hardness requirement of the blade. These alloy composites are characterized by increased hardness and wear resistance due to the increasing content of C, Mo, Cr, and V. Also, by carrying out optimal quenching and tempering heat treatment after precision casting, a result in which the work-life was extended 20 times or more compared to the 27%Cr cast iron blade that had been used in the past was obtained. For similar purposes, Sekwang Shot Machinery Co., Ltd. invented an alloy composite3) for manufacturing shot blasting machine blades in 2008. The alloy composite was 1.5~2.0% C, 0.30~0.50% Si, 0.40~0.70 % Mn, 10~14% Cr, 1.0~1.5% Mo, 0.35~0.50% V, 0.20~0.50% Ni, 0.05~0.10% Cu, 0~0.05% P, 0~0.05% W, 0~0.05% Co, 0~0.05% Sn, and 0~0.05% Pb by weight (wt.%). When optimal quenching and tempering were carried out, the result for this alloy composite was measured to be HRC63~64, and an announcement was made that it satisfied the hardness requirement of a shot blasting machine blade. In addition, it was said that the blade manufactured with this alloy composite displayed a lifetime of 800 hours, which is a 4x improvement over the 200-hour lifetime of the blade manufactured with the traditional 27%Cr steel. However, it was verified that the life was well short of the 1344-hours that had been the goal of this study because the C content and the content of Cr, Mo, and V, which are the carbide forming elements, were not high. Therefore, it can be seen as inappropriate for an alloy composite design of white cast iron. In addition, Sekwang Shot Machinery Co., Ltd.4) mentioned in 2013 that the blade was the most important component in the impeller projection device of the shot blasting machine, as well as being the part in which the wear was most severe and since the blade was being replaced more frequently compared to other parts, that the problems due to a decline in work efficiency and a decline in productivity because of this were severe. To solve this problem, a blade for a shot blasting machine that was composed of an alloy composite of 0.350~0.420% C, 0.800~1.200% Si, 0.250~0.500% Mn, 0.001~0.030% P, 0.001~0.020% S, 4.800~5.500% Cr, 1.000~1.500% Mo, and 0.800~1.150% V by weight% (wt.%) was manufactured4). It was said that the work-life of this blade displayed an extended effect several times compared to the existing 27%Cr cast iron blade because the wear resistance of this blade had been improved. However, it can be seen that hardness is somewhat low and wear resistance is very insufficient even when optimal heat treatment is carried out after precision casting because the content of C and Cr is low even though the content of Mo and V is slightly large.

1.5 Directional effects of carbide on wear in high Cr white cast iron5, 6)

High Cr white cast iron is a material with a very high abrasive wear resistance due to its high carbide content. The abrasive wear resistance is greater when the bar shape or blade shape of carbide grows in a direction perpendicular to the abrasion surface compared to other directions, and fine carbide is known to be more effective than coarse carbide. However, when sand casting white cast iron in a cast state, it has been reported that process carbides grow parallel to the direction of heat flow in the columnar zone, displaying a high anisotropic structure and that the orientation of the process carbide is related to the abrasion surface plays a large role in determining the wear resistance of high Cr white cast iron. Based on this, N. Doan et al.[5)] studied the abrasion resistance of the columnar zone in high Cr white cast iron and the directional effect of carbide on abrasion and reported that better abrasive wear resistance is displayed when the long axis of the carbide is parallel to the abrasion surface compared to when the long axis of the carbide is perpendicular to the abrasion surface[5)]. Later, Shouren Wang et al.[6)] manufactured a hypereutectic alloy cast iron that has the highest C with a precision casting method by using a high Cr white cast iron for the blade of a shot blasting machine to investigate the carbide directional effect that affects the impact abrasive wear resistance of high Cr white cast iron that was recently used in a shot blasting machine. To manufacture with unidirectional solidification, the investigation was conducted by controlling the cooling speed to be mutually different. As a result, by observing the bar-shaped M_7C_3 carbide in the longitudinal direction and the lath shaped M_7C_3 carbide in the horizontal and vertical directions, it was reported that the high Cr white cast iron displayed higher hardness (HRC65~66) and destructive toughness when the long axis of the bar carbide is parallel to the shot ball flowing direction compared to when it was perpendicular to the shot ball flowing direction. These results show that the blades with M_7C_3 carbide directionality in the longitudinal direction display superior impact-abrasive wear resistance compared to the case for the horizontal and vertical directions. When precision casting high Cr white cast iron blades in the future, it will be possible to manufacture blades with excellent hardness and wear resistance if they carry out directional solidification.

