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# RECENT QUALITY CONTROL OF 13Cr-4Ni CAST STEEL RUNNER

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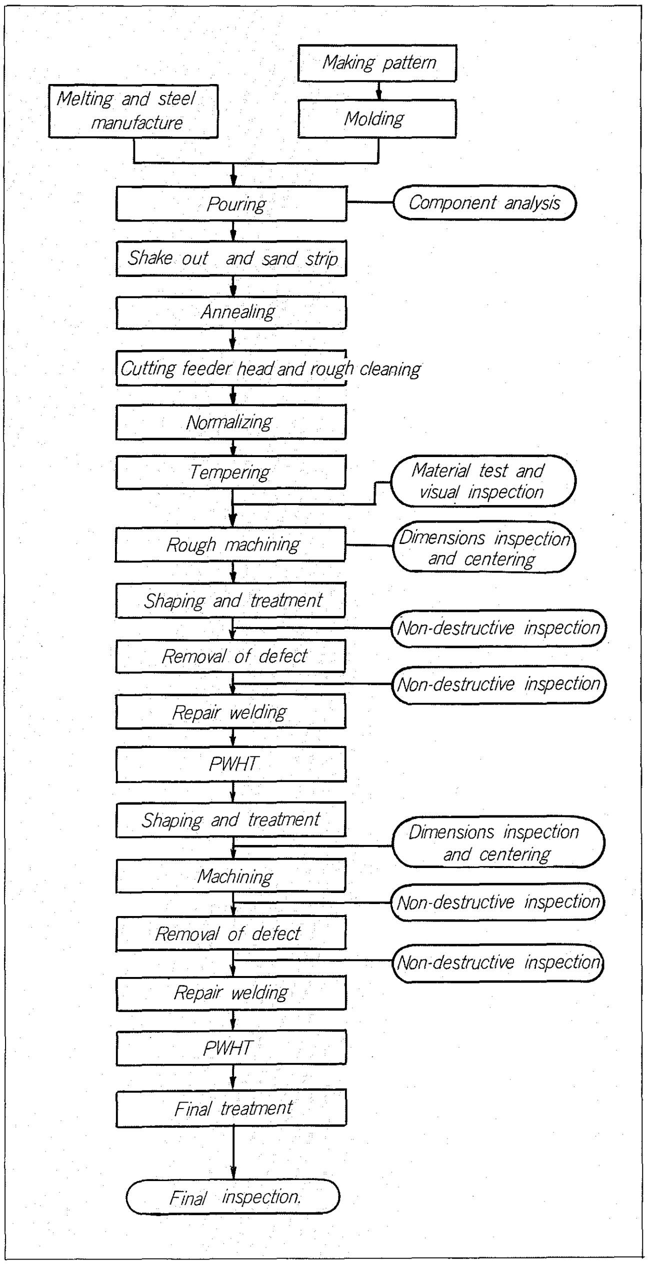
## 1 INTRODUCTION

To reduce hydraulic power generating cost, every efforts have been continuously made to increase speed of water turbine, reduce dimensions of the water turbine and increase the head. In addition, to increase total power generated per year, such a trend as to operate the water turbine even in a flow/head range which is greatly deviated from the normal operating condition has been remarkable. In response to these trends, level of the fluctuation load applied to the runner has increased more and more, causing cavitations to occur more easily. For this reason, for materials of the runners, those the corrosion fatigue stress in water of which is high in the high cycle range of fatigue life ($N>10^8$) and excellent in toughness and anti-cavitation, anti-corrosion performances are needed. On the other hand, the runners are designed into a complicated three-dimensional shape so that they will display high performance, and very severe dimensional accuracy is required. Further, it is important that the material is of a high weldability for the manufacturing.

To satisfy these various requirements, 13%Cr-4%Ni stainless steel (equivalent to JIS-SCS 5) having martensite structure is often used for runner materials during recent years. This 13%Cr-4%Ni cast steel (hereinafter abbreviated to 13-4 cast steel) was developed in 1960s as a cast steel modified from 13%Cr cast steel (JIS-SCS 1). Fuji Electric first used this 13-4 cast steel for the Francis water turbine runner of 183 MW output in 1969. Since then, Fuji Electric has used this 13-4 cast steel for more than 90 water turbine, pump turbine runners including those being presently manufactured, and piled up the accomplishments and experience. Recently, high head and large capacity pump turbine runners used in Japan and 13-4 cast steel runners has invited a higher interest by the people concerned.

