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13Cr-3.5Ni Martensitic Stainless Steel Castings for Hydraulic Turbine Runners

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Synopsis :

A 13Cr-3.5Ni martensite stainless steel is used for the hydraulic turbine runner, because it is suitable for high strength, high corrosion resistant and high abrasion resistant materials. These material properties are affected sensitively by heat treatment of normarizing and tempering. In manufacturing the hydraulic turbine runner, Kawasaki Steel established quality control in the manufacturing process, using the following technical improvements: (1) design of casting plans with solidification simulation using CAD, (2) control of the volume of gases that are generated from the core, (3) control of core drying, (4) control of the pouring process by sealing with the argon gas, (5) control of the knockout temperature, (6) control of heat treatment, (7) control of repair welding. It has now become possible to manufacture satisfactory products of the three types of runners: Francis, Kaplan, and Pelton runners.

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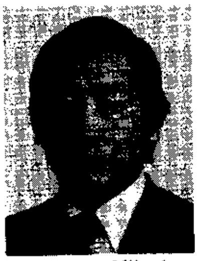
13Cr-3.5Ni Martensitic Stainless Steel Castings for Hydraulic Turbine Runners*



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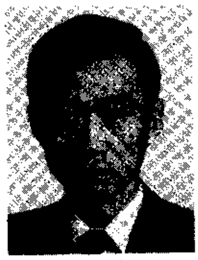

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1 Introduction

Among the most rigorous quality requirements for steel castings are those imposed on hydraulic turbine runner. Almost all hydraulic turbine runners are now made from 13Cr-3.5Ni martensitic stainless steels[1,2] because these materials provide the required high strength and resistance to corrosion and abrasion.

Kawasaki Steel has a long history of manufacturing hydraulic turbine runners. Ordinary steels (SC 46) were first used, and then replaced with 13Cr stainless steels, which in turn were replaced with 13Cr-3.5Ni stainless steels. The company has increased the number of types of runners it can supply and now produces all types, Francis, Kaplan and Pelton. As quality requirements for these runners have become increasingly strict, the company has taken various measures to improve quality, and, as well, to reduce cost and shorten delivery time.

This paper describes the types and features of hydraulic turbine runners, the manufacturing process and important control items, and changes in material properties under various tempering conditions.

2 Types and Features of Hydraulic Turbine Runners

As shown in **Figs. 1, 2** and **3**, there are three types of hydraulic turbine runners: the Francis type, the Kaplan type, and the Pelton type. Kawasaki Steel has produced all the three types. The features of the three types are described below.

(1) Francis type

Francis turbine runners are used in medium-head, medium-water-volume power plants, which account for 80% of power plants presently in opera-

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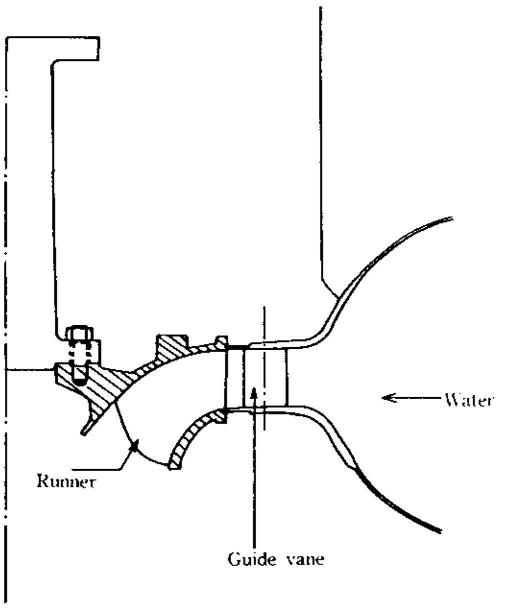

Fig. 1 Profile of Francis runner

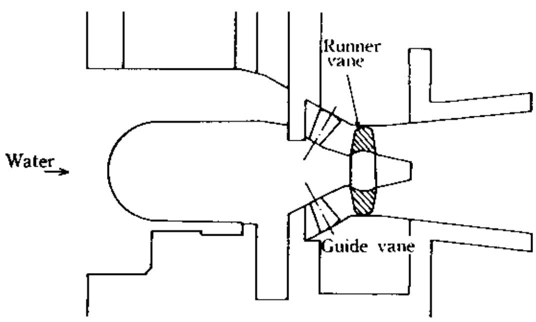

Fig. 2 Profile of Kaplan runner

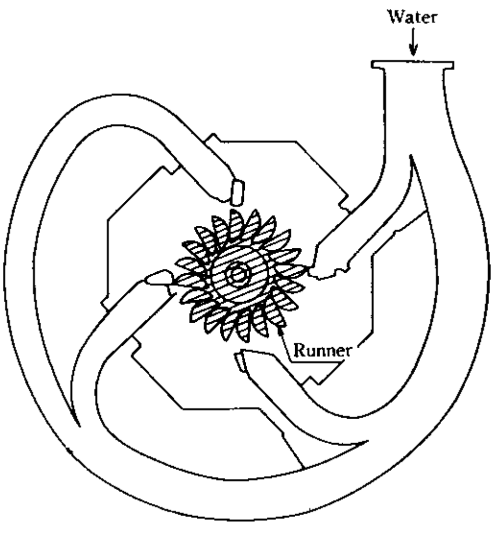

Fig. 3 Profile of Pelton runner

tion. This is the mainstream of hydraulic turbine runners.

(2) Kaplan type
Kaplan turbine runners are used in low-head, large-water-volume power plants, which account for 10% of the power plants presently in operation. This type can be installed in agricultural irrigation canals. The number of plants using this type will tend to increase in the future.

(3) Pelton type
Pelton turbine runners are used in high-head, small-water-volume power plants, which account for 10% of the power plants presently in operation. The number of plants of this type is expected to increase in the future because the cost of such dam construction and power plant equipment is low compared with that of facilities where the Francis type is used. Requirements placed on the Pelton type are considered the most severe among the three types, and their manufacture is difficult.

3 Properties of 13Cr-3.5Ni Martensitic Stainless Steel

3.1 Metallurgical Properties

Table 1 gives the chemical composition of the 13Cr-3.5Ni martensitic stainless cast steel for hydraulic turbine runners produced by Kawasaki Steel, in comparison with that of ASTM A743/743M, CA-6NM (12Cr-4Ni) steel. The molybdenum content of this steel is smaller than that of CA-6NM, which is a corrosion-resistant steel. The addition of molybdenum increases the temper softening resistance of steel[3] and retards the precipitation of carbides at austenite grain boundaries, which cuases deterioration of toughness.[4] The molybdenum content of this steel, developed by Kawasaki, is the minimum necessary for maintaining these positive effects.

Because this stainless steel shows martensite at room temperature, it is most important to obtain a stable single phase of austenite at a normalizing temperature (or quenching temperature). Mechanical properties, especially toughness, tend to deteriorate if the ferrite

Table 1 Chemical composition of 13Cr-3.5Ni cast steel used (%)

	C	Si	Mn	P	S	Ni	Cr	Mo
ASTM CA-6NM*	≤0.06	≤1.00	≤1.00	≤0.040	≤0.030	3.5~4.5	11.5~14.0	0.40~1.0
13Cr-3.5Ni	0.04~0.06	0.35~0.45	0.65~0.75	≤0.020	≤0.010	3.60~3.90	11.70~12.70	0.20~0.30

* ASTM A743/743M, CA-6NM

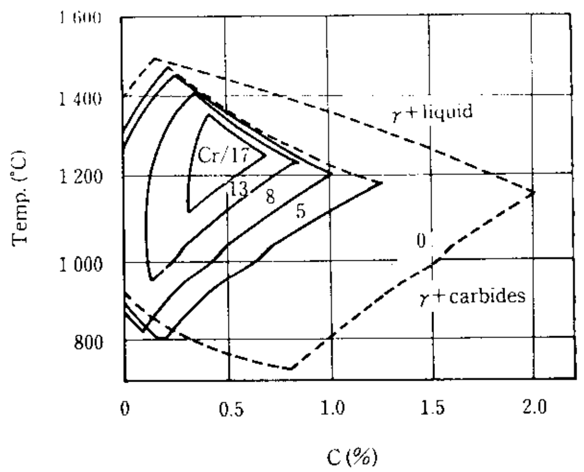

Fig. 4 Variation of the amount of austenite in accordance with chromium contents

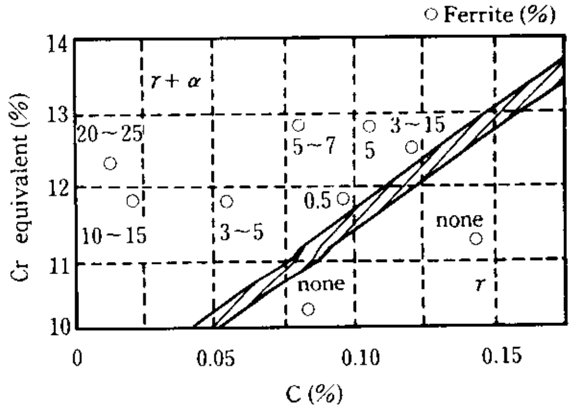

Fig. 5 Effect of carbon content and chromium equivalent on the amount of ferrite

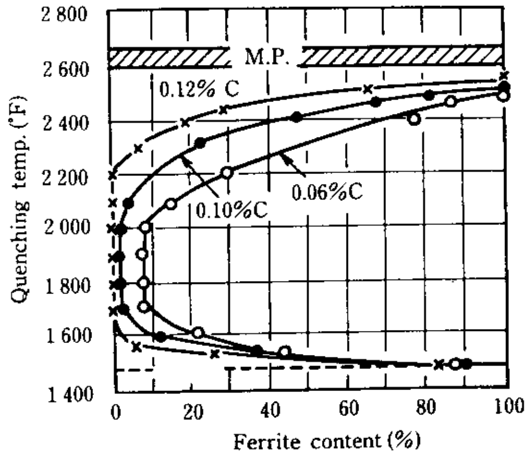

Fig. 6 Variation of the amount of ferrite with quenching temperature and carbon contents in 12.5 Cr steel

phase remains.[5] Therefore, one of the control items for the manufacture of this material is to ensure that this ferrite phase (generally called δ-ferrite) does not remain at the normalizing temperature. This ferrite is greatly affected by chemical compositions and heat treatment conditions.

Figure 4[6] shows how the austenite region shown in an Fe-C equilibrium diagram is narrowed by an increase in chromium content. In this figure, the lines on the right indicate the precipitation of carbides, and those on the left, the boundary between ferrite plus austenite and the single phase of austenite. When the carbon content is 0.5% and chromium content is 22%, the single phase of austenite occurs at 1 275°C. However, the single phase of austenite does not occur at higher chromium contents.

With the 13Cr-3.5Ni steel shown in Table 1, it is difficult to judge from the ranges of carbon and chromium whether the single phase of austenite or the dual phase of austenite plus ferrite occurs at normalizing temperatures (900°C or above) on the basis of Fig. 4 alone. This is because there are alloying elements other than chromium which are related to the formation of a stable austenite region.

Figure 5[7] shows the relation of carbon content and chromium equivalent (Cr_{eq} = Cr + 2Si + 1.5Mo − 2Ni − 1Mn − 15N) to whether the structure formed at normalizing temperatures is the single phase of austenite or austenite plus ferrite. It is apparent that, with the runner material produced by Kawasaki Steel, the danger of the presence of ferrite is eliminated, as the carbon content reaches no more than 0.04 to 0.06%, because the chromium equivalent, regardless of calculated attempts to increase it, is no higher than 8%.

Figure 6[6] shows that the amount of ferrite varies depending on the quenching temperature (or normalizing temperature) even with materials of the same chemical composition. It is apparent that the amount of ferrite is at its minimum when the quenching temperature is 927 to 1 093°C (1 700 to 2 000°F).

In addition to ferrite, carbides have a major effect on the quality of the runner material, as mentioned above. **Figure 7**[6] shows the solid solubility of carbon in 13%Cr steel. It is apparent that $M_{23}C_6$ carbides exist when the carbon content is 0.04 to 0.06%. As mentioned above, these carbides precipitate at austenite grain boundaries, sometimes decreasing toughness. The degree of decrease in toughness depends on heat treatment conditions.

It is apparent from the above that the structure of this material is composed of martensite, retained austenite, and carbides. **Photo 1** shows the structure of this 13Cr-3.5Ni steel in the as-cast condition. Although the structure is coarse martensite, some white uncorroded portions may be observed. These are retained austenite

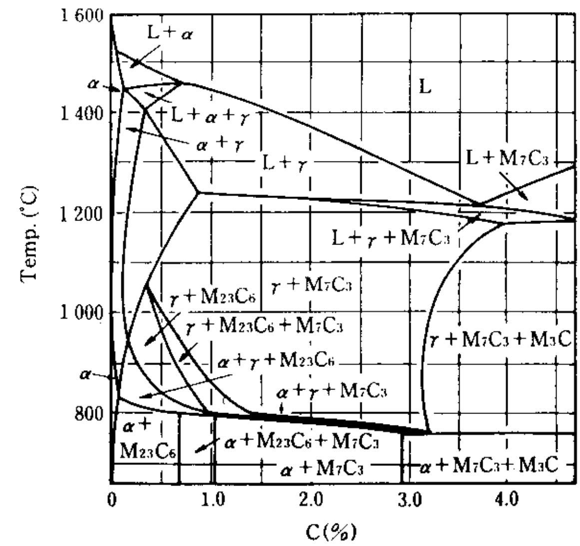

Fig. 7 Effect of carbon content on equilibrium relationships of 13% Cr stainless steel

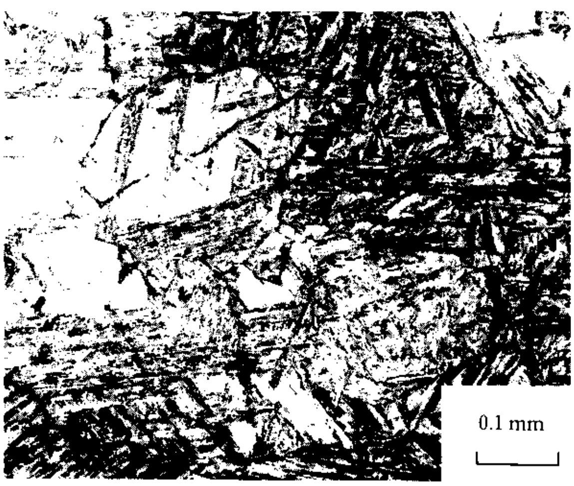

Photo 1 Microstructure of 13Cr-3.5Ni cast steel at as-cast

which has not undergone martensitic transformation.

This cast structure changes to a tough martensite structure after heat treatment in the following process. Therefore, it may fairly be said that the quality of this runner material is produced in the heat treatment process. This point will be discussed in more detail in Sec. 4, below.

3.2 Mechanical Properties

In view of the service environment of hydraulic turbine runners, corrosion resistance and cavitation erosion resistance to water and abrasion resistance to sand are reqired.[8] Because, as is known, higher tensile strengths and hardnesses provide better cavitation corrosion resistance,[9] requirements for tensile strength and hardness are high. **Table 2** shows the mechanical properties specified for this runner material. The tensile strength is 75 kgf/mm^2 or more and the Charpy impact value at 0°C is 6 kgf·m/cm^2 or more, showing the high strength and toughness requirements for steel castings for hydraulic turbine runners. Furthermore, high hardness values are also required, because hardness is most closely related to resistance to abrasion due to sand.[10]

It is expected that material for hydraulic turbine runners will be required to meet increasingly severe standards in regard to the above-mentioned properties, based on service condition considerations.

Table 2 Mechanical properties of 13Cr-3.5Ni cast steel

YP (kgf/mm²)	*TS* (kgf/mm²)	*El* (%)	*RA* (%)	HB	Charpy impact value (kgf·m/cm²)
≧55	≧75	≧15	≧40	217~302	≧6 (0°C)

4 Examination of Material Quality Under Differing Tempering Conditions

4.1 Relationship of Mechanical Properties and Tempering Conditions

In the as-cast condition, this 13Cr-3.5Ni steel has a mixed structure of martensite and retained austenite. The ordinary heat treatment process comprises diffusion annealing and normalizing and tempering. When repair welding is performed, stress relief annealing is also performed after welding. As normalizing and tempering, what is called NTT, i.e. normalizing and two-step tempering is performed.

Figure 8 shows the relationship between the mechanical properties of the 13Cr-3.5Ni steel and second step normalizing conditions. As pretreatment, normalizing was conducted at 980°C after diffusion annealing at 1 000°C, and first-step tempering was conducted at 650°C. It is apparent that although strength decreases slightly, ductility and toughness increase as the temper parameter *P* in second-step tempering increases; i.e., as tempering conditions in the second step shift toward the high-temperature, long-time side. The increase in toughness is especially large in relation to the decrease in strength. Thus the effect of NTT treatment on toughness[1] is great, and, therefore, it is important to thoroughly examine the relation of mechanical properties to tempering conditions when setting tempering conditions for this steel.

When repair welding is performed, stress relief annealing is performed after welding, as mentioned above. However, an increase in the frequency of stress relief annealing results in deterioration of mechanical

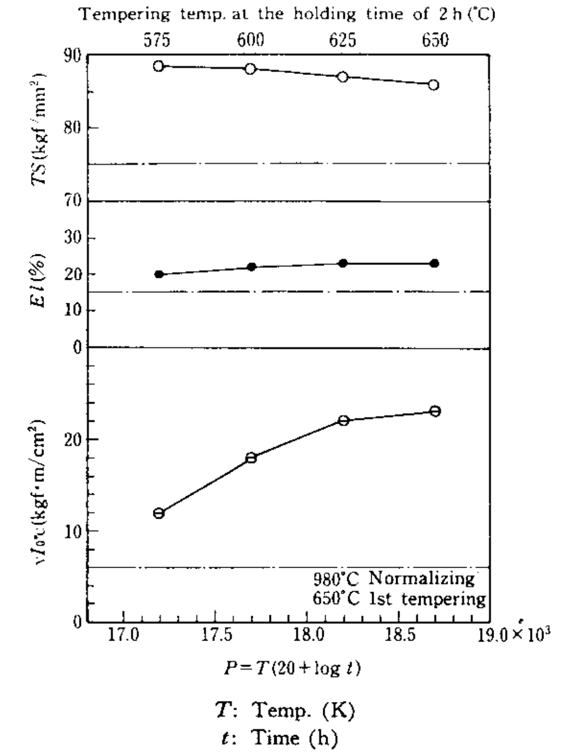

Fig. 8 Relation between mechanical properties and tempering conditions

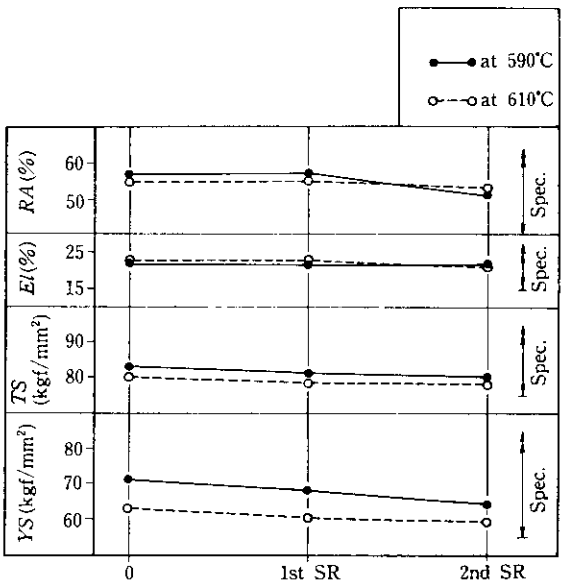

Fig. 9 Variation of tensile test properties with the repeated number of SR

properties, especially toughness. The relationship between tensile properties and frequency of stress relief annealing is shown in **Fig. 9**. In this figure, zero SR indicates the case where only diffusion annealing and normalizing and tempering (NTT) are conducted. Heating was conducted at two temperatures, 590°C and 610°C; the tempering temperature during NTT was the same as the stress relief annealing temperature. Both strength and ductility tend to decrease with increasing frequency of stress relief annealing. The decrease in yield stress (at 0.2% elongation) is especially great. The difference in temperature between 590°C and 610°C does not greatly affect ductility. However, this difference has a marked effect on strength, especially yield point, with the lower values shown at 610°C.

The relationship between toughness and the frequency of stress relief annealing is shown in **Fig. 10**. As the frequency of stress relief annealing increases, toughness tends to decrease and, at the same time, variations in toughness increases. This behavior of toughness is also observed at a tempering temperature and stress relief temperature of 590°C. At 610°C, however, toughness is high, but variations are also great. This seems to suggest that there is some case in which a decrease in toughness occurs even under the same tempering and stress relief annealing conditions.

According to excellent studies by Y. Iwabuchi, *et al.*[4,11-13] on the decrease in the toughness of 13Cr-3.5Ni steel, this deterioration is caused by the stability of the austenite that precipitates due to tempering heating and

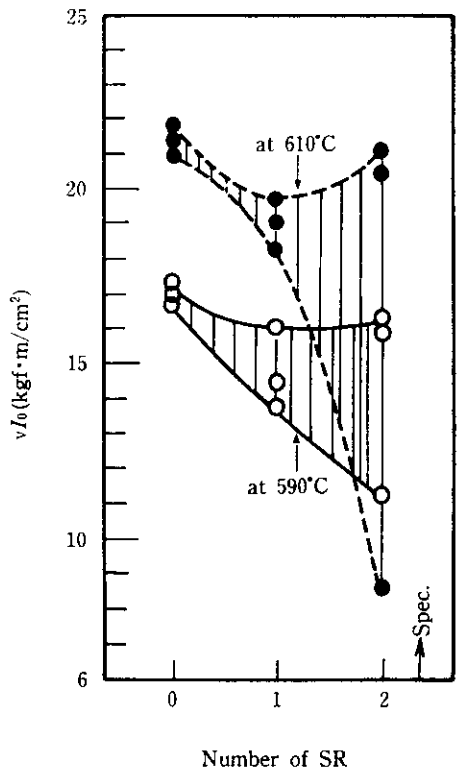

Fig. 10 Variation of Charpy impact value with the repeated number of SR

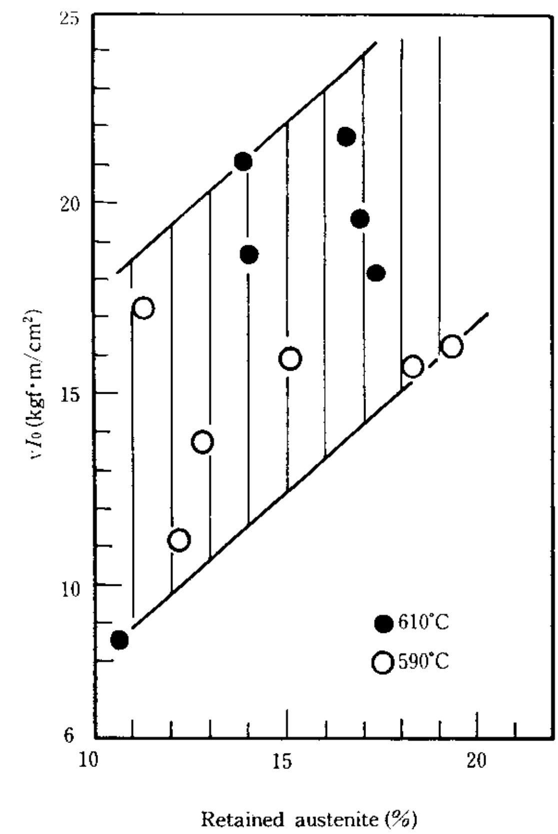

Fig. 11 Relation between the amount of retained austenite and Charpy impact value

the precipitaion of carbides at austenite grain boundaries. If the precipitated austenite is stable, it should be measured as retained austenite. Therefore, the data in Fig. 10 has been rearranged in terms of retained austenite and is shown in **Fig. 11.** Toughness tends to increase with increasing amounts of retained austenite. However, differences in toughness exist even with equal amounts of retained austenite, showing that evaluation is impossible based on the amount of retained austenite alone. This seems to be because the carbides precipitated at grain boundaries, in addition to the retained austenite, are a cause of this deterioration, as pointed out by Y. Iwabuchi, *et al.*

As mentioned above, tempering conditions and the frequency of stress relief annealing have a great effect on the mechanical properties, especially toughness, of this runner material. Especially, repeated stress relief annealing after normalizing and tempering poses a problem and, therefore, it is desirable to conduct repair welding before normalizing and tempering. If repair welding must be conducted after normalizing and tempering, it is necessary to minimize the frequency of stress relief annealing.

4.2 Changes in Transformation Point with Tempering Conditions

The preceding section described the marked effect of tempering conditions on the mechanical properties of this 13Cr-3.5Ni steel, with the conclusion that one cause is the stability of the austenite which precipitates during the temper heating process.

Figure 12 shows an example of a thermal expansion curve of this steel. The specimen expands with an increase in temperature, with the degree of expansion changing at about 612°C. This seems to be the temperature at which austenite begins to precipitate at martensite grain boundaries.[13] The relationship between this temperature Ac_{1S} and the frequency of tempering and stress relief annealing is shown in **Fig. 13**. It is apparent that Ac_{1S} shifts toward the low-temperature side as this frequency increases. The extent of this temperature drop is great on the first and second instances of tempering and stress relief annealing, but decreases gradually as annealing is repeated three or four times. However, it seems that the difference in temperature between 590°C and 610°C has little effect on Ac_{1S}. In this steel, Ac_{1S}, the temperature at which austenite is beginning to precipitate, decreases to 510~520°C when the frequency of tempering during NTT is increased. It subsequently decreases somewhat with each two repetitions of stress relief annealing. This suggests that austenite precipitates at lower temperatures when the frequency of tempering and stress relief annealing is increased. It seems that the higher the heating temperature reached, the larger the amount of precipitated austenite. If this austenite is stable, it contributes to the improvement of toughness, in which case the larger amounts of austenite are considered desirable. On the other hand, however, it seems

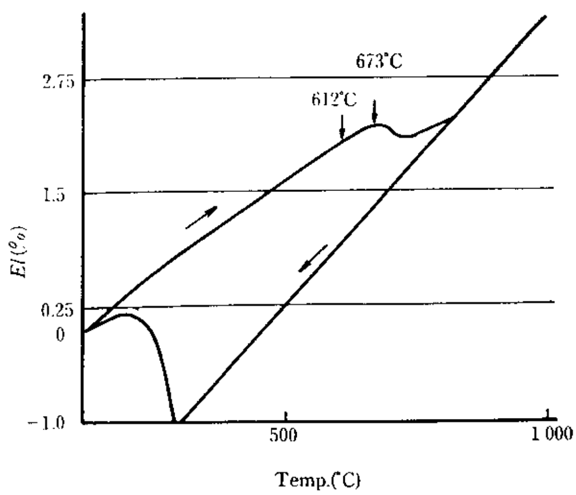

Fig. 12 Thermal expansion curve of 13Cr-3.5Ni cast steel

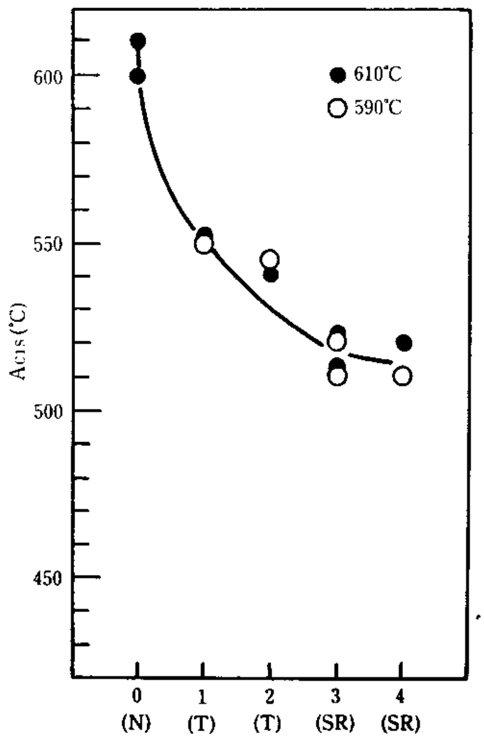

Fig. 13 Variation of re-tempering condition on Ac_{1S} temperature

that the stability of austenite depends on the temperature at which it begins to precipitate[13] and, as a result, precipitated austenite is not necessarily stable austenite. Accordingly, a thorough grasp of the behavior of precipitated austenite is required when designing the properties of this steel for runners.

5 Manufacturing Process and Quality Control

5.1 Manufacturing Process

Since the blade area of the Kaplan runner vane is large, incline molding, shown in **Photo 2**, has been adopted. Furthermore, various measures to prevent deformation during heat treatment are taken in manufacturing Kaplan runner vanes. In other respects, the manufacturing process is basically the same as with Francis runners, and the manufacturing process for Pelton runners is also quite similar. Therefore, the manufacturing process of Francis runners will be described in the following.

A manufacturing process flow chart for a Francis runner is shown in **Fig. 14**. The manufacture of hydraulic turbine runners is characterized by the fact that the number of steps is very large compared with that of steel castings in general. In this process, when no defects are

Photo 2 Pouring

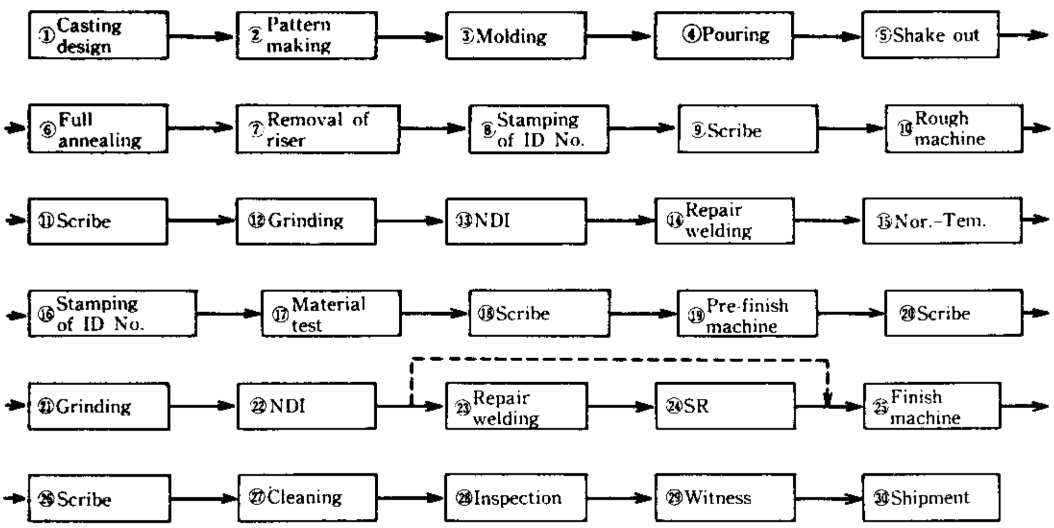

Fig. 14 Manufacturing flow chart of Francis runner

found by nondestructive inspection in step ㉒, the dotted line indicates that steps ㉓ and ㉔ are omitted. Kawasaki's basic concept is that all defects be detected by the nondestructive inspection in step ⑬ and that defects detected be corrected completely by repair welding in step ⑭. At present, about half the hydraulic turbine runners produced at Kawasaki Steel are finish-machined without the stress relief annealing in step ㉔.

5.2 Important Control Items

The basic concept of important control items in the manufacturing process is described in the following.

5.2.1 Casting plan

The distinctive feature of Kawasaki's casting plans is that casting plans are checked and quality predicts made using the two-dimensional solidification analysis system, BACCAS (binding application for CAD and computational analysis of solidification), developed by the company. Castings generally have complicated shapes; therefore, preparation of analysis data is time-consuming. It had previously been impossible to perform the analysis of solidification on a daily basis. With BACCAS, using computer-aided design for input and output, data for solidification analysis is automatically prepared simply by entering the casting shape by CAD and selecting calculation conditions, such as values of physical properties and boundary conditions, from the library already created. This system can be applied daily to casting plans because of the speed with which the analysis of solidification can be performed.

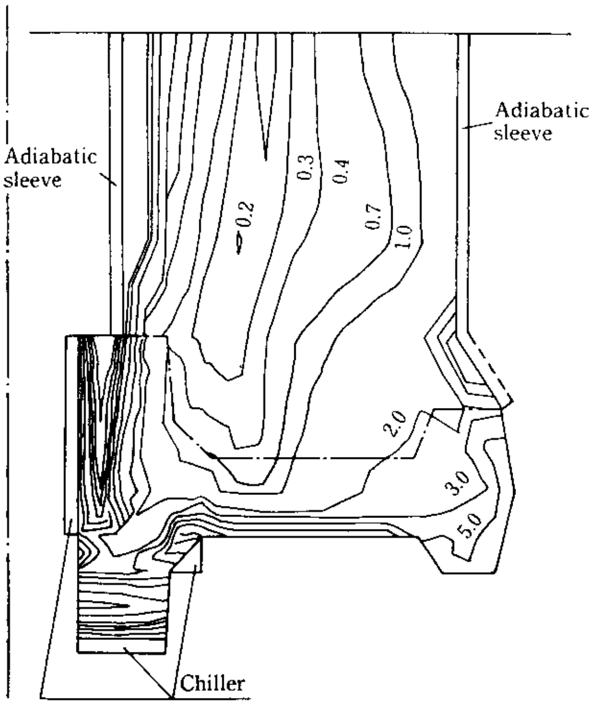

Fig. 16 Computer simulation results of Pelton runner (Figures indicate temperature gradient)

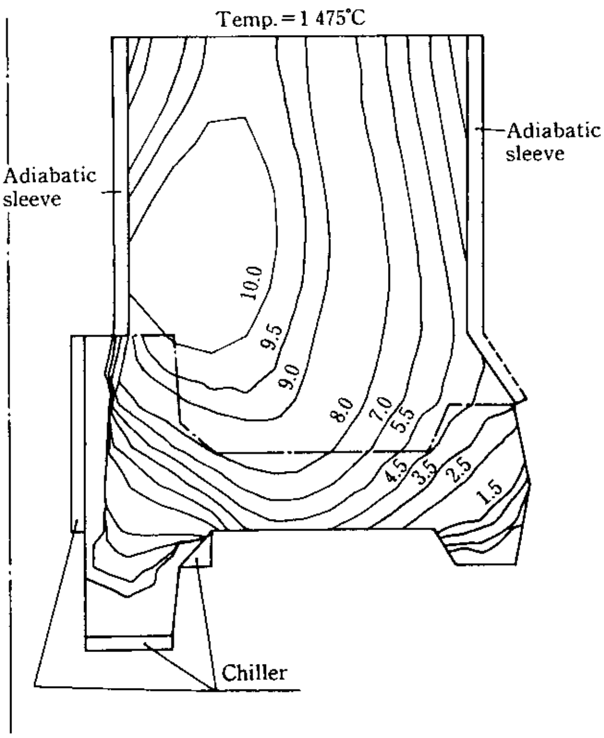

Fig. 15 Computer simulation results of Pelton runner (Figures indicate solidification time)

Figures 15 and **16** show an example of a solidification analysis for a Pelton runner perforned with this BACCAS system. Figure 15 shows the solidification time at a solidification ratio of 60%, while Fig. 16 shows the temperature gradient under the same conditions.

5.2.2 Mold

The selection and drying of core sand are very important, because the basic excess thickness at the running water surface is 2 to 3 mm, including the thickness to be scaled off during heat treatment. Easily stripped chromite phenolic-urethane molds are used by Kawasaki Steel. The volume of gases generated from core sand differs, depending on the mixing ratios of resin and catalyst. **Figure 17** shows the gas volume in an atmosphere at 1 200°C when the proportions (by weight) of resin and catalyst relative to sand are both 0.75%, in one case, and 0.5%, in another case. As is apparent from this figure, the gas volume decreases by about 30% when the proportions of resin and catalyst are 0.5%. Therefore, 0.5% proportions are used.

Figure 18 shows the relationship between the drying temperature and strength after cooling of phenolic urethane molds. Cores are dried at 100 to 150°C based on

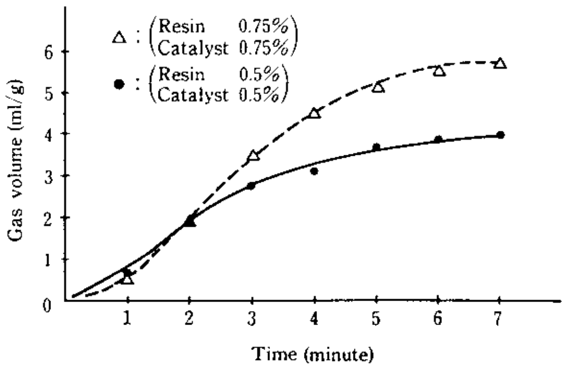

Fig. 17 Time-volume profile of gaseous effluent from phenolic urethan molds

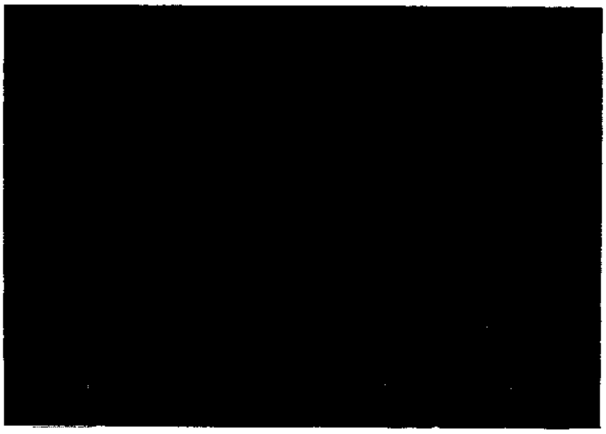

Photo 3 Core assembly of Francis runner

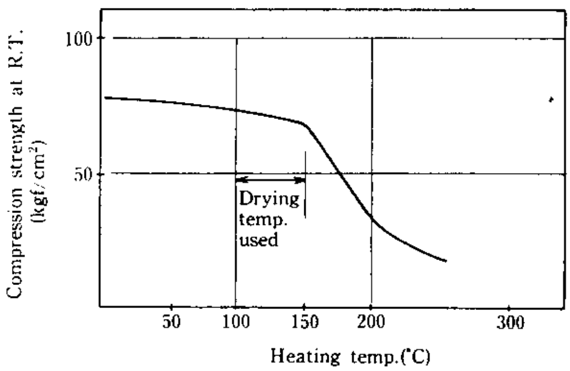

Fig. 18 Variation of retained strength with heating temperature for phenolic urethan molds

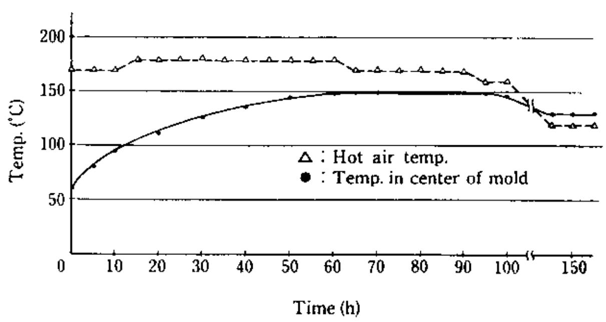

Fig. 19 Time-mold temperature profile of Francis runner core drying after mold assembly

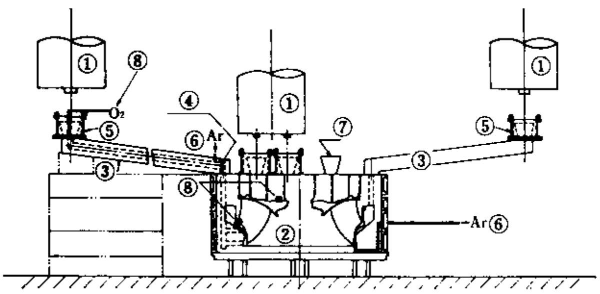

Fig. 20 Non-oxidation atmosphere casting

this relationship. **Figure 19** shows records of core drying. The core temperature is controlled using thermocouples as the core is being dried with an electric hot-air dryer. A completed core assembly is shown in **Photo 3.**

5.2.3 Pouring

The argon-shielded pouring method is used. **Figure 20** is a schematic diagram of this method. In this method, contact of poured molten steel with air between the ladle and the sprout is prevented by an argon gas sealing box. The molten steel is shielded with an argon shower during pouring. The atmosphere surrounding the poured molten steel is controlled to O_2 concentrations of 0.2 to 1%. The atmosphere in the spout is replaced by argon gas immediately before pouring to ensure complete sealing. The atmosphere in the mold is replaced by argon beforehand and argon supply is stopped simultaneously with pouring. **Figure 21** shows changes in the O_2 concentration in the mold. As can be seen, the O_2 concentration at pouring is 2% or less.

5.2.4 Knockout

The 13Cr-3.5Ni steel is a martensitic stainless steel. The M_s point is 260 to 270°C and the M_f point is 80 to 90°C. Therefore, knockout temperature control is important. Knockout is conducted when the mold temperature has reached 80°C. However, the number of in-mold cooling days increases when in-mold cooling is allowed to proceed naturally. **Figure 22** shows a cooling curve for natural cooling. At present, in-mold cooling time is shortened by adopting the forced cooling method, as shown in **Fig. 23.**

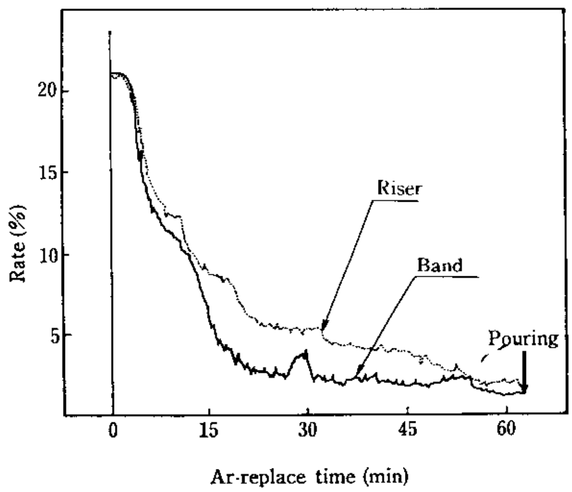

Fig. 21 Time-volume profile of oxygen in mold cavity

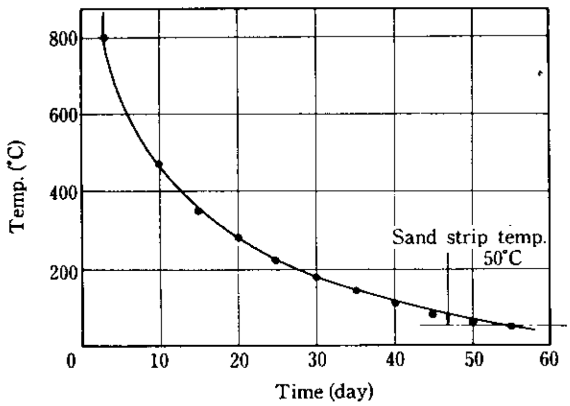

Fig. 22 Cooling curve in mold after pouring for Francis runner at air cooling

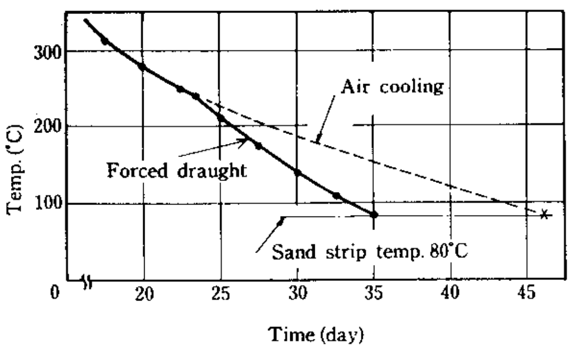

Fig. 23 Cooling curves in mold after pouring for Francis runner at forced draught

5.2.5 Heat treatment

Since the quality of the 13Cr-3.5Ni steel depends greatly on the heat treatment temperature, heat treatment is the most important control item and is conducted by controlling the temperature of the casting surface. The steel temperature is controlled to within ±20°C of settings, with measurements at two locations on the band outlet diagonals as thin portions, two locations on the crown inlet diagonals as thick portions, and at one location on the coupling rear side. Since tempering temperature is important, this is controlled to ±15°C using a recirculation-type tempering furnace.

5.2.6 Repair welding

Weld defects are repaired under strict welding operation control, including monitoring of overall preheating before welding, heat retention during welding, interpass temperature, welding current, voltage, welding speed, electrodes, and the welder.

Furthermore, heat retention is carried out for the diffusion of hydrogen in deposited metal, and slