Concurrent engineering solution for the design of ship and offshore bracket parts and fabrication process

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ABSTRACT: Brackets in ships and offshore structures are added structures that can endure stress concentrations. In this study, a concurrent engineering solution was proposed, and a high strength low carbon cast steel alloy applicable to offshore structures was designed and developed. The yield strength and ultimate tensile strength of the designed steel were 480 and 600 MPa, respectively. The carbon equivalent of the steel was 0.446 with a weld crack susceptibility index of 0.219. The optimal structural design of the brackets for offshore structures was evaluated using ANSYS commercial software. The possibility of replacing an assembly of conventional built-up brackets with a single casting bulb bracket was verified. The casting process was simulated using MAGMAsoft commercial software, and a casting fabrication process was designed. For the proposed bulb bracket, it was possible to reduce the size and weight by approximately 30% and 50%, respectively, compared to the conventional type of bracket.

KEY WORDS: Steel structure; Offshore structure; Bracket; Casting steel; Reduction of volume.

INTRODUCTION

The need to develop low temperature and high strength casting steel for offshore structures has increased in line with the expanding resource development in areas, such as the Arctic Ocean. The brackets used for vessels or lathe structures are normally “⌋” or “T” shaped, and are used as supplementary structures to accommodate stress concentrations on the corners where columns meet, or where a beam and a triangular shape occurs. For a large bracket, the end part is designed using a curve to reduce interference, weight, and stress transfer (Lee, 2008).

A bracket for a vessel and structure is manufactured in plank form. When reinforcement is required, a face plate, flange, and side stiffener are welded to the bracket. The thickness of the bracket is basically determined by the girder, beam, or web plate. The thickness of the bracket is normally determined by the thickness of the web plate of the basic material. The bracket connects to the beam or column. For the bracket built-up type, a thickness adjustment and shape optimization considering the stresses are difficult. Moreover, a thicker member increases the welding requirements. Hence, a larger size and heavier member reduces the efficient use of space.

A study to change the design of the bracket girder or beam was conducted to solve these problems (Lee et al., 2004). Lee et al. attempted to omit the face bar by increasing the thickness from the standpoint of production efficiency (Lee et al., 2006). In another study, the bracket was removed from the structure, including the longitudinal stiffener or vertical stiffener (Kim et al., 2003). On the other hand, the weight of a vessel and its structure inevitably increases when a bracket is removed by strengthening the girder or beam. For a better design of the bulb bracket, a side stiffener and curve were adopted on the diagonal

surface line instead of the face plate. As a result, the size and weight could be reduced by 30% and 50%, respectively, using the bulb bracket fabricated in the casting process instead of the built-up type.

The authors propose a concurrent engineering solution to interconnect systematically all the processes from the material design and fabrication process design. Therefore, to produce an optimal bracket shape for an offshore structure that requires stricter weight control and efficient spatial use, it is necessary to design a low temperature, high strength, low carbon steel material for a standard bulb bracket vessel structure, instead of a built-up type. The authors evaluated the optimal structure design using the ANSYS program and designed the optimized casting process using MAGMASoft-V5 [<http://www.magma-soft.com>]. The authors considered the fabrication of parts through material development, parts design, and casting process analysis of the designed parts to identify the mechanical characteristics and development method of a carbon steel bracket.

ALLOY DESIGN

Alloy design and its fabrication

The development of the raw material of the bulb bracket was carried out after setting a quantitative goal (Caron and Krauss, 1972; Offshore standard DNV-OS-B101 Metallic Materials, 2009). In the manufacturing process, low carbon scrap iron and pig iron were mixed and melted at a certain ratio. When melting reached 50%, manganese (Mn) was added initially because the melting time of Mn is longer than any other metal. After melting all the metal materials, trace minerals, such as Ni, Si, and Cr, were added based on an initial analysis Data Base (D.B) to obtain the target material. From the melted material, impurities and oxidezers were removed using a slurry remover, and deoxidization was performed using an aluminum deoxidizer as soon as melting was complete.

Preparation of alloy sample and evaluation of its chemical composition

To measure the component ratio of the alloy, a 100 mm thickness sample was cut and polished using a polishing machine. Five points were measured using SPECTRO MAX. Table 1 lists the average values.