When manufacturing a turbine runner in a monoblock casting, the manufacturing process is complicated, and even if the details are omitted and only the main flow is shown, it appears as shown in *Fig. 1*. To improve quality of a runner, correct manufacturing technique and adequate quality control must be applied by each process. This paper intro-

*Fig. 1* Example of monoblock casting runner manufacturing process



duces the present particulars for quality improvement of Fuji Electric's 13-4 cast steel runners and discusses several problem points.

## 2 STEEL MANUFACTURE AND CHEMICAL COMPONENTS

*Table 1* shows an example of chemical components of Fuji Electric's 13-4 cast steel runners. For component compounding, the following ideas are taken into considerations.

(1) Cr is limited to 12.5±1% because δ-ferrite increases when Cr is too much and the stainless property is adversely affected when Cr is insufficient.

(2) A proper volume of Ni (about 4±0.5%) is added to improve the hardenability and compensate drop down of the strength due to low carbon, and stable retained austenite is evenly distributed in the tempered martensite to improve anti-corrosivity and weldability.

(3) A small volume of Mo (about 0.5±0.2%) is added to suppress temper brittleness and to improve anti-corrosivity.

(4) C is minimized (less than 0.06%) to suppress precipitation of carbide on the grain boundary, increase the toughness and to improve weldability.

(5) It is aimed at reduction of Si (0.5% or less) and formation of δ-ferrite is suppressed to improve the toughness.

(6) Reduction of non-metalic inclusions and suppression of δ-ferrite are taken into consideration, and Mn is limited to 0.5 to 0.8%.

(7) P and S are reduced as much as possible to reduce hot tear and micro-porosity.

Out of the above components, Cr, Mo and Si are ferrite forming elements, and Cr equivalent is calculated by the following formula.

$$\text{Cr equivalent} = \text{Cr} + \text{Mo} + 1.5\text{Si} \quad \ldots\ldots\ (1)$$

Further, Ni, C and Mn are austenite forming elements, and Ni equivalent is obtained by the following formula.

$$\text{Ni equivalent} = \text{Ni} + 30\text{C} + 0.5\text{Mn} \quad \ldots\ldots\ (2)$$

To obtain high quality and stable structure, these component elements must be adequately compounded and precisely controlled. Chemical components of molten metal are checked through the ladle analysis before pouring, and further confirmed through the product analysis at the stage of final inspection.

Generally, steel is manufactured by means of basic furnace. Recently, however, trials to minimize impurities such as P and S and gas components such as H, N and O for enhancing quality of the molten metal by means of the ladle refining and vacuum degassing process are being expanded.

*Table 1* Example of chemical components of 13-4 cast steel

(Unit of measure: Mass %)

| Cr | Ni | Mo | C | Si | Mn | P | S | Cr equivalent | Ni equivalent |
|---|---|---|---|---|---|---|---|---|---|
| 12.3 | 3.8 | 0.47 | 0.05 | 0.37 | 0.67 | 0.017 | 0.006 | 13.33 | 5.64 |

## 3 MOLDING, POURING AND CASTING DEFECTS

As long as the 13-4 cast steel runner is a cast product, casting defects cannot be eliminated completely. Except for artificial defects due to improper control and carelessness, cast defects contained in material can be classified into four types by the causes as shown below.

(1) Cavity due to gas and inclusions due to impurity in molten metal.

(2) Non-metalic inclusions such as sand and slag during pouring.

(3) Cavity due to gas which intrudes into molten metal from mold after pouring.

(4) Micro cavity and hot tear (among dendrites) due to shrinkage which unavoidably occur at the process when molten metal changes from fluid phase to solid phase after pouring.

Out of these casting defects, gas and impurity included in molten metal were already described above in Chapter 2. In this chapter, defects related to molding and pouring are described.

### 3.1 Inclusions during pouring

When pouring temperature is too high, the molten metal is easily oxidized and surface folding of mold is likely to occur. Contrary, when pouring temperature is too low, fluidity is adversely affected, causing defects to increase. For this reason, keeping the pouring temperature at 1550 to 1600°C, pouring is made as quickly as possible within a short period of time. It is important that molten metal flows smoothly through ingate, sprue runner and mold, and such an occurrence as that molten metal flow runs against the mold interior surface must be avoided as much as possible. Further, the passage must be properly shaped so that un-uniform flow due to secondary flow within a curved passage and stagnation due to separation of flow are minimized. To reduce separation of sand grain during pouring, it is necessary to increase strength of surface of the mold (increasing sand grain binding force, using finer sand grain, increasing sand density, etc.). In this case, however, the matter of collapsibility of mold described later which must be taken into consideration for reduction of hot tear must be carefully examined. Further, it is effective to use refractory materials for the sprue runner and ingate. Generally, the molten metal which first flow out of ladle is likely to contain more inclusions. Therefore, runner extension is not only provided in the end of the sprue runner so that the first molten metal does not enter the mold but the molten metal containing inclusions is collected into the riser.

