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Manufacture of Cask Forgings for Spent Nuclear Fuel Transport*


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1 Introduction

In recent years, along with the increased relative importance of nuclear power generation, the amount of spent nuclear fuel has also increased. After cooling in the fuel storage at the power plant, spent nuclear fuel is transported to reprocessing plants. Carefully thought-out shielding measures are necessary during transportation, and a special container is used for this purpose. Such containers for transporting spent nuclear fuel are called casks.

In Japan, 24 light water reactors are presently in operation, generating about 500 t/year of spent nuclear fuel. However, only the pilot plant at Tokai Works of the Power Reactor and Nuclear Fuel Development Corporation serves as a reprocessing plant, and consequently much of the spent nuclear fuel generated in Japan is reprocessed in foreign countries such as Britain and France. A plan to construct a second reprocessing plant on the Shimokita peninsula is under way as part of a program for instituting domestically a complete nuclear fuel cycle in Japan. Against this background, the demand for casks seems to increase steadily in the future.

In 1983, Kawasaki Steel received an order for cask forgings for five container, which have been manufactured and delivered. This report presents results of a preliminary investigation on the chemical composition of steel related to the manufacture of these cask forgings, as well as manufacturing results and future problems.

2 Types and Features of Cask

Casks are classified into wet type and dry type,[1] depending on whether they contain water or gas. **Table 1** gives the features of the two types. **Figures 1** and **2**

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Table 1 Characteristic differences between dry and wet type cask

Index \ Type	Wet	Dry
Coolant for decay heat	Water	Gas (N_2)
γ-lay shield	Lead	Steel
Neutron shield	Water	Resin
Brand	EXCELLOX-seriese HZ-75 NH-25	TN-seriese MAGNOX-type

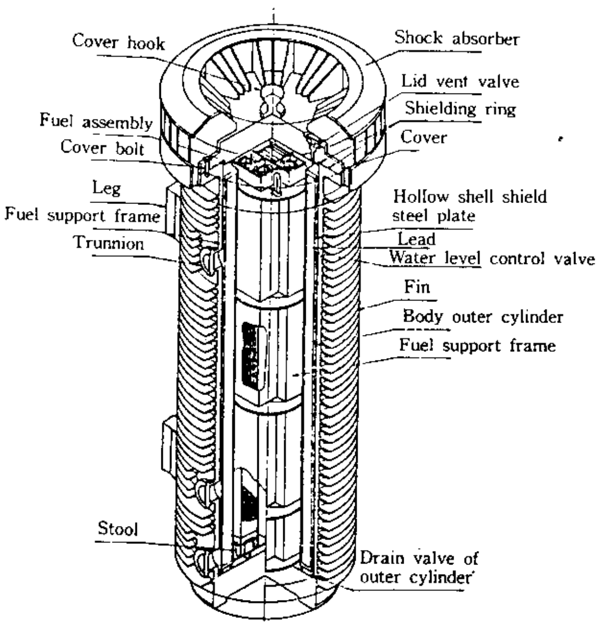

Fig. 1 Example of wet-type cask[1)]

show bird's-eye views of representative casks.[1)] In these two examples, the cask proper is a cylindrical container. The wet type cylindrical container is made of multiple steel plates of small wall thickness, with lead used as shielding. In the dry type, steel plates of large wall thickness are used instead of lead. In a dry type cask of simple construction, adoption of forgings permits use of fewer welds, providing a structural advantage.

In Japan, casks must conform to the Safety Standard of BM-type Second Fission Transportation contained in the Safety Standards for Transportation of Radioactive Materials given in **Table 2**. Furthermore, casks are required to comply with the Rules for Safe Transportation of Radioactive Materials of IAEA (International Atomic Energy Agency) as well as the regulations of the destination country and transit countries when shipped internationally. In addition, the spent nuclear fuel to be transported requires approval for each reactor. Therefore, specifications for steel products are not common. At least the following characteristics,[2, 3)] however, must be taken into consideration:

(1) Thermal conductivity
(2) Coefficient of thermal expansion
(3) Strength in the range from room temperature to design temperature (20 to 300°C)
(4) Fracture toughness (T_{NDT} and K_{Id})

Especially with respect to fracture toughness, it may be required that casks meet very severe requirements in line with safety design concepts and the climate conditions of transit areas.

At present, there is no standardized steel material for casks. Development of steels for casks which satisfy diverse customer requirements and at the same time, are economical would be extremely significant.