The carbon equivalent is the relative ratio of the alloy element acting as carbon or playing carbon-like role in a metal material. Various equations have been applied to the carbon equivalent. In Ceq (1), the maximum value is considered up to 0.45, and up to 0.25 in Pcm (2).

$$\text{Ceq: } C + \text{Mn}/6 + \text{Si}/24 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14 \quad (1)$$

$$\text{Pcm: } C + \text{Si}/30 + (\text{Mn} + \text{Cu} + \text{Cr})/20 + \text{Ni}/60 + \text{Mo}/15 + \text{V}/10 + 5\text{B} \quad (2)$$

The critical cooling speed and transformation temperature were lowered according to the carbon equivalent, which allowed easy transformation to martensite to increase the hardenability. Higher hardenability causes bending deformation and cracks. Therefore, bending and cracks might be avoided by preheating before welding at the interlayer temperature. Therefore, the carbon equivalent in welding serves as a barometer for determining the preheating and interlayer temperature. The Pcm and Ceq of the sample, as shown in Table 1, were confirmed to be within the allowable range.

Table 1 Chemical properties based on chemical analysis of the sample (%) (before casting).

C	Pcm	Ceq	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.112	0.219	0.446	0.367	0.96	0.019	0.014	0.5	0.5	0.185	0.023

HEAT TREATMENT

Experimental set-up

Heat treatment was carried out to achieve the target mechanical properties, such as yield strength of 490 MPa, tensile st-

length of 600 MPa, 20% elongation, 50% minimum reduction in area, and impact energy of 50 J at -20 °C. 0.12% C can reach the austenite state when heated at 912 °C or above. To make a stable austenite state, martensite can be obtained after quenching or rapid cooling with water after being maintained for 4 hr at 930 °C. Martensite remains in α steel as a solid solution because it has no time to expand due to rapid cooling. The size of an interstitial site that the carbon element can occupy is smaller in α steel than in γ steel, so the grid inevitably expands. The hardness increases due to the stress occurring during such a process. In this study, yield strength of 490 MPa, tensile strength of 600 MPa, and 20% elongation were required instead of a hardened texture. In addition, a tempering process was carried out (550 °C, 4 hr air cooling) to obtain an impact energy of 50 J at 20 °C.

Considering the temperature maintenance and heating time as the heat treatment conditions, a heat treatment furnace was used for quenching and super kanthal was used as the heating element. The maximum heating temperature was 1,600 °C. To measure the internal and material temperature, a thermocouple measurable up to 1,300 °C was used at high temperatures, but was not used at low temperatures because of the significant temperature deviations. Therefore, a heat treatment furnace for low temperature tempering was used. The normal kanthal heater used as a heating element could heat up to 1,000 °C. The heater had a heat plate manufactured with a heat-resistant paste, which was treated at high temperatures for high impact resistance and uniform temperature distribution.

The refined structure before heat treatment depending on the carbon content and transformed martensite depending on the tempering conditions after quenching was compared. A specimen size of 10 × 10 mm was used. A Buehler Simplimet 2000 mounting machine and TransOptic™ powder were used for more efficient grinding after sampling. After mounting, the samples were ground with silicon carbide grinding paper using a Buehler Graninder polisher before polishing again with a polishing cloth. Ultrasonic cleaning with ethyl alcohol was then carried out for 10 min, followed by surface cleaning with acetone. Corrosion was attempted using 5% nital (ethyl alcohol + nitric acid (5%)) for the optimal time. The structure was monitored using an Olympus optical microscope. A tensile test was conducted at room temperature using an Material Test System (MTS) universal tension testing machine (Instron Co. Ltd.).

The specimen was machined according to the ASTM A370 standard. During the tension test, the yield strength, tensile strength and elongation were measured. The contraction percentage in area was also measured after the tensile test. The surface where the contraction was most prominent was measured using Kandon digital vernier calipers. A hardness test was conducted using the specimen taken for photographing the structure, considering that the test surface and rear surface were parallel to meet the requirements for the hardness test. A hardness test is needed to measure the mechanical properties, or structural change due to heat treatment. The measurement was carried out at least five times using a Brinell harness tester at room temperature.

The impact test was carried out using a Charpy-type impact testing machine. An ASTM E 23 and Type A specimen was adopted according to ASTM E 23. Table 2 provides details of the impact test device.