Further, inspections of the ladle for cleanliness and drying before pouring are also control items which should be executed.

### 3.2 Cavity due to gas generated from mold

If moisture exists into a mold, it is condensed as it comes into contact with molten metal, and it may be melted into steel in the forms of hydrogen gas and atomic hydrogen. The hydrogen super-saturated at the time of solidification causes pin hole and blow hole to occur. For this reason, some types of molds must be dried by means of hot blast until pouring starts to eliminate moisture thoroughly.

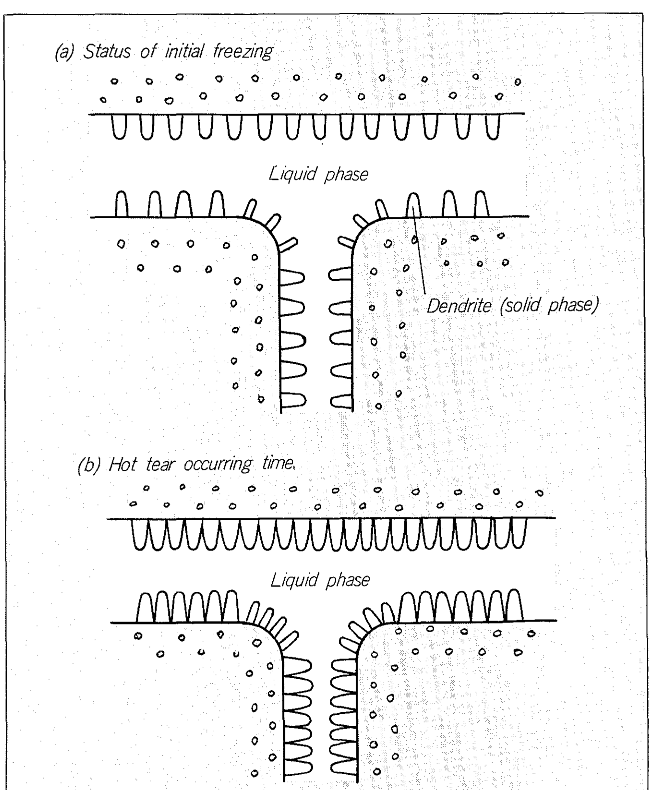
In many cases, self-hardening organic binder (Furan resin) is used to improve dimensional accuracy of the mold (especially core) and anti-fusion penetration. In this case, as molten metal is poured, the furan mold is heated and gas is generated. Therefore, optimum quantity control of binder, permeability control of mold, and control of optimum quantity of vent (Saran pipe, etc.) within the mold must be executed so that the gas generated from the mold will not blown into the molten metal.

### 3.3 Faults occurred in solidification process

Temperature of poured molten metal rapidly drops, and freezing starts from the surface which is in contact with the mold at about 1460°C. *Fig. 2* (a) shows the initial status of the freezing. From the surface to the center, the dendrite begins to grow. Since each dendrite does not contain impurities such as P and S, density of impurities of the liquid around it gradually increases.

As the freezing proceeds, the dendrite further grows, and it becomes as shown in *Fig. 2* (b). As heat is radiated from the molten metal, the mold is heated, and hot spot is produced at the root of crown and blade (corner of the core). At these positions, the freezing delays in comparison with other portions because temperature is hardly to drop.

*Fig. 2* Hot tear occurring mechanism




For this reason, liquid film still remained between individual dendrites. Surface of the metal shrinks due to the freezing, and on the other hand, the mold expands. As the result, tensile force acts on the surface and a crack occurs in the liquid film. In this case, if the molten metal is poured from the liquid portion, the crack is filled. However, when a crack occurs in the liquid film with the freezing proceeded and molten metal not poured, the crack remains. This is called hot tear. When the freezing further proceeds and the micro liquid cavity remained between proceeds and the micro liquid cavity remained between dendrites finally shrinks or if a gas is generated using the micro-inclusions as a core, micro-porosity (also called micro shrinkage or blow hole) occurs.

As described above, the period of time when temperature of the cast steel is 1460 to 1380°C is the period in which both solid and liquid exist, and in this period of time, hot tear and micro porosity are likely to occur. It is necessary to achieve collapsibility of the mold (especially, core) so that no tensile force is applied to the cast steel during this time band. To equalize freezing speed, radius of the hot spot portion is increased or chills are used some times. To reduce hot tear and micro porosity, efforts have been made continuously to minimize impurities and micro inclusions in the molten metal.