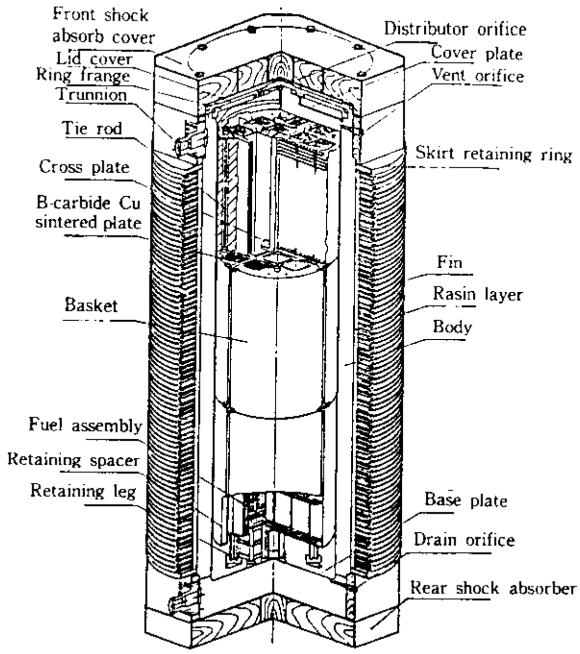

Fig. 2 Example of dry-type cask[1)]

3 Manufacture of Cask Forgings

3.1 Outline

Cask forgings made for the subject purpose were the body and base plate for a dry-type TN-12/12 cask. The profiles of these cask forgings are shown in **Fig. 3**. They are heavy steel plates with a thickness of about 300 mm. The mechanical properties required of the material are shown in **Table 3**. Because the steel thickness is great for the purpose of γ-ray shielding, a small design stress is permissible, and the strength required of the material is not high. For this reason, conventional mild steels with tensile strengthes in the 45 kgf/mm^2 class have previously been used. In this case, however, mild

Table 2 Safety standard of BM-type 2nd fission transportation

Test condition	Criterion
I. Standard proof test (1) Rain proof Spraying water equivalent to 50 mm/h rain (2) Free fall descent proof under 5 t……1.2 m 5-10 t……0.9 m 10-15 t……0.6 m over 15 t……0.3 m (3) Compression proof Putting 5 times weight on Cask for 24 h (4) Penetration proof Dropping 3.2 cm dia. bar of 6 kg weight from 1 m height (5) Environmental proof Keeping one week at 38°C after tests through 1-4	(1) Specific dose of radiation at surface less than 200 mrem/h (2) Radiation dosage less than 10 mrem/h apart from 1 m distance (3) Leakage ratio less than 10^{-6} A_2/h (4) Surface temperature less than 50°C in the shade (5) Surface density less than the allowable value (6) The critical state is not achieved in the case of arbitrary arrangement of casks more than 5 times of numbers restricted for transportation, after tests.
II. Special test (1) Stiffness test a) Free dropping from 9 m height b) Dropping from 1 m height over horizontal section of bar with 15 cm dia. extruded 20 cm height (2) Fire proof Keeping 800°C for 30 min (3) Water proof Keeping for 8 h under 15 m depth (4) Environmental proof Keeping for one week at 38°C atmosphere after tests through (1)-(3)	(1) Radiation dosage less than 1 000 mrem/h apart from 1 m distance (2) Leakage ratio less than A_2/week, and ^{85}Kr less than 10 000 Ci/week (3) The critical state is not achieved in the case of arbitrary arrangement of casks more than 5 times of numbers restricted for transportation, after tests.

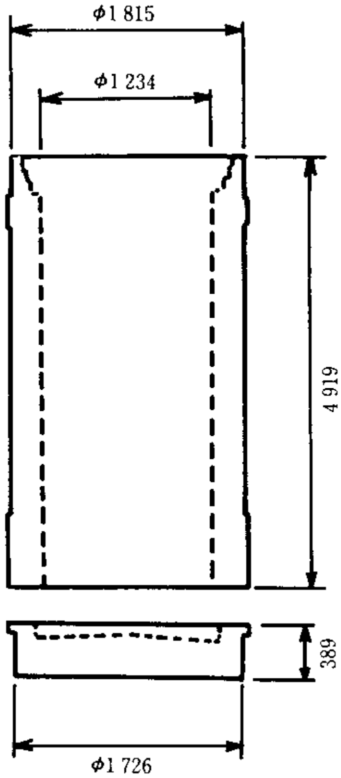

Fig. 3 Profile of cask forgings, TN-12/12 type

Table 3 Mechanical property requirements

Tensile property			Impact property		DWT
TS (kgf/mm²)	El (%)	RA (%)	$_vE_{-30}$ (kgf·m)	$_vE_{-46}$ (kgf·m)	T_{NDT} (°C)
≥43	≥20	≥30	≥6.92	≥2.78	≤−40

steel could not be used for forgings because of fracture toughness requirements as shown in Table 3. Consequently a preliminary investigation was made prior to manufacture as to chemical composition in order to obtain a proper material.