1.6 Effects of adding the alloy elements V and Ti and heat treatment on the properties of high Cr white cast iron[7, 8)]

The hypoeutectic high Cr white cast iron of Class II, which is the study's goal, has excellent hardness and wear resistance as described previously. And it is a well-known fact that M_7C_3, M_3C, M_3C_2, and $M_{23}C_6$ are the carbides mainly formed on the matrix structure of the high Cr white cast iron. In particular, in the hypoeutectic high Cr white cast iron, the M_7C_3 carbide is a process carbide that grows continuously and coarsely. The M_3C carbide is a secondary carbide that is distributed discontinuously and finely. These are precipitated on the matrix structure to display excellent wear resistance. Also, while it is well known that the mechanical characteristic is noticeably affected by structural factors like the carbide amount, type, shape, etc., in addition to the hardness of the matrix structure, the noticeable decline of impact toughness due to the precipitation of large amounts of the Cr carbide has become a problem. An appropriate combination of wear resistance and impact toughness for high Cr white cast iron is important. Since the structural factors for this, like the carbide shape, size, distribution state, and matrix structure strengthening, can be controlled to some degree by the carbon amount, the added elements, and the quenching and tempering heat treatment, Kim et al.[7)] considered the point of view like this and conducted a study on the effect of the alloy elements V and Ti, and heat treatment on the mechanical properties of high Cr white cast iron. In other words, to maintain the excellent wear resistance of the hypoeutectic high Cr white cast iron while improving the impact toughness at the same time, the effects of these alloy elements and heat treatment on the matrix structure and the mechanical properties were investigated by changing the content of the alloy elements V (0~2.2wt.%) and Ti (0~0.6wt.%) and by carrying out destabilization heat treatment. It was reported that the residual austenite amount increased as the amount of V and Ti were increased. The hardness decreased because the carbide amount decreased as the tempering temperature increased, and an improvement in wear resistance due to an increase in hardness appeared because the hardness increased. The impact energy decreased due to the increase in the carbide amount as the V, and Ti amount was increased[7)]. However, it is difficult to know in detail the effect of adding Ti for high Cr white cast iron that contains Ti since the range for the amount of Ti that is added is very narrow compared to adding V. There have been no reports on the role of the TiC carbide or on adding 1wt.% or more of Ti. Similarly, Khaled. M. Ibrahimnt[8)] recently reported the effect of Ti on the structure and characteristics of high Cr-Mo white cast iron as cast. In the casting state, the microstructure of the high Cr-Mo white cast iron was reported to be composed of the process mixture matrix of $(Fe, Cr)_7C_3$ carbide and austenite and the dendrite of austenite. In addition, quenching and tempering heat treatment was carried out to increase the white cast iron product's impact toughness and wear resistivity. As a result, it was said that an austenitizing temperature that is too high decreased the hardness by leaving high residual austenite on the structure by increasing the stabilization of the austenite. Also, an austenitizing temperature that is too low was said to decrease the hardness and wear resistance by making low C martensite. Therefore, while a successful heat treatment is to precipitate the secondary carbide inside the austenite matrix with destabilization treatment and tempering heat treatment of the austenite if heat treatment is excluded, it was emphasized that another strategy for augmenting the toughness and wear resistance of white case iron is to add carbide forming elements like V, W, Nb, and Ti. In particular, Ti is a strong carbide forming element, and TiC is known as the phase that precipitates first during solidification due to its high formation temperature. Therefore, Ti addition and heat treatment conditions were investigated on wear resistance, impact toughness, and microstructure. As a result, the structure of the samples treated at 980°C, which is the optimal austenitizing temperature of the alloy, consisted of fine spherical martensite, the fine sediment of secondary carbide, a small amount of residual austenite, TiC particles, and process carbide M_7C_3. Also, the TiC particles were distributed evenly in the heat-treated matrix structure up to 1.31 wt.%. When Ti was added at a high level of 1.78 wt.%, they started to gather in a lump form, and the effect was degraded instead. Like this, the addition of Ti becomes the cause for the increase in the hardness since a slight TiC formation is combined with the M_7C_3 carbide and the secondary carbide included in the heat-treated matrix. In particular, it was reported that tensile strength and wear resistance displayed the maximum values when 1.3wt.% of Ti was added$^{8)}$.