## 4 HEAT TREATMENT AND MECHANICAL PROPERTIES

To provide 13-4 cast steel with mechanical properties required as a runner, the heat treatments shown in *Fig. 3* are executed. Each heat treatment temperature is decided based on the transformation point of the 13-4 cast steel shown in *Table 2*. Out of various heat treatment, the normalizing and tempering for the purpose of refining and annealing for the purpose of residual stress relieving after repair welding are described.

### 4.1 Normalizing and tempering

After breaking down the as-cast structure through annealing, the riser is cut off and the runner is roughly cleaned. Then, the runner is refined. The purpose of the normalizing is to obtain a fine martensite structure. In this process, the runner is first normalized at the temperature higher than the austenitizing end point ($A_{C3}$), and then, rapidly quenched. When the normalizing temperature exceeds 1050°C, austenite grain becomes coarse and on the other hand, when the normalizing temperature is 920°C or below, the carbide is not thoroughly solved. Therefore, the normalizing temperature must be selected in the range of 975 to 1025°C. When the runner is heated in a heat treatment furnace, temperature rises faster at thin portions such

*Table 2* Transformation point of 13-4 cast steel

| Austenite transformation point | | Martensite transformation point | |
|---|---|---|---|
| Finish ($A_{C3}$) | Start ($A_{C1}$) | Start ($M_S$) | Finish ($M_f$) |
| 880°C | 580°C | 260°C | 80°C |

*Fig. 3* Heat treatment for 13-4 cast steel runner

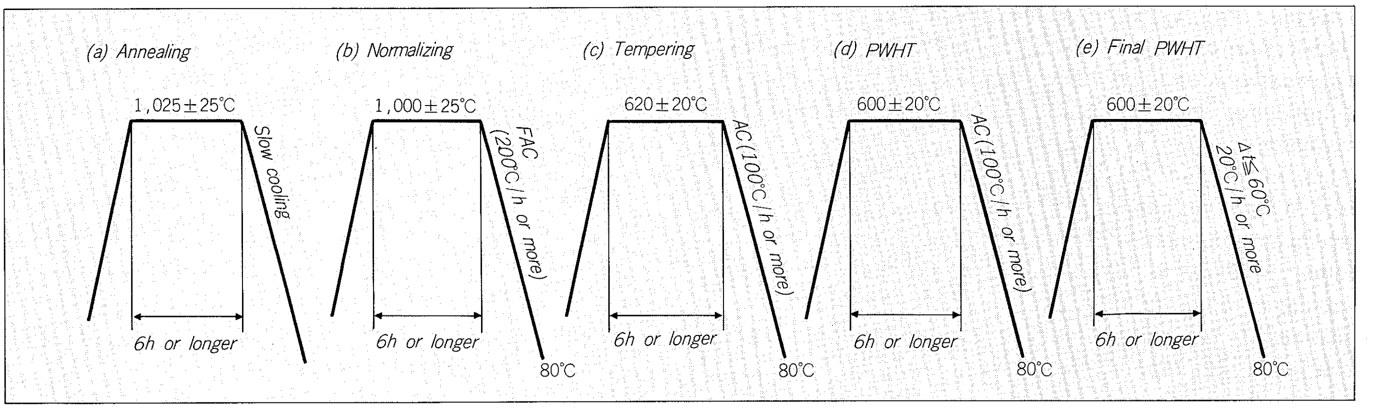



*Table 3* Example of mechanical properties of 13-4 cast steel

| Tensile strength (kg/mm²) | 0.2% yield strength (kg/mm²) | Elongation (%) | Reduction of area (%) | Charpy impact energy 0°C-V (kg-m) | Brinell hardness $H_B$ |
|---|---|---|---|---|---|
| 80.9 | 65.2 | 23.0 | 63.6 | 11 | 255 |

as trailing edge of blade and temperature rise delays at thicker portions. When temperature at each portion of the runner enters the objective temperature range (976 to 1025 °C), the runner is left in a constant temperature for a proper holding time (0.2 h/cm x Maximum thickness (cm) + 2 hours or longer). Thereafter, the runner is removed from the furnace, forcedly air-cooled by means of a blower within the atmospheric air, and by lowering temperature below Mf, the martensitic transformation is completed.