3.2 Preliminary Investigation

The investigation was conducted using 100-kg experimental ingots to obtain an appropriate chemical composition that would ensure the mechanical properties given in Table 3. The basic composition is that of a 0.10%C-1.20%Mn carbon steel equivalent to ASTM A350 grade LF1. The C, Mn and Ni contents were varied and an investigation was made into their respective effects on mechanical properties after

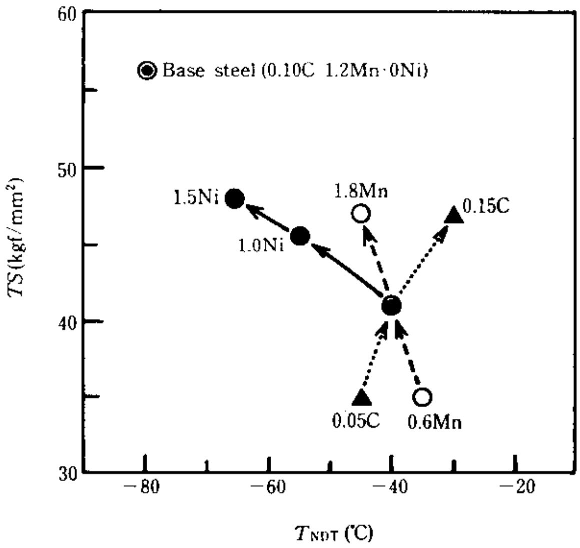

Fig. 4 Effect of C, Mn and Ni contents on strength and toughness

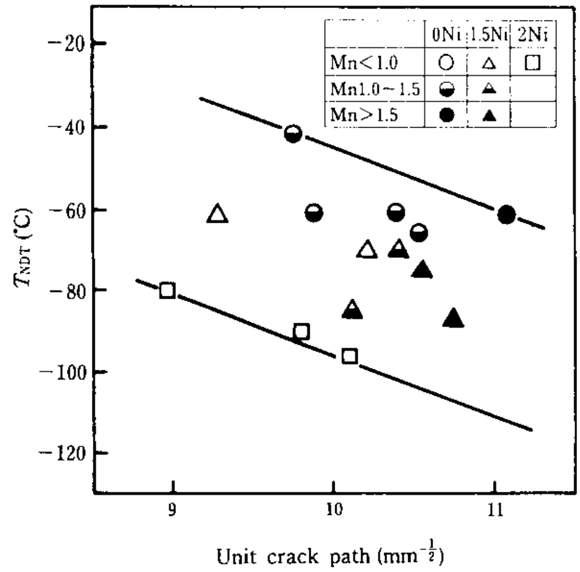

Fig. 5 Relation between T_{NDT} and fracture unit

quenching and tempering.

Figure 4 shows the effects of C, Mn and Ni contents on the strength and toughness of a simulate-heat-treated sample corresponding to a 1/2 thickness of a 300-mm steel product. Although an increase in the content of any of these elements results in an increase in strength, especially an increase in the C content causes toughness deterioration. An increase in the Mn and Ni contents improves thoughness; the effect of Ni is striking. It is necessary to add about 1.5% Ni in order to satisfy both the strength and the toughness requirements in Table 3.

The optical microstructure of the heat-treated steels is shown in **Photo 1**. The amount of pearlite increases due to an increase in the C content, and ferrite grains are refined by an increase in the Mn content. It is understood that these structural changes are effective in increasing strength and toughness. The relationship between T_{NDT} and the fracture unit path on fractured surfaces of specimens after the drop weight test, is shown in **Fig. 5**. When the Mn content is high, the fracture unit is small. This indicates an improvement in toughness by structure refinement. On the other hand, the Ni content has little effect on structure refinement. Even with the same fracture unit, however, the higher the Ni content, the better the toughness. It is considered that Ni increases the toughness of the matrix itself.

In consideration of the results shown in Fig. 4, 0.1%C-1.20%Mn-1.5%Ni steel was selected as the cask material on this occasion. The influence of the cooling rate at quenching on the strength and toughness of this