1.7 Types of defects that occur due to the nonconformity state for each factor in the precision casting process$^{9)}$

During the precision casting of the alloying high C-high Cr white cast iron, casting by adding high C and Ti can cause big problems in the quality of the casting like surface cracks, shrinkage porosity, and gas porosities that are important cast defects due to the nonconformity state for each factor in the precision casting process. In particular, there is a lot of know-how in the dissolution due to the addition of Ti, and it can be seen that a lot of caution is needed when preparing a cast or injecting molten metal. The following Table 1 shows the types of defects that occur due to the nonconformity state for each factor in the precision casting process among the contents of the ICI illustrated defect book$^{9)}$.

Table 1. Types of defects that occur due to the nonconformity state for each factor in the precision casting process

Factor	State	Expected defect shape
Material	Wet material (oil, moisture, shell residue)	Gas defect, slag defect, inclusion defect
	Dirty material (rust, shell residue)	Gas defect, slag defect, inclusion defect
Cast	High coating degree	Gas defect, fluidity defect
	Short plastic time	Gas defect
	High shell strength	Hot-tear defect
	High cast temperature	Shrinkage porosity defect, oxidation crack defect
	Shell with a crack	Oxidation crack defect
	Low shell strength	shell float defect
	Low shell permeability	Gas defect, Cold shuts defect, slag defect, Hot-tear defect, Fluidity defect
	Kiln with insufficient oxygen	Slag defect, Gas defect
	Low cast temperature	Gas defect
	Uncharged home region	Shell float defect
Melting	High C, Cr, Ti content	Cast crack defect and shrinkage porosity defect
Injection	Injection pressure is low	Cold shuts defect
	The injection speed is slow.	Cold shuts defect
	Injection far from the gate	Gas defect
	Intermittent injection	Fluidity defect
	The injection speed is slow.	Fluidity defect
	Insufficient molten metal injection	Gate part shrinkage porosity defect
	Low injection temperature	Fluidity defect
	Rough out-put gate	Gas defect, Cold shuts defect, slag defect.

2. Experimental Method

2.1 Alloy design of the Ti-added high C-high Cr white cast iron

Table 2 shows the target chemical composition of the high C-high Cr white cast iron alloy containing Ti. It is characterized by the addition of Ti with a strong carbide formation effect instead of adding V.

Table 2. Target chemical composition of high C-high Cr cast iron alloy containing Ti (wt.%)

C	Si	Mn	P	S	Cr	Mo	Ti	Fe
2.45~2.65	1.00~1.20	0.50~0.80	0~0.05	0~0.05	15.0~16.5	1.50~1.75	1.5~1.8	Bal.