A Charpy impact test impacts the rear side of the notch of the specimen, which was supported on both ends with a hammer for a single time. The impact speed was varied depending on the rising angle of the hammer, but the impact speed of the tester was normally 10 m/s. Therefore, the speed had no effect on the test result providing it was within a range of 10 m/s. The mean value of three tests was taken. The test procedure was performed at room temperature. A hammer was raised slightly while the specimen was placed on the deck, and the hammer was then dropped after setting the gauge. After stopping the vibration of the brake hammer, the hammer angle, or absorption energy value after rupture, was recorded, and the ruptured surface was monitored. The impact test at low temperatures was carried out when the material temperature reached -40 °C. The specimen was left at -40 °C for 5 min before the impact test.

Table 2 Conditions of the Charpy impact test.

Capacity (kgf·m)	Weight of the hammer (kgf)	Initial angle of enhanced hammer (°)	Anvil gap (mm)	Center distance between the hammer (mm)	Angle of impact blade (°)	Size of the tester (mm)
30	25.79	135	40	750	30	600 × 1,000 × 1,100

Results and discussion of material development

To observe the refined structure of the specimen, the structure before heat treatment was examined. The result is shown in Fig. 1(a). According to the histology classification, the nucleation and growth of ferrite or cementite occur along the austenite crystal. Such a crystal is a crystal allotriomorph, which forms when maintained for extended periods at a region where two phases coexist or when they slowly pass by slow cooling, i.e. a state near equilibrium. Under such conditions, the time for diffusion is sufficient while the thermodynamic driving force is small. Therefore, a relatively larger core was extracted heterogeneously to an austenite crystal. Such a process minimizes the increase in interfacial energy by nucleation from the new core and the existing austenite crystal. In Fig. 1, the part in white is free ferrite and the part in black is pearlite. The connection of free ferrite is often discontinued, unlike a Widmanstatten structure, because of an incoherent interface due to the poor atomic configuration between the ferrite and the other side of austenite.

To transform the sample structure to a martensitic structure, it was heated at $930\text{ }^{\circ}\text{C}$ for 24 hr to austenite, and then cooled rapidly in water at room temperature. As a result, a fine martensitic structure was obtained, as shown in Fig. 1(b), and significant bundles in parallel developed. The appearance of martensitic bundles was attributed to different corrosion characteristics from different variants, or directivity of the bundles.

Fig. 1 shows the martensite structure after tempering for 4 hr at $550\text{ }^{\circ}\text{C}$ (Zia-Ebrahimi and Krauss, 1984). Tempering at high temperatures was used to obtain an improved toughness. After natal etching, the samples were monitored at $500\times$ and $1,000\times$ magnification using an optical microscope. As a result of visual monitoring, the size of the martensitic structure became fine after tempering.

Fig. 1 Microstructures of the designed alloy after each heat treatment process.

Fig. 2 X-ray non-destructive inspection after the fabrication of bracket material.

Table 3 Mechanical properties of the samples.

	Yield strength (MPa)	Tensile strength (MPa)	Shrinkage (%)	Elongation (%)	Impact energy (J)	Hardness (Hb)
Target	480	600	50	20	50	190
Test	521	640	67	26	95.9	198.2

Table 3 lists the mechanical properties of the sample. Quenching was carried out after maintaining the sample at 930 °C for 4 hr and tempering at 550 °C for 4 hr. The tensile test was then conducted. The fracture of the specimen was a cup-cone shape, indicating the macro-characteristics of ductile breaking. The yield strength, tensile strength, contraction of the cross-sectional area, and elongation was 521 MPa, 640 MPa, 67% and 23%, respectively, which satisfied the final target values of the study. The mean value of the impact test at -40 °C far exceeded the target value of 95.9 J. The test at -40 °C, instead of the target temperature at -20 °C, was intended to satisfy the toughness requirement, considering the trend requiring -40 °C rather than -20 °C, because of the increasing applications at extremely low temperatures. When obtaining the target value at -40 °C, the value was assumed to have a high impact energy at -20 °C. On the other hand, the hardness of steel is 198.2Hb, which satisfies the required target hardness value. Fig. 2 summarizes the radiographic test results, and shows no pores or impurities that would have an adverse effect on the mechanical properties of the material after the casting process.