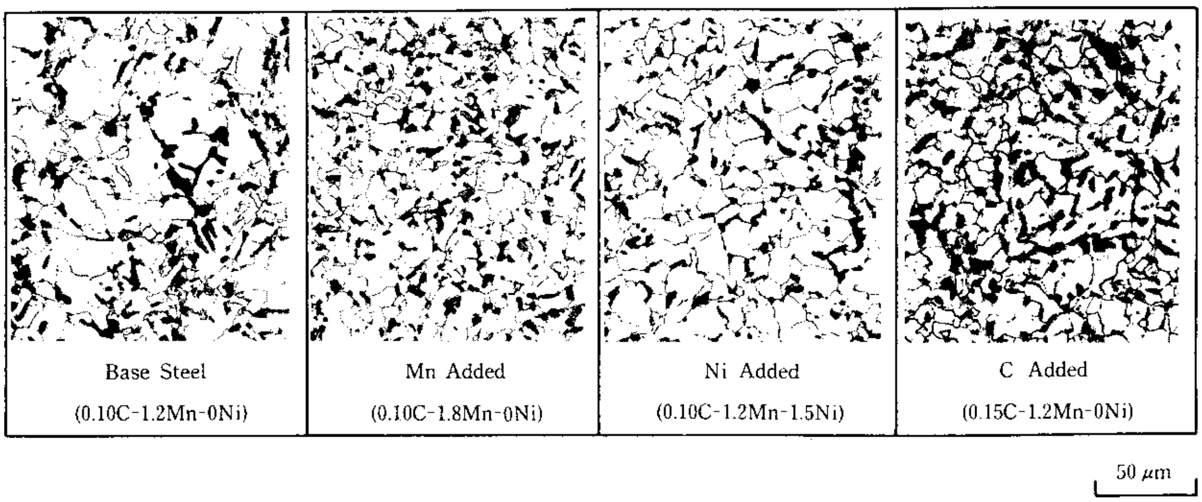

Photo 1 Microstructure of steels tested

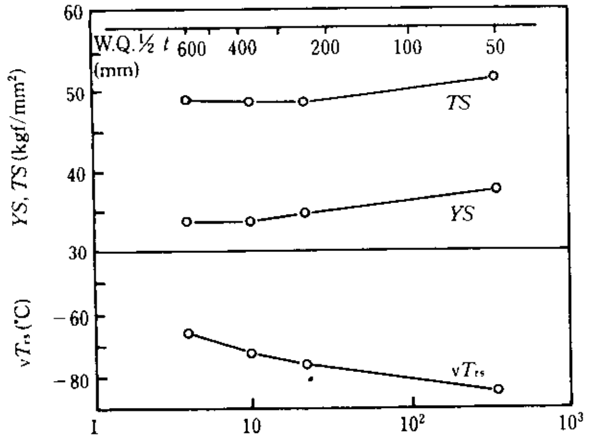

Fig. 6 Influence of cooling rate on mechanical properties of 0.1C–1.2Mn–1.5Ni steel

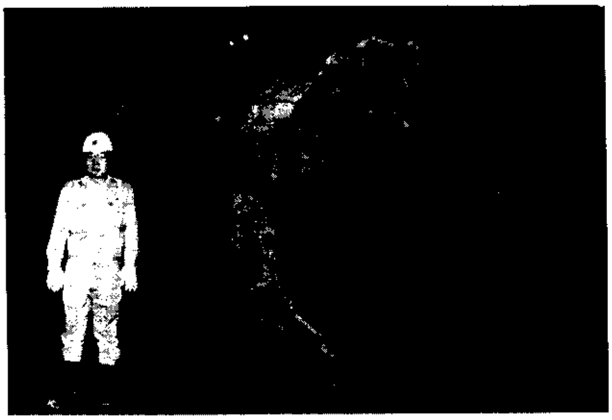

Photo 2 External view of 100 ton hollow ingot for cask shell

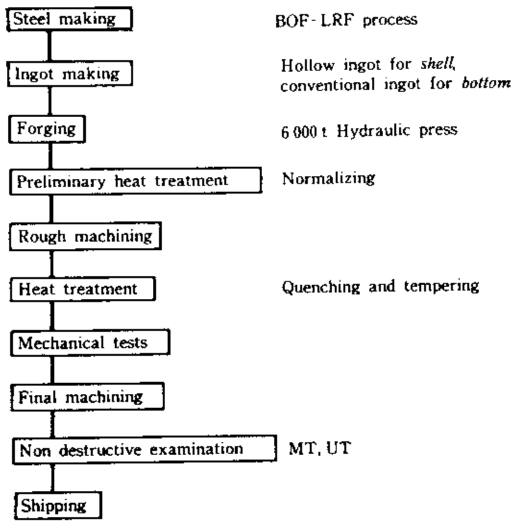

Fig. 7 Manufacturing process for cask forgings

steel grade is shown in **Fig. 6**. As is apparent from this figure, the dependence of this steel grade on the cooling rate is relatively small, and good performance can be expected in each part of the wall thickness when this steel is used in extra-heavy cask forgings.

3.3 Manufacturing Plan

The target chemical composition selected, based on the results of the preliminary investigation, is shown in **Table 4**. A hollow ingot, as developed by Kawasaki Steel, was used as the material for the body. Hollow ingots show little segregation because of their solidification characteristics. The internal surface of a cylindrical product made from a hollow ingot is very clean and homogeneous compared to that made from a conventional solid ingot.[4,5] A hollow ingot is an optimum material for pressure vessels in which joints are made by welding and the internal surface is overlay-welded. The body of the cask is joined to the base plate by welding and stainless steel is overlay-welded on the internal surface. Therefore, use of a hollow ingot is advantageous. **Photo 2** shows the appearance of the 100-t hollow ingot used for making the cask body.

The base plate was made by upsetting a conventional solid ingot. However, forging was carried out in such a way that the weld groove was on the bottom side of the ingot. Quenching and tempering were carried out as heat treatment. The austenitizing temperature for quenching was 800°C and water quenching was conducted. Tempering after quenching was at 630°C. The manufacturing process for the cask forgings is shown in **Fig. 7**.