2.2 Precision casting of Ti added high C-high Cr white cast iron

Fig. 1 shows the manufacturing process for the precision casting of high C-high Cr white cast iron alloyed by adding Ti, a carbide forming element. It was conducted in collaboration with Daewon Tech Co., Ltd., a company specializing in precision casting. First, after accurately matching the nozzle of the hydraulic injection machine and the mold inlet, the wax model was injected by injecting the heated wax into a blade mold. The gate part of the wax model is heated with electric iron and bonded so that four become one set. At this time, assembly was done uniformly to facilitate cutting during dewaxing and post-treatment. The surface of the completed mold was covered with refracted material, from the 1st coating (zircon sand) to the 6th and 7th coating (chamotte), and then dried. Subsequently, the dried cast was placed in a high-pressure kiln and dewaxed with steam heat. The dewaxed cast was calcinated at 1050℃ to burn off the remaining wax and increase cast strength. Then the cast was put on stand-by for the injection.

Meanwhile, the high C-high Cr white cast iron was loaded into a high-frequency furnace (250 kg) by matching the ferroalloy mixture and dissolved in atmospheric conditions. The dissolved alloy molten metal was injected into a ceramic cast preheated to 1050°C and air-cooled. The completely solidified cast was dismantled, the sand was removed, and the product was cut and collected. The completed product was analyzed for chemical composition by using a spectrometer. Table 3 shows the analytical chemical composition of the high C-high Cr white cast iron manufactured with precision casting. As shown in Table 3, it was predicted that the hardness value would be affected because the content of C, Cr, Mo, and Ti would be slightly deficient from the target value.

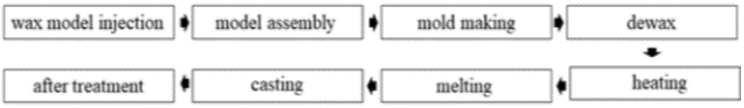


Fig. 1 Steps in the investment casting process for high carbon high chromium white cast iron

Table 3. Chemical composition of sample alloys (wt.%)

C	Si	Mn	P	S	Cr	Mo	Ti	Fe
2.1815	0.673	0.647	〈0.03	〈0.03	12.202	0.95	1.389	Bal.

2.3 Heat treatment of high C-high Cr white cast iron blades added with Ti

For the heat treatment of the blade product, first preheating was carried out for 1 hour at 600°C, and second, preheating was carried out for 5 hours at 950°C. Then after the homogenization heat treatment was carried out, destabilization heat treatment was carried out for 2 hours at 990°C. All heat treatments were carried out in a vacuum furnace and quenching by blowing nitrogen (N_2) gas into the vacuum furnace. Immediately after the heat treatment, tempering was carried out to remove stress and increase the impact toughness. For the tempering, it was maintained for 4 hours at 200°C and then air-cooled. This was carried out in collaboration with Daehan Vacuum Heat Treatment Co., Ltd. Fig. 2 shows the quenching and tempering heat treatment cycle of high C-high Cr white cast iron manufactured with precision casting.