BRACKET DESIGN USING SIMULATION ANALYSIS

Material properties

The material for the rolling process of the bulb bracket and built-up bracket is a DH36 class plate, which is normally used for the plate and rolling processes. The DH36 class plate has a 500 MPa tensile strength and 350 MPa yield strength, which are approximately two-thirds of the values of cast steel. The casting material for the bulb bracket is a low temperature high strength material developed in this study. This material has a carbon content of 0.12% or less, a tensile strength of 600 MPa or more, yield strength of 480 MPa or more, and an impact strength at -40 °C of 50 J or more. Ceq and Pcm is 0.446 and 0.219, respectively, indicating superior welding performance properties.

Shape model

As shown in Fig. 3, the standard shape of the four bulb brackets using two types of rolled steel (cases 1 and 2) fabricated with DH36, and two types of cast steel (cases 3 and 4) fabricated with the material developed in this study, was designed to include a notch welding bead. For the built-up bracket produced to use the plate cutting and welding process, the face bar was applied to the medium or large size. Depending on the type of stress, a side stiffener was attached in parallel with a face bar, or

Fig. 3 Shape models of various bracket parts.

vertically to the web plate of the bracket. The thickness of the bracket web plate was determined to be less than the thickness of the web plate of the girder or beam. The face bar was less than twice the thickness of the web plate, taking into account the welding workability. The side stiffener had a basic shape within the thickness of the web plate, and the size varied according to the working load of the design. A small bracket that requires no reinforcement and no welding process was cut to size only.

The slope of the bracket was designed as a combination of a circular curve and a straight line for efficient transfer and expansion of the stress to reduce the size as well as secure the installation for accessory. Bending is required when installing the face bar. In a permanent design, an L-shape face bar is often used after cutting the face bar and bending the edge, but is not commonly used for offshore structures, which have many stress concentration points and relatively larger concentrated loads. The bulb bracket has a thicker face bar and side stiffener depending on the distribution of the stress working based on the basic shape of the built-up bracket and the connection between the curve and straight section was designed to be gentle, referring to the part of shape of bulb flat. A rolled shape requires less welding than a built-up type, and the thickness can be increased. A rolled shape has the advantage of lower manufacturing cost and better mass production compared to cast steel, but the rolling process has difficulties in producing diverse curves and adjusting the thickness.

For a thickness adjustment, a method was used to calculate the induced stress (σ) after computing the section modulus (Z , b is horizontal length of the square structure and h is the vertical length of the square structure) of the square structure described in Eqs. (3) and (4) for the difference in the stress distribution at each mesh and bending moment (M). Another method involving the application of a 1:25 Snip to both ends of the face bar and side stiffener was attempted for optimization, and was verified using ANSYS Finite Elements Method (FEM) analysis software. The following equations were used:

$$\sigma = M / Z \quad (3)$$

$$Z = bh^2 / 6 \quad (4)$$

Analytical model

The beam and girder, which is the main structure serving the framework, was T-shaped and manufactured from DH36 steel. DH36 was used for bracket cases 1 and 2. Casting steel was used for cases 3 and 4. The shape for the analysis model was developed using the ANSYS program, as shown in Fig. 4. The main structure consisted of a 2,500 mm high beam (T500 × 400 × 15/30) and a 5,000 mm long girder (T500 × 400 × 15/30). At the corner where the girder and beam met, four models were produced based on the bracket according to the type.

A bilateral symmetric structure with a DH36 beam and girder was produced. A uniform load differentiated by two vertical loads, 52 MPa and 14 MPa, were placed on top of the structure and after fixing the beam's bottom points. By searching using the trial and error method, the optimal bracket weight, size, and deformation according to the case, which reaches the critical stress, were determined. To identify the variation in the slope shape, face bar and stiffener, and the installation efficiency of the equipment at the lower space of the structure depending on the size with a fixed bracket thickness, the height (H) and short cut from the vertex to the slope was compared, instead of comparing the length (L) and weight among the cases.

Fig. 4 Dimensions of the bulb bracket structure and its stress distribution.

Fig. 5 Mesh data for structural analysis.