Table 4 Target chemistry for cask forging (wt%)

C	Si	Mn	P	S	Ni	Cr
0.09 ~0.11	0.20 ~0.30	1.15 ~1.35	≤0.010	≤0.005	1.40 ~1.60	0.10 ~0.30

3.4 Results of Manufacturing

After heat treatment (quenching and tempering), specimens were taken from the position shown in **Fig. 8**, and various tests were conducted to confirm mechanical properties. The macrostructure and sulfur print of the cross section are shown in **Photo 3**. It can be seen that the internal surface is very clean. The through-thickness distribution of elements is shown in **Fig. 9**. The through-thickness distribution of mechanical properties is shown in **Fig. 10**. The segregation of elements is very slight although the specimens were taken from the top side of the ingot; the required values of mechanical properties shown in Table 3 are sufficiently met. In addition, variations are very small. As is apparent from **Table 5**, which

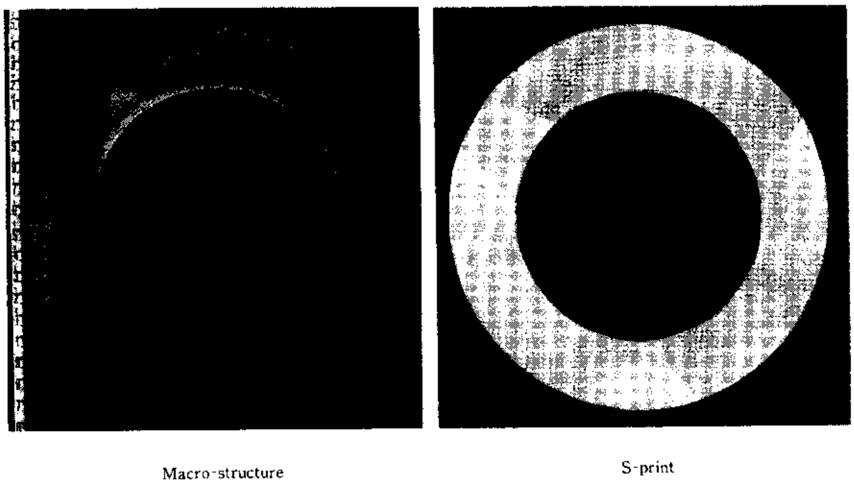

Photo 3 Macrostructure and S-print of cross section

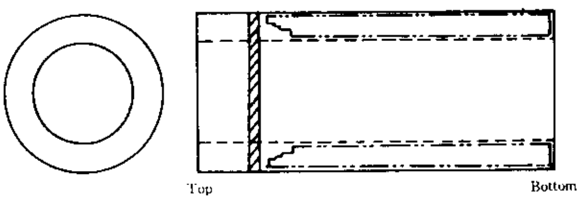

Fig. 8 Sampling position for test specimens

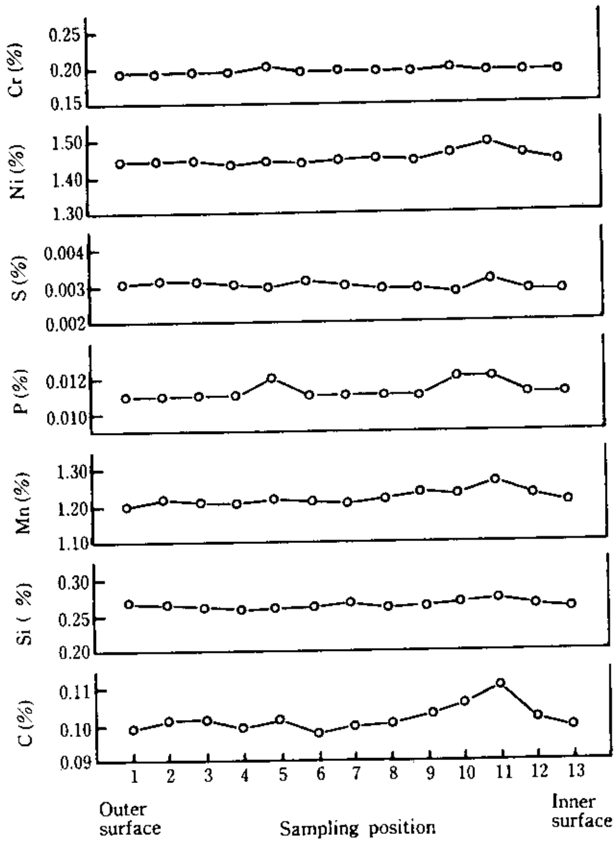

Fig. 9 Chemical analysis on cross section

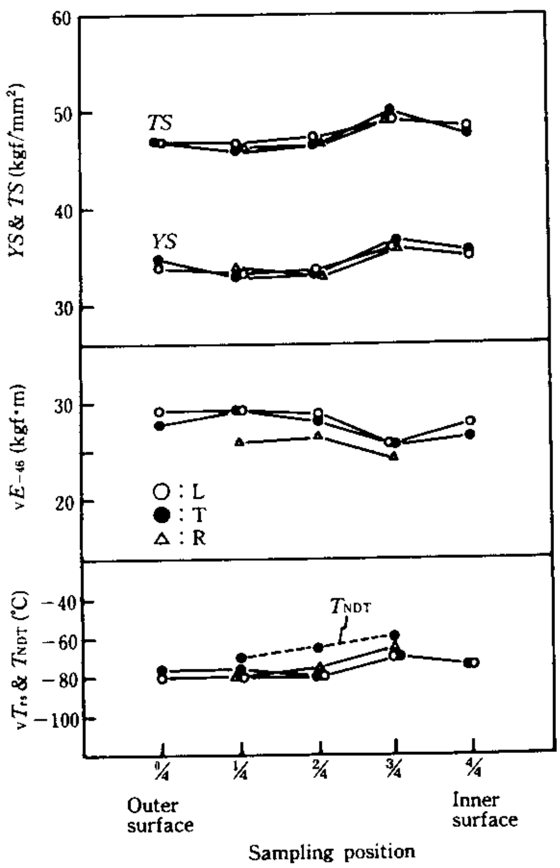

Fig. 10 Distribution of mechanical properties

shows results of measurement of thermal conductivity and coefficient of thermal expansion, all the target values are sufficiently obtained.

3.5 Fracture Toughness

In addition to the Charpy impact test, tests were conducted to determine dynamic fracture toughness (K_{Id})

Table 5 Data on thermal-conductivity and thermal-expansion[b]

Thermal conductivity (W/m·K)	Thermal-expansion coefficient $\times 10^{-6} K^{-1}$
50°C : 41.9 200°C : 43.6 (≥35.6)[a]	13.9 (≥12.0)[a]