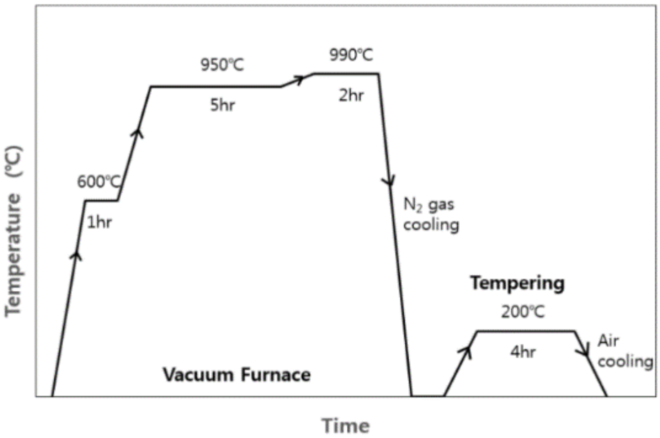


Fig. 2 Heat treatment cycles for high carbon high chromium white cast iron

3. Results and Considerations

For high C-high Cr white cast iron material to be used for shot blasting machine blades with high durability, an appropriate combination of high-wear resistance and high-toughness of the blade material is important. Adjusting the chemical composition and heat treatment are the most important techniques that enhance white cast iron's toughness and wear resistance. Since the heat treatment method is similar and determined by the white cast iron class, it can be said that the change in chemical composition is most important. Recently, a method in which an appropriate amount of carbide forming elements like V, W, Nb, and Ti are added has emerged to improve the high wear resistance and toughness of white cast iron. V is most widely used effectively as a strong carbide forming element if W, which has a brittleness risk, is excluded. In numerous studies, it is improving wear resistance and impact toughness by actually being added to high Cr white cast iron. The core technology of this development technology is a carbide forming element, which is known to be a stronger carbide forming element than V. After manufacturing, with precision casting, a blade that is made of a high C-high Cr white cast iron (ASTM Class II) material added with 1.5~1.8wt.% (target composition) of Ti, which can greatly improve the hardness by promoting TiC formation, the goal is to develop long-life impeller blades with high hardness and high wear resistance by carrying out quenching and tempering heat treatment.

3.1 Method to Cut Blade Samples and Make Test Pieces

To observe the structure and measure the hardness. Then the microstructure of the cross-section was observed, and the Rockwell hardness was measured, as shown in Fig. 3.

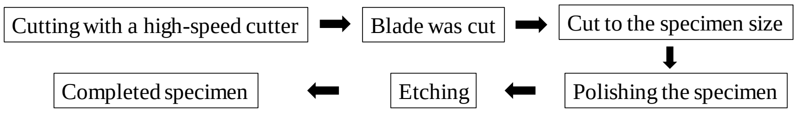


Fig. 3 Method to cut the blade and make test pieces

Structure observation and hardness measurements were carried out by dividing them according to the As cast, quenching (Q), and quenching and tempering (Q.T.) state. Blade samples were cut using a high-speed cutter since the hardness was high. After cutting the central part of the blade, each piece was cut into the test piece size of length 20mm x width 10mm. The Emery Powder on Paper #100~#2000 was used to polish the test pieces. Two test pieces were polished. After one of them was etched using a 10% Nital etching regent (10cc HNO_3 + 90cc H_2O), the structure was observed using an optical microscope. With the other test piece, the hardness (HRC) was measured using a Rockwell Hardness Machine. After taking 10 measurements, the average was calculated.

3.2 Structure Observation and Hardness Measurement Results

Fig. 4 shows the microstructure of the high C-high Cr white cast iron containing Ti observed with an optical microscope. In the as-cast structure, the white part is iron carbide, and the gray part is a pearlite structure that has not been decomposed. Therefore, the hardness value is low as to cast. It can be seen that the hardness value has increased to HRC57 because large amounts of primary crystals and process carbides were precipitated by Cr, Mo, Ti, etc., after quenching and tempering. However, the hardness value after quenching and tempering fell short of achieving the target value of HRC58 or greater due to inappropriate heat treatment conditions on top of insufficient C, Cr, Mo, and Ti content, as shown in Table 2.