As shown in Table 4, the main structure has more nodes and elements for analysis, which was attributed to the difference in size, as indicated in Fig. 5. The mesh interval in the main structure was 100 mm and the interval between the bracket and the surrounding structure, which was needed to evaluate the stress distribution pattern, was determined to be 300 mm. The yield strength and tensile strength of the casting steel for the casting bracket was assumed to be 450 MPa and 600 MPa, respectively, which are 1.2 times the 350 MPa yield strength and 500 MPa tensile strength of DH36. During the material test, the yield strength, area contraction, and elongation were confirmed using a tensile strength test. The safety against the force on the actual structure could be determined by the yield strength.

The safety factor of the yield strength was not considered separately because the same load was applied to each case. The analysis was intended as a relative comparison and was applied within the maximum value. The displacement was checked by monitoring the deflection at the center of the beam. The maximum allowance was set to 10 mm, which is the maximum tolerance for site installation. Torsion, buckling, or fatigue of the bracket was excluded by considering that the bracket is a supplementary member, not the main member, and the vertical load (which is the main load) could be accommodated by the face bar of the web plate and side stiffener.

Table 4 Conditions of material and modeling.

Name	Material	Number of nodes	Number of elements
Structure	DH 36	118,296	58,954
Bracket	Casting steel / DH36	4,087	2,114

Results and discussion

Figs. 6 and 7 present the results of structural analysis of each case under the same load conditions. The load working on the deck was concentrated on the girder, and then transferred to the beam or wall, except for the locally-applied load. Therefore, most of the loads on the bracket at the end, where the girder and beam met, were vertical loads, and the stresses were concentrated on the end of the lower part of the bracket, not on the upper part. The load on the bracket to be installed at the lower part of the beam showed a similar pattern of the load on top but the working point became symmetric.

Fig. 6 Results of an analysis of the brackets and structures.

Fig. 7 Results of the analysis of the brackets and structures.

Fig. 8 3D modeling of the optimized bulb bracket.

Fig. 9 2D design drawing of the optimized bracket part.

The size of the built-up bracket is dependent on the availability of the face bar and side stiffener as well as on the installation location, and when applying a double circular curve to a slope pattern, a gentle load flow transfer has a greater effect on the maximum stress distribution point, which will move closer to the vertex at the lower part or welding bead when the face bar is installed. For the built-up bracket, the structural stability is increased by installing a side stiffener closer to the slope than to the face bar, whereas most of the load is concentrated on the end part of the slope for the bulb bracket. This suggests that the role of the side stiffener for structural stability is insignificant. For the bulb bracket in cases 3 and 4, which features a double circular curve at the end part of the slope, the load was distributed more uniformly over the entire part compared to cases 1 and 2. As shown in Fig. 6, although the rolled bulb bracket used the same material as the built-up bracket, the decrease in the size and weight was only 40%. Mass production is expected to increase the cost efficiency. The bulb bracket made from cast steel had its size and weight decreased by 20% and 50%, respectively, compared to rolled steel (case 1 versus case 3).

The displacement in all four cases was 5 mm or less at the center of the girder, indicating no structural problems. As indicated in Fig. 6 and Table 5, regarding the optimal shape of bulb bracket, case 1 in rolled steel and case 4 in casting steel would be superior to a built-up bracket from the viewpoint of weight and size under the same load distribution conditions. This was attributed to the sufficient thickness of the bulb bracket corresponding to the face bar, which can deal appropriately with the torsion or buckling load on the side up to 600 to 800 mm in length (the scantling space) without a side stiffener. In the case of an

800 mm-long or longer large bracket, the side stiffener was expected to prevent torsion. As shown in Fig. 7, the lug of the bulb bracket based on a basic pattern with an optimal design value applied to rolled steel can be used in a variety of ways depending on the load pattern. Application of the lug on either side or both sides is possible for a bulb bracket in casting steel, as shown in Figs. 7-9 present a 3-D model of the bulb bracket in casting steel, and a process drawing with the optimal shape obtained from structural analysis, respectively.

Table 5 Properties of each case bracket.

Classification	Size (H: mm)	Weight (kg)	Displacement (mm)	Remarks
Case 1	286	24	3.899	Rolled beam
Case 2	286	27	3.874	Rolled beam
Case 3	234	13	4.308	Casting steel
Case 4	230	13	4.319	Casting steel

MOLD DESIGN AND PROTOTYPE CASTING ANALYSIS

To develop the parts designed in this study, the authors found a material with a carbon content closer to the developed product using the MAGMASOFT-V5 Database. As a result, GS16Mn5 was used for casting analysis.