In the tempering, the runner is tempered at the temperature near the austenitizing starting point to soften the martensite structure hardened by the quenching and to improve toughness. When tempering temperature is raised above 650°C, the runner is hardened again and sufficient toughness cannot be obtained at 580°C or below. Therefore, the temperature is selected in the range of 600 to 640°C (immediate above $A_{C1}$). Thus, the martensite is softened and further, extremely fine tempered austenite can be distributed evenly into the martensite structure. Not only obtaining the good combination of strength and toughness, but also it is important to improve fatigue strength in corrosive environment by making it hard to occur intergranular corrosion.

The tempering temperature holding time is the same as normalizing. To avoid temper brittleness due to carbide precipitation at the vicinity of 550°C, normally, the runner is air-cooled. However, when the stress relieving (described below) can be eliminated, the same considerations as the cooling from PWHT are required to avoid occurrence of residual stress.

The test piece of 13-4 cast steel runner having the components indicated in *Table 1* is heat-treated under the conditions of *Fig. 3*. *Table 3* shows the mechanical properties.

### 4.2 Repair welding and stress relieving

After completing the heat refining, the runner is roughly machined, shaped and cleaned. Then the runner is checked for casting defects by non-destructive inspection. Those exceeding the allowable dimensions of defects are further treated to remove the defects by means of a grinder, etc., and after confirming that the defects have been removed by means of groove inspection, repair welding is performed on the runner. For the electrode, those of the same components as the base metal are used, and welding is performed after thoroughly drying the electrode. The repaired portions are preheated to 100 to 150°C, and care is exercised so that interlayer temperature is within the range of 100 to 300°C during the welding and it is within 200 to 250°C (immediately below Ms point) as much as possible. After completing the welding, the surface is smoothened by means of a grinder, and after cleaning, the runner is checked again by means of non-destructive inspection.

When the repair is completed, the runner is stress relieved to soften the portions hardened by the welding and to relieve residual stress. The PWHT temperature is selected at lower level than the tempering temperature so that the refined structure will not be changed. The holding time is selected so that Larson-Miller value of the following formula becomes a proper value (18.2 to 18.6).

$$P = \{t\,(^\circ\mathrm{C}) + 273\} \cdot \{20 + \log T\,(\mathrm{h})\} \quad \ldots\ldots (3)$$

As for cooling after PWHT, the runner is air-cooled in the manner similar to the tempering to avoid temper brittleness. When cooling speed is too high, however, the residual stress relieved by the PWHT is anticipated to be reproduced.

*Fig. 4* shows variation of yield strength (Y.S.) and elongation ($\delta$) of the 13-4 cast steel against temperatures. The yield strength increases rapidly at 600 to 450°C, and elongation reduces rapidly at 600 to 500°C. If a large temperature difference occurs at each runner portion within these temperature ranges during the cooling process from the PWHT temperature, strain may occur due to the constraint difference, and if it is frozen, residual stress is anticipated to occur. For this reason, only for the final PWHT, furnace cooling must be performed so that the runner is cooled as quickly as possible to such an extent as that temperature difference between each portions is not

*Fig. 4* Mechanical properties of 13-4 cast steel at high temperature

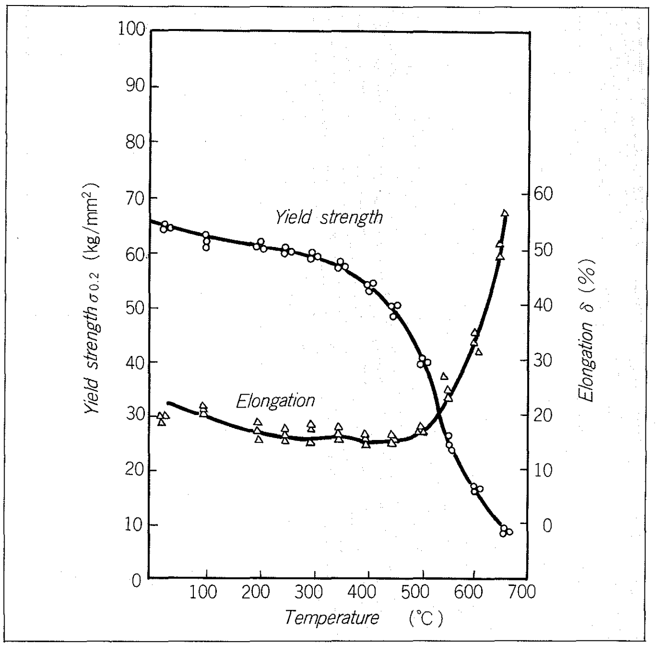



*Table 4* Examples of residual stress and hardness of welded portion

| | Deposited metal | Heat-affected zone | Base metal |
|---|---|---|---|
| Hardness $H_B$ | 268 | 275 | 255 |
| Residual stress ($kg/mm^2$) | +5.4 | −3.6 | +3.6 |

considerable. *Table 3* shows the examples of mechanical properties obtained through the final PWHT performed with the above idea taken into considerations. Further, *Table 4* shows the examples of measurements of residual stress (measured by X-ray analysis method) and hardness distribution (measured by echo tip) of the repair-welded portions. When the final PWHT is performed properly, residual stress of the runner is within plus or minus 10 kg/ $mm^2$, and Brinell harness at the repair-welded portion does not exceed 320.