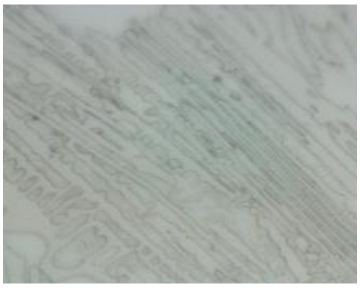
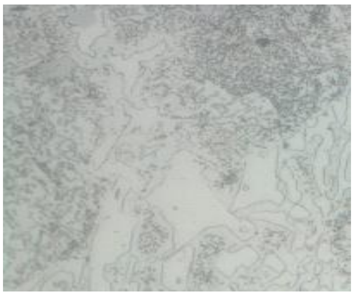
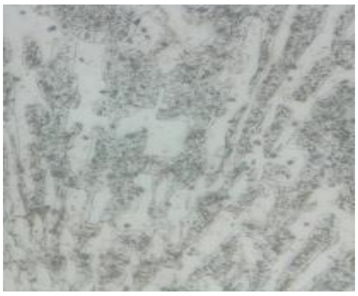
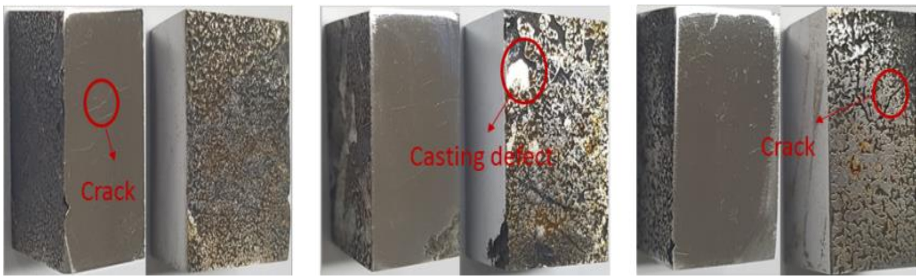
As cast		Quenching		Tempering after quenching	
					
Average hardness	39.3	Average hardness	58.6	Average hardness	57.0
* Average of 10 measured values, unit: HRC		* Average of 10 measured values, unit: HRC		* Average of 10 measured values, unit: HRC	

Fig. 4 Microstructure (X500, Nital etching) and average hardness values of high C-high Cr white cast iron containing Ti

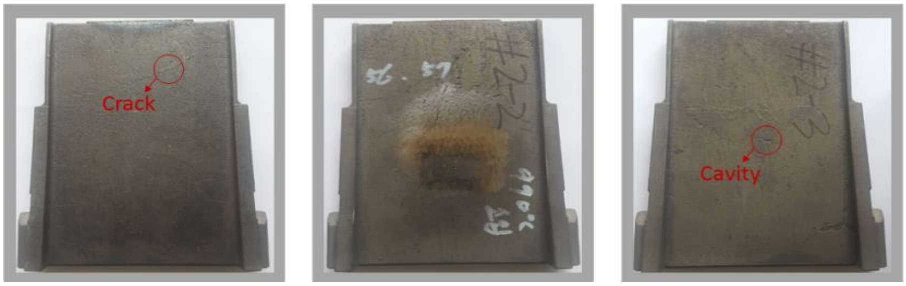
3.3 Observation and Shape of the Surface and Cross-Section of the Blade Sample

The photos of cross-sectional and surface features of white cast iron added with titanium that was precision cast are shown in Fig. 5. Even when seen with the naked eye, micro cracks and cast defects due to precision casting can be observed on the cross-section and the surface in part of the samples. In addition, it can be noted that the beautiful surface of the precision casting is not visible. For these defects, cracks are expected to be easily formed at and propagate from locations where microcrack or cast defects were created due to the strong impact wear of the field test. It was predicted that the possibility that wear will proceed rapidly on the blade surface is very high. Fig. 6 shows some of the blades put into the actual field test, and the cast defects that appeared in the test pieces of the blade sample were observed identically. Fig. 7 shows the structure, including gas porosity and shrinkage porosity.



As-cast **Quenching** **Tempering after quenching**

Fig. 5 Surface and cross-section features of white cast iron added with titanium



As-cast **Quenching** **Tempering after quenching**

Fig. 6 Features of cast steel blades made by using white cast iron added with titanium