An analysis of the mold material was carried out using Furan, which is similar to artificial silica sand. Furan has higher strength than resin or hardener, provides the accurate dimensions of the mold, and has higher warm strength and caloric power. Moreover, it has superior flexibility when mulling, has less smoke and odor than with organic solvents, and provides more options in terms of price, strength, casting material, and workability. Because it has a wide range of hardener options and low viscosity, Furan minimizes the problems at low temperatures. Mulling and hardening can be improved in the low temperature range by giving the resin high activity. Hardening can be identified by monitoring the changes in mold color. The initial temperature of the molten metal was set to 1,630 °C, and the initial molding temperature was to 20 °C for analysis, as shown in Table 6. The heat transfer coefficient was dependent on the temperature of the molten metal, and a temperature-dependent coefficient was set. The charging time was set as the actual pouring time: 45 s for casting analysis.

Fig. 10 shows casting methods 1 to 4, which were used to identify the optimal casting method of the bulb bracket. The bulb bracket was relatively thinner than that with other casting steels. Cast steel has poorer flexibility than cast iron. Therefore, the area of ingate, where the cavity is connected directly to the runner, is reduced to increase the speed of molten metal into the cavity for easy charging of the molten metal into the cavity. The casting method was designed through consultation with casting factory experts for an efficient casting process, and by immediately incorporating the casting analysis results into the casting process. What is more important in casting method for bulb bracket is the runner pattern design for smooth flow without gas inflow through turbulent flow from the inlet where the molten metal flows into the cavity and the inlet design to effectively fill the molten metal with low liquidity for casting and a relatively thinner cavity and design of the location and size of the feeder to deal with the contraction, which occurred in the solidifying process of casting steel.

Table 6 Boundary conditions used in casting solidification analysis.

Parameters	Symbol	Unit	Values
Solidus temperature	T_s	°C	1442
Liquidus temperature	T_l	°C	1510
Initial inlet temperature	T_i	°C	1630
Initial mold temperature	T_m	°C	20
Heat transfer coefficient between material and mold	h_m	W/m ² K	Temperature-dependent
Filling time	t	second	45

Fig. 10 Casting plan for fabrication of the bracket.

Table 7 Volume of each region according to the casting design (unit: cm^3).

Gate system	Mold 1.	Mold 2.	Mold 3.	Mold 4.
Cavity	13284	13284	13284	13284
Ingate	42	112	113	430
Runner	1336	2601	2766	2216
Feeder	3842	11660	13973	6763
Feeder neck	33	129	247	255

Table 7 lists the design-volume of the parts in casting methods 1 to 4. The volume of the bulb bracket and the cavity volume were identical, and the volume of the runner or ingate varies depending on the casting method. Casting analysis was carried out using different volumes and locations of the feeder to determine the appropriate feeder design for supplementing insufficient molten metal due to solidification contraction. Table 7 lists the volume of the feeder and the volume of the feeder neck that connects the feeder to the cavity.

When the feeder and cavity contact each other, the contact area is expanded, creating a risk of hot spots that can generate pores. The feeder neck functions to reduce such a contact area to move the hot spot inside the feeder instead of the cavity, and cause molten metal in the feeder to move rapidly into the cavity to fill the contracted part with molten metal. If the contact area of the feeder neck is too small, molten metal in the feeder can barely move into the cavity. When the contact area is too large, a hot spot might remain around the cavity or feeder neck. Therefore, the appropriate design is important.

Fig. 11 shows the charging liquidity pattern of each casting method. Viewing the charging liquidity pattern of casting method 1 requiring one ingate at the center, the liquidity in the molten metal after passing ingate filled the vertex of the bulb bracket first at early stages of cavity filling. In this case, the gas remaining in the cavity did not flow out smoothly, causing residual gas to remain at both edges that were filled at a later stage, which resulted in pore generation. For the gas remaining inside to flow out smoothly, it is necessary to provide an air vent at the parts where charging is completed at a later stage and gas solidification occurred by charging molten metal in a liquidity pattern. In addition, it is important to stimulate the flow of molten metal through a redesign of the ingate.