## 5 FATIGUE STRENGTH AND CRACK PROPAGATION RATE

During operations toward many years, the runners are exposed to various levels of stress fluctuations in water corrosive environment. To estimate fatigue life of runner, fatigue strength of the 13-4 cast steel in water must be known. On the other hand, the small casting defects described in Chapter 3 exist within cast steel products. It is considered that a fatigue crack is propagated from a defect, and for material characteristics of cast steel, crack propagation rate in water must also be obtained.

### 5.1 Alternating stress and number of cycles

Level of alternating stress applied to runners and number of cycles vary with the type of water turbine, specific speed, effective head and operation pattern, etc. These factors are classified into two major factors as shown below.

(1) Those of slightly large alternating stress level but number of cycles is low ($10^3$ to $10^5$) such as start-stop, load fluctuation (APC operations, etc.), and load rejection-stop. Normally, it is seldom that an alternating stress of this type affects the fatigue life directly.

(2) Including the normal operation and operation of (1) above, stress alternation caused as the runner rotates. Stress amplitude is small but number of cycles is extremely large ($10^9$ to $10^{11}$). For example, in case of a pelton runner, very small stress alternation caused as the bucket runs across the jet corresponds this, and in case of a reaction runner, very small stress alternation caused as the runner vane runs across the wake and main flow after passing through guide vanes. Since number of cycles is large and fluctuation load of type (1) above is superimposed, if modified Miner's rule is applied, fatigue strength of the material is greatly reduced, and in many cases, it affect fatigue life of the runner.

To calculate number of cycles of stress amplitude by each runner, the life limit is set to 20 years. Further, length of crack which can be found on a runner during a periodical inspection, etc. is normally an order of 2.5 to 5 mm. Therefore, fatigue life is calculated by allowing that a 2.5 mm long crack could be propagated locally (mainly, portions such as the root of a vane to which high stress is applied) on the runner 20 years later. For an example, number of cycles of type (2) applied to a 6-nozzle pelton runner of 450 rpm during 20 years operations (operated 8000 hours per year) is given as follows.

$N_{(2)}$ = 6 (nozzles/revolution) x 450 (revolutions/minute) x 60 (minutes/hour) x 8000 (hours/year) x 20 (years)
= $2.6 \times 10^{10}$

As described above, as a 13-4 cast steel runner, data of fatigue strength in water against number of cycles up to $10^{11}$ is required. However, it is impossible to obtain this data directly. Hense, to estimate fatigue strength in a super high cycle domain, the devise described below is required.

### 5.2 Fatigue strength in-water of smooth specimen

A case in which a very small cast defect internally exists in high stress portion of a runner is examined. The stress distribution occurred near the defect due to load fluctuation during operation is fluctuation of three-dimensional stress both value and direction of which fluctuate. However, when micro stress gradient adjacent to the defect is disregarded, the stress gradient of the place is minor. To represent this condition with an about 12 mm diameter small test piece, the axial tensile-compression test is most suitable, and accuracy is high. On the other hand, if loading frequency is too high during the fatigue test, failure occurs within a short time, and even if the test is conducted in-water, influence of the corrosion environment does not

*Fig. 5* High cycle fatigue test in-water of 13-4 cast steel (load controlled)

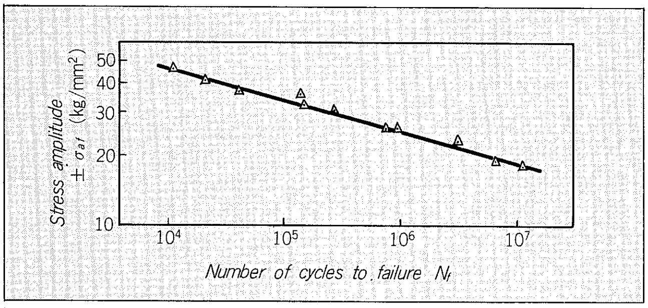



*Fig. 6* Low cycle fatigue test in-water of 13-4 cast steel (strain controlled)