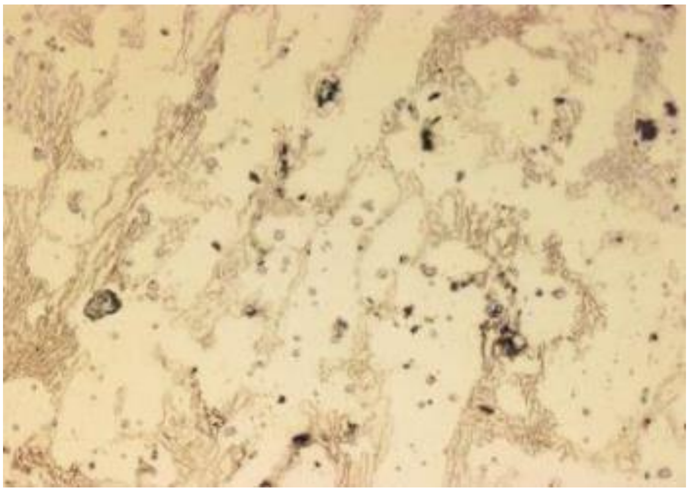


Fig. 7 Optical microstructure of white cast iron added with titanium (×200, Nital etching)

3.4 Photographs of the Research Prototype and the Developed Product

Fig. 8 shows the research prototype and the developed products of the high C-high Cr white cast iron blade for the field test.

Fig. 8 Research prototype and develop products of high C-high Cr white cast iron blades

In addition, some microcracks and cast defects were found at numerous locations on the surface and the cross-sections of the blade sample due to inappropriate casting methods for precision casting of white cast iron containing Ti. Accordingly, wear occurred rapidly due to the rapid propagation of cracks caused by impact wear, and the replacement cycle of blades due to the field tests was far short of achieving the final development goal. The following Table 4 summarizes the results of field tests related to development performance.

Table 4. Summary of development performance and field test results of high C-high Cr cast iron material blades containing Ti

Sample No.	S.P. (3)
	High C-high Cr white cast iron added with Ti
Characteristic	A blade product that was precision cast with an alloy composite added with about 1.5~1.8wt.% of Ti for the composition of a high C-high Cr white cast iron to improve the wear resistance of the shot blasting machine wheel blade
Hardness	HRC57
Usage life	2 weeks
Cause of the failure	After quenching and tempering heat treatment, the hardness value of the Ti-added high C-high Cr white cast iron appeared low at HRC57, and the replacement cycle fell short of achieving the target value during the field test. It can be seen that the decline of hardness is due to the heat treatment conditions that were not appropriate and because the content of C, Cr, Mo, and

	Ti was far below the target composition. In particular, the biggest reason for failing to meet the replacement cycle of the blade can be seen as a problem of not establishing a casting method for the addition of Ti. In other words, many cast defects like the microcracks created during precision casting of the blade were observed not only on the surface but also on the cross-sections. It is judged that the failure to achieve the replacement cycle was because impact wear propagated more rapidly due to the strong impact of the shot ball at these locations.
Blade surface shape before the test and after the test	 **Before the test**  **After the test**

4. Conclusion

In this study, we attempted to produce a blade having high hardness and high resistance with a precision casting method by adding a small amount of Ti, which is a carbide forming element, when a shot blasting machine impeller blade was produced with high C-high Cr white cast iron. A high C-high Cr white cast iron blade with high hardness and high wear resistance was produced with a precision casting method by designing the target alloy composite of C; 2.45~2.65wt.%, Si; 1.00~1.20wt.%, Cr; 15.0~16.5wt.%, Mo; 1.5~1.75wt.%, Ti; 1.50~1.80wt.%. However, the analysis results of the chemical composition for the developed product were as follows. The content of C, Cr, Mo and Ti failed to reach the target composition, and the hardness value failed to achieve the development target of HRC58 or greater due to inappropriate heat treatment conditions. In other words, some microcracks and cast defects were found at numerous locations on the surface and cross-sections of the blade sample due to the inappropriateness of the casting method for the precision casting of the white cast iron containing Ti. The Ti-added high C-high Cr cast iron blade developed in this study failed because it failed to meet the blade replacement cycle target of 1344 hours, which was the most important factor in the field test.

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