Fig. 11 Filling ratio of regarding casting case.

Fig. 11 Continued.

With a view to the fluidity pattern of casting methods 2 and 3 requiring 2 ingates, unlike casting method 1, in which the vertex is filled first, charging was carried out from both edges, not the vertex. By charging from the edges to the vertex, the air vent on the vertex is expected to allow residual gas to flow out. Although the volume was lower compared to casting method 1, charging with molten metal was made later at the center in methods 2 and 3, which also caused the solidification of residual gas.

With the fluidity pattern of casting method 4 requiring four ingates, the molten metal charging pattern was completely different from that of methods 1 to 3. In casting method 4, the molten metal, after passing four ingates, filled the cavity toward the vertex gradually. During this gradual filling, the solidification of residual gas was reduced significantly, and the residual gas flowed out through the air vent on the vertex. The residual gas in the side stiffener (where charging was completed last), and the lugs at both ends at the bottom, could be discharged through the feeder.

According to the fluidity pattern of each casting method, casting method 4 with four ingates showed gradual charging from the ingate, which indicated the most stable charging pattern. Casting method 4, which was designed with four ingates, appeared to be more desirable with respect to performing the casting process.

Fig. 12 shows the air pressure pattern after charging the cavity with molten metal. To prevent residual gas from coagulation by charging liquidity when analyzing the casting, an air vent was installed at the part where gas solidification is likely before casting analysis. For casting methods 1 to 3, the residual gas was not removed completely, which was attributed to gas gathering at the other points where the air vents were not installed.

For the cavity and runner, ingate, feeder, and feeder neck, the design was carried out using the CATIA V5 3-D modeling program. For the air vent, the design was carried out using the analysis program, MAGMASoft, which resulted in low accuracy. Therefore, the air vent design was not modeled accurately in casting analysis, and gas collection was detected, even at the part where the air vent was installed. The air pressure result might be referred to when determining the air vent location in a casting process.

Fig. 12 shows the air pressure pattern. The pressure increased by heated air expansion at the location where gas gathering was monitored. The MAGMASoft results revealed the air pressure pattern numerically. Increased air pressure due to gas gathering caused pore generation, which resulted in pore and surface defects. For production quality, air vents to discharge the gas should be provided at the appropriate locations.

Fig. 13 shows hot spot patterns based on solidification analysis of each casting method. A hot spot, which is combined with air pressure, is the decisive factor causing a defect. The hot spot, when coagulated, indicates a higher temperature than the surroundings. As solidification occurs last, it causes contraction, which leads to porous defects in the product. A final defect analysis was carried out by comparing the hot spot result with the porosity result.

Fig. 12 Amount of each air pressure casting method.

Fig. 13 Hot spot patterns for each casting method.

Casting analysis showed that a hot spot on the product could be eliminated by moving the hot spots to the runner part by redesigning the runner and ingate, or by providing a feeder or chiller to the hot spot area. In this study, the aim was to remove the hot spot by changing the design of the runner and ingate while providing a feeder to the hot spot area. After installing the feeder on the side stiffener and lugs on both ends, casting analysis was carried out for casting method 1. The hot spot on the lugs was still monitored. With casting method 2, which has 2 ingates and 2 feeders on the lug, and casting method 3, which has four feeders on the lug, no hot spot was monitored inside the product. The hot spot was moved to the runner part, causing no problems with the product. In the case of casting method 4 with four ingates and four feeders on the lug, no hot spot was monitored inside the product but on the runner part, causing no defect. No hot spot defects with casting methods 2, 3 and 4 were noted. A comparison of the volumes of the feeders showed that the feeder volume of casting methods 2, 3 and 4 was $11,660.8 \text{ m}^3$, $13,973.2 \text{ m}^3$, and $6,763.08 \text{ m}^3$ (which was about one-half of methods 2 and 3), respectively. This means casting method 4 can produce a quality product using far less molten metal.

Fig. 14 shows the porosity pattern after solidification analysis of each casting method. Porosity is represented directly as a defect as a result of casting analysis, suggesting that the pores formed during solidification. The porosity pattern is critical in analyzing casting because another casting method must be sought if porosity exists inside the product. As shown in Fig. 14, the porosity was monitored around the ingates on the lug where the hot spot occurred in casting method 1. Therefore, an improvement in the casting method is needed before starting the casting process.

For casting methods 2 and 3, no defects with hot spots were observed. This suggests that the monitoring and measurement need to be improved to prevent potential defects in the casting process. For casting method 4, no porosity pattern was detected, as the case of the hot spot, and quality production is expected. After monitoring the porosity pattern of each casting method, casting method 4 was considered to be the optimal casting process. A wooden pattern model of the bulb bracket was fabricated based on the casting methods using MAGMAsoft. A parting line was separated to the top and bottom model to produce a product with an accurate cavity inside the mold. The parting line of the top and bottom model was determined, and a wooden model was fabricated, as shown in Fig. 15.

Fig. 14 Porosity characteristics of each casting method.

Fig. 15 Wooden pattern for a steel casting for bulb bracket.

Fig. 16 Bulb bracket manufactured by the steel casting process.

CHARACTERISTIC EVALUATION OF BULB BRACKET

Chemical analysis and a mechanical property evaluation of the bulb bracket fabricated by the casting process were performed to determine if the quantitative target had been accomplished. As shown in Fig. 16, two Y-blocks were installed on the side when fabricating the bulb bracket. Chemical analysis of the Y-block was carried out while producing the specimen for the tensile test, impact test and hardness test. A specimen with the same properties was produced for a property evaluation.

Chemical composition

Chemical analysis of the bulb bracket was conducted with the specimen taken from the Y-block using a SPECTRO MAX component analyzer. Table 8 lists the chemical component analysis results of the bulb bracket. As shown in the table, the quantitative targets were satisfied. According to Eqs.(1) and (2), Pcm and Ceq were 0.203 and 0.43, respectively, which satisfied the target values of 0.23 and 0.45.

Table 8 Chemical compositions of the bulb brackets analyzed after casting (%).

Spec	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Nb
Max	0.12	0.43	1.18	0.025	0.025	0.95	0.5	0.4	0.03	0.03
Test	0.097	0.340	1.00	0.02	0.01	0.5	0.479	0.176	0.019	0.004

Mechanical properties

Table 9 Mechanical properties evaluation results of the bulb bracket (after casting).

	Yield strength (MPa)	Tensile strength (MPa)	Shrinkage (%)	Elongation (%)	Impact energy (J)	Hardness (Hb)
Target	480	600	50	20	50	190
Test	532	651	68	26	115	198

A tensile strength test was conducted at room temperature using a universal tensile tester, and the specimen was produced in accordance with the ASTM A370 standard. During the tensile test, the yield strength, tensile strength, and elongation mechanical properties were measured. After the test, the contraction percentage area was measured based on the part with the highest value. An impact test was carried out using a Charpy-type impact testing machine. An ASTM E 23 and Type A specimen was adopted according to ASTM E 23 (a standard specimen with a square section (10 mm) and a 2 mm-deep notch). The test temperature was -40 °C.

A hardness test was carried out using a Brinell hardness tester at room temperature after cutting a Y-block and grinding both sides to make them parallel. The test was carried out three times for each specimen. A tensile test, impact test and hardness test were conducted. As shown in Table 9, the results were all acceptable with respect to the target value.

CONCLUSIONS

- (1) A low carbon cast steel with carbon content of 0.12% was developed for offshore structural application. For this steel, Pcm and Ceq were estimated to be 0.23 and 0.45, respectively, that indicates a high weldability. The mechanical properties of cast steel satisfied the required target values for offshore structures.
- (2) Fabrication of a new type of bulb bracket through a casting process was developed. The optimum design of brackets for strict weight control and the efficient utilization of space in offshore structures were sought. The shape of bulb brackets was designed and decided by ANSYS structural analysis, and it was compared with that of built-up brackets. The bracket with a double circle curved hypotenuse of the triangular type was more effective in comparison with the bracket with a straight-line hypotenuse of the triangular type (case 4).
- (3) MAGMASOFT was employed to simulate casting process of the designed bulb brackets. Flow pattern was studied for four different casting plans. The optimal casting plan was developed by considering residual gas, hot spots and porosity. A casting plan with four ingates was designed (casting 4).
- (4) A bracket was manufactured according to the developed optimal shape and casting process. The chemical composition and mechanical properties of the sample was in accordance with the required properties.

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