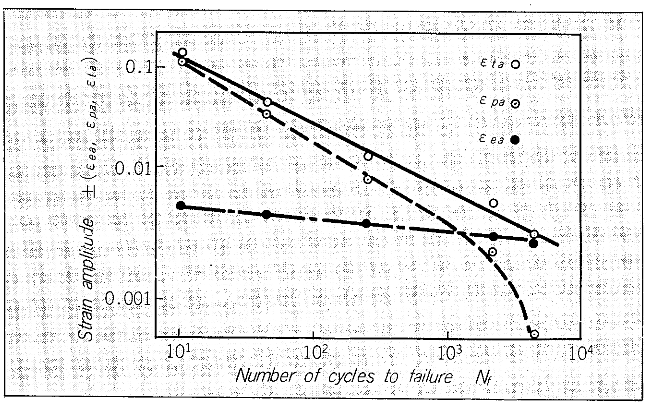
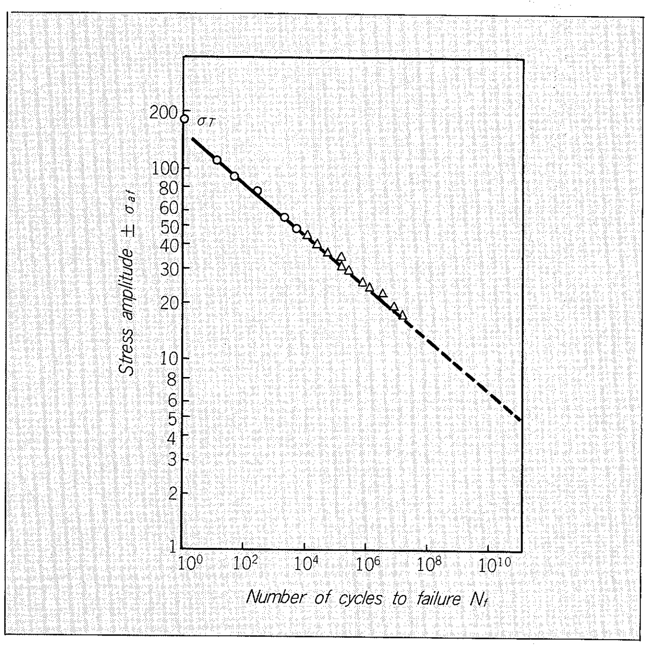



*Fig. 7* Fatigue strength in-water of 13-4 cast steel




appear correctly. To obtain highly reliable fatigue strength in-water, it is necessary to suppress the test frequency sufficiently (5 Hz or less).

Under the condition like this, high cycle load controlled fatigue test in-water was conducted on a smooth specimen for the range of $10^4$ to $10^7$ cycles to failure. *Fig. 5* shows the result. Likewise, low cycle strain controlled fatigue test in-water was conducted on smooth specimen for the range of $10^1$ to $10^4$ cycles to failure. *Fig. 6* shows the result. In the figure, total strain (full line) was divided into plastic strain (dash line) and elastic strain (dash dot line) and elastic strain component was converted to the stress. *Fig. 7* shows the converted result and result of *Fig. 5*. As it is well known, the elastic strain component of low cycle fatigue and data of high cycle fatigue are on the same straight line. Moreover, the true fracture stress obtained by tensile test is indicated on the ordinate axis at $10^0$ in the *Fig. 7*.

By the above method, high reliable fatigue strength in-water can be obtained toward a wide range of number of cycles from $10^0$ to $10^7$. Since the reliability of gradient of the straight line is high, the reliability of estimation of fatigue strength in super high cycle domain where the number of cycles is $10^9$ to $10^{11}$ by the modified Miner's rule can also be improved.

### 5.3 Notch factor

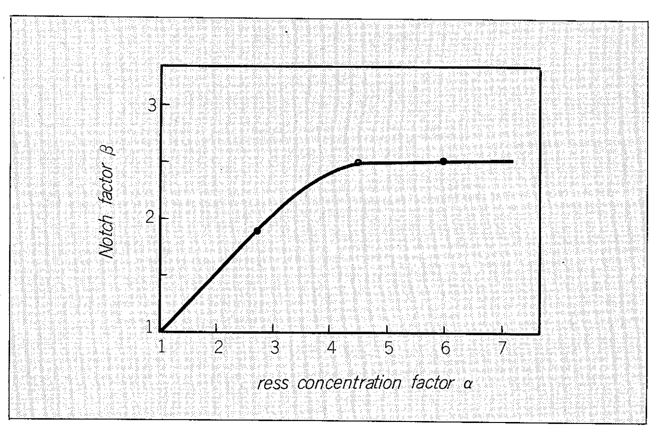
There is no such a guarantee as that a cast defect existing inside a small size smooth specimen represents a cast defect existing inside the high stress portion of a runner. Hence, the specimen was artificially notched and under the same conditions as a smooth specimen, high cycle fatigue tests were conducted for stress concentration factors. When fatigue strength of the smooth specimen at $10^6$ is expressed as $\sigma_0$, and fatigue strength of notched specimen and stress concentration factor of which is $\alpha$ at $10^6$ is expressed as $\sigma_k$, the notch factor $\beta$ can be expressed by the following formula.

$$\beta = \sigma_0 / \sigma_k \quad \cdots\cdots \quad (4)$$

To be descriptive, larger the $\beta$ may be, drop of fatigue strength due to a defect is larger, and notch sensitivity is higher.

*Fig. 8* shows the relationship between stress concentration factor $\alpha$ and notch factor $\beta$. When $\alpha$ is 4.5 or higher, $\beta$ is constant at 2.5. In other words, even if the stress concentration is high due to a defect, the fatigue strength in-water

*Fig. 8* Notch factor of 13-4 cast steel

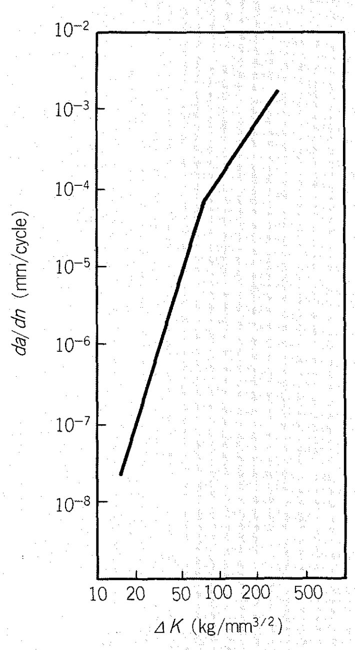


never drops below 1/2.5 of the result (*Fig. 7*) obtained through the smooth specimen.

### 5.4 Crack propagation rate

As for material characteristics examined by a fracture mechanics approach, fracture toughness value $K_{IC}$ and threshold stress intensity factor range $\Delta K$th against the crack propagation rate can be pointed out. There is almost no such an operating condition under which the runner is exposed to a hazard of macro brittle fracture, and for this reason, it is not so important to examine $K_{IC}$ of the 13-4 cast steel. While, for the material characteristics of the cast steel in which a defect exists, it is important to examine the crack propagation characteristics and $\Delta K$th for runners.

*Fig. 9* Crack propagation characteristics of 13-4 cast steel




Using a 10 mm thick compact tension specimen, crack propagation characteristics in-water of the normally heat-treated (*Fig. 3*) 13-4 cast steel were obtained with single swing tensile load ($R = 0$) applied by $\Delta K$ gradually reducing method. *Fig. 9* shows the results. For the range of $5 \times 10^{-5}$ to $5 \times 10^{-8}$, the crack propagation rate $da/dn$ is approximately linear against the stress intensity factor range $\Delta K$, and the following Paris equation is established.

$$da/dn = 4.29 \times 10^{-14} (\Delta K)^{4.83} \quad \cdots\cdots\cdots\cdots \quad (5)$$

Within the above test range, threshold stress intensity factor range $\Delta K$th could not be obtained. The crack propagation rate is $da/dn = 10^{-7}$ mm/cycle when $10^7$ times of alternating stress are applied until the crack propagated from an internally existing defect reaches a 1 mm long crack. In this case, $\Delta K$ is about 20 kg/mm$^{3/2}$ as known from the *Fig. 9*, and the normally manufactured 13-4 cast steel indicates excellent characteristics also against crack propagation.

## 6 POSTSCRIPT

A part of the recent trend for quality improvement of 13-4 cast steel runners was described. In addition to the items discussed in this paper, the following important themes are remained.

(1) Dimensional accuracy and casting method
(2) Permissible defect dimensions and non-destructive judgment standard
(3) Surface working layer and residual stress
(4) Influences of hardness given to notch factor and crack propagation rate

We are willing to take these items on separate papers.

Taking this opportunity, we should like to express our deep appreciations to those who provided us with valuable opinion and advice especially to Takasago Plant, Kobe Steel, Ltd., Muroran Plant, Japan Steel Works, Ltd., George Fischer Ltd., Schaffhausen, Switzerland, Creusot-Loire steel foundry, Creusot-Loire.