[a] Thermal property requirements
[b] Chemical composition: 0.10%C, 0.24%Si, 1.27%Mn, 0.005%P, 0.004%S, 1.51%Ni, 0.19%Cr

and crack arrest toughness (K_{Ia}), which can be used as measures of the fracture toughness characteristics of the cask forgings in consideration of fracture dynamics. All specimens were taken from a 1/4 depth from the sheet surface in a tangential direction (a 90° angle to the main forging direction).

The dynamic fracture toughness test was conducted at −40°C on fatigue notched specimens ($a/W=0.5$) with the same shape as the Charpy impact test specimen, using a Charpy impact tester with instruments. Brittle fracture did not occur in the state of plane strain. The dynamic fracture toughness value, $K(J_d)$, converted from the J-integral value, J_d, calculated from the energy consumed until the maximum load is reached was 1 000 kgf·$\sqrt{\text{mm}}$/mm^2 or more, and K_{Id} could not be measured.

The MRL-type compact crack test[6] was conducted to investigate crack arrest toughness. The dimensions of the compact test specimen are shown in **Fig. 11**. A notch was made in the specimen 50 × 200 × 200 mm in such a way that the leading end of the notch was located in brittle weld metal. In the test, the notch was opened by pushing a wedge into a round hole after the specimen had been held at a specified temperature. **Figure 12** shows changes in representative load and crack opening displacement of the clip gauge with time. When brittle fracture occurs, there is an abrupt increase in the crack opening displacement of the clip gauge and a coresponding decrease in load. Displacement values when the rapid increase stopped were regarded as the crack opening displacement, Δ_f, upon brittle crack arrest.

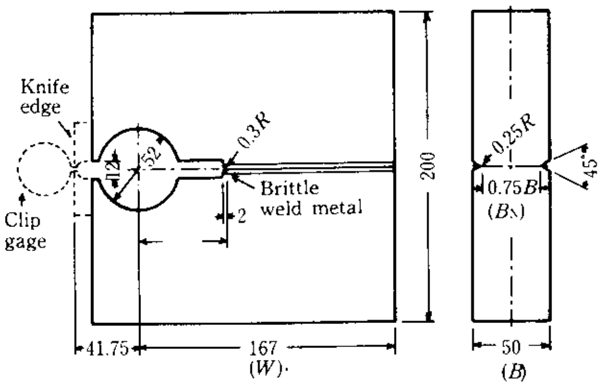

Fig. 11 Dimension of Compact-Specimen

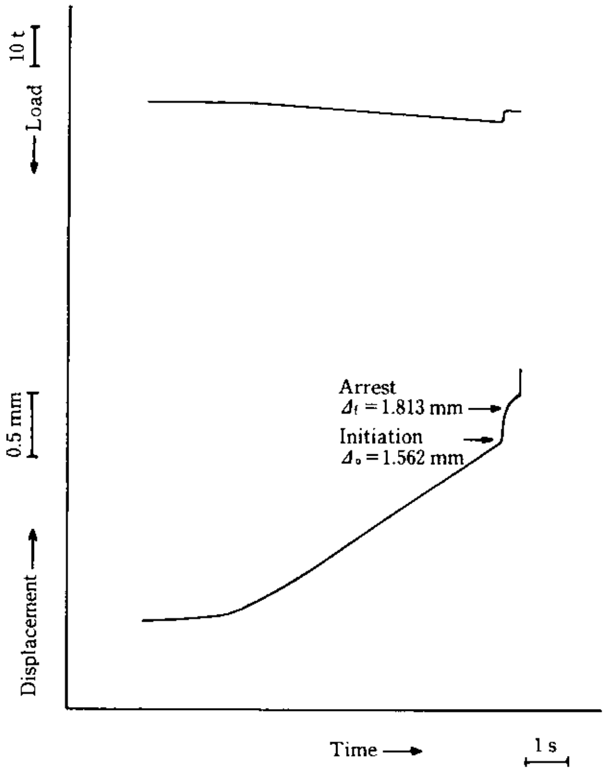

Fig. 12 Time dependence of load and crack opening displacement

An example of the fracture appearance of a compact test specimen is shown in **Photo 4**. The black area of the fractured surface was formed when the specimen was oxidized by heating before the final rupture after the arrest of the brittle fracture. This black area corresponds to the crack propagation region measured. Crack arrest toughness K_{Ia}(kgf·$\sqrt{\text{mm}}$/mm^2) was calculated by Eq.(1)[6] using the crack opening displacement Δ_f(mm) upon crack arrest and the crack length a_f(mm) defined as the distance from the load axis to the leading end of the arrested crack.

$$K_{Ia} = Y \Delta_f E \sqrt{\frac{B}{B_N W}} \quad \cdots\cdots\cdots\cdots (1)$$

where B, B_N and W are the dimensions defined in Fig. 11 and Y is given by Eq.(2):

$$Y = \frac{2.24(1.72 - 0.9\alpha + \alpha^2)\sqrt{1-\alpha}}{(9.85 - 0.17\alpha + 11.0\alpha^2)} \quad \cdots\cdots (2)$$

$$\alpha = a_f / W$$

The relationship between crack arrest toughness K_{Ia} and $(T - RT_{NDT})$ is shown in **Fig. 13**. T is the test temperature, and RT_{NDT} is the reference temperature deter-

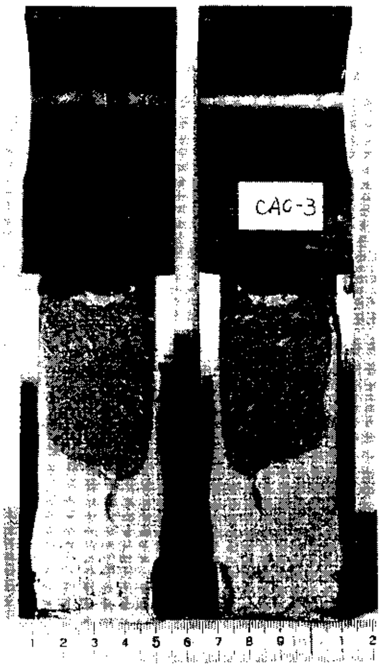

Photo 4 Fracture appearance of Compact-Specimen

mined from the nil-ductility transition temperature T_{NDT} and the Charpy impact test temperature and was −65°C. All K_{Ia} values are above the K_{IR} curve given in the ASME Boiler and Pressure Vessel Code, Sec. III, Appendix G. For example, K_{Ia} is higher than the K_{IR} curve by about 70 kgf · $\sqrt{mm}/mm^2$ at RT_{NDT}. The relationship between K_{Ia} and $(T - RT_{NDT})$ of the present cask forgings is equivalent to those[7)] obtained in A 533B class 1 or A 508 class 3 steels for pressure vessels of light water reactors. The above-mentioned dynamic fracture thoughness was also equivalent to values[7)] obtained from the steels for pressure vessels of light water reactors

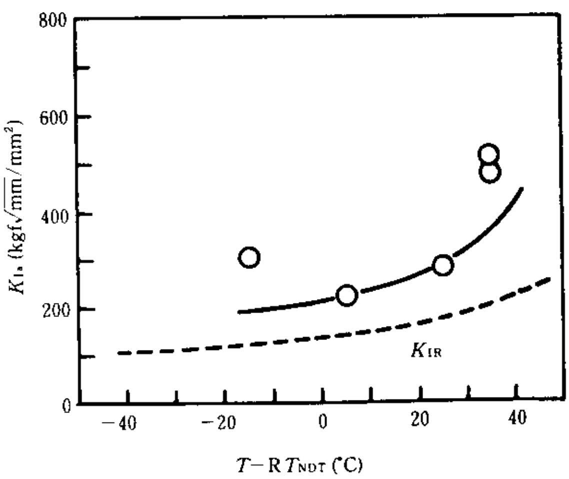

Fig. 13 Crack arrest toughness K_{Ia} as a function of temperature T-RT_{NDT}

in terms of $(T - RT_{NDT})$. Since K_{Id} and K_{Ia} give lower limits of various fracture toughness values, including the static fracture toughness value K_{IC}, it may be said that the fracture toughness of the present cask forgings can be positively evaluated by applying the K_{IR} curve given by ASME code.

4 Future Tasks

With demand for casks expected to increase steadily, it is important to examine the manufacture of materials in terms of economy. The hollow ingot technique developed by Kawasaki Steel is very useful in this respect. With regard to chemical composition of cask materials, the reduction of Ni, a costly element, was examined.

In the above-shown Fig. 4, both Mn and Ni contribute to an increase in strength and toughness. Economic advantages would be obtained if expensive Ni could be replaced by inexpensive Mn. Therefore, mechanical properties were examined with varying Mn and Ni contents. A number of 100-kg ingots of the chemical composition given in **Table 6** were refined in an induction heating furnace, forged into 25-mm thick plates, and quenched and tempered after normalizing at 950°C for 5 h. Austenitizing for the purpose of quenching was carried out at 880°C for 5 h, and quenching was conducted using a heat treatment simulator. The cooling rate employed was 20°C/min. This cooling rate corresponds to the level at mid-plate thickness during the cooling of a 250-mm thick plate. Tempering was conducted at 630°C for 8 h, with in-furnace cooling conducted after tempering.

Table 6 Chemical composition of steels tested (wt%)

C	Si	Mn	P	S	Ni	Cr
0.05 ~0.19	0.01 ~0.30	0.60 ~2.11	0.007	0.005	0.01 ~2.43	0.01 ~0.40

Based on the experimental results, the following multiple regression equation was obtained:

$$YS(\text{kgf/mm}^2) = 14 + 7(\%\text{Cr}) + 12(\%\text{Si}) + 9(\%\text{Mn}) + 5(\%\text{Ni}) + (\%\text{Cr}) \quad \cdots\cdots (3)$$

$$TS(\text{kgf/mm}^2) = 19 + 66(\%\text{C}) + 11(\%\text{Si}) + 10(\%\text{Mn}) + 5(\%\text{Ni}) + 10(\%\text{Cr}) \quad \cdots\cdots (4)$$

$$_{v}T_{rs}(°\text{C}) = -55 + 515(\%\text{C}) - 4(\%\text{Si}) - 29(\%\text{Mn}) - 23(\%\text{Ni}) - 18(\%\text{Cr}) \quad \cdots\cdots (5)$$

$$T_{NDT}(°C) = -65 + 115(\%C) - 36(\%Si) - 4(\%Mn) - 14(\%Ni) + 8(\%Cr) \quad \cdots\cdots\cdots\cdots\cdots (6)$$

The effects of Mn and Ni contents on tensile strength and T_{NDT} were rearranged using Eqs.(4) and (6), with the results shown in **Fig. 14**. It is apparent from this figure that the desired performance can be obtained by an Mn content of 2% even in the case of 0% Ni, provided that the target tensile strength is 43 kgf/mm^2 or more and the target T_{NDT} is −45°C or below.

It is necessary to take into consideration the likelihood of higher performance requirement in the future, especially for toughness. If designs are made in accordance with ASME Section III, the T_{NDT} required would be very low. For the minimum service temperature of, for example, −30°C, T_{NDT} of about −70°C would be required. Such high performance, even if required, can well be met by a proper combination of Ni and Mn contents as shown in Fig. 14. In this case, a 0.05%C-1.3%Mn-2.25%Ni steel can be recommended.

5 Conclusions

Based on experimental results conducted to develop cask forgings, large cask forgings about 70 t in weight were manufactured by applying the hollow ingot technique developed by Kawasaki Steel, thus attaining the desired performance satisfactorily.

An investigation was also made on alloy design requirements of prospective materials that will meet growing customer needs in economy and performance sophistication.

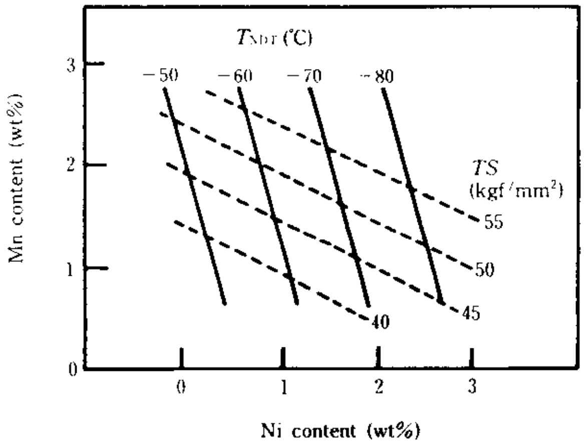

Fig. 14 Effect of Ni and Mn contents on strength and toughness (0.05%C steel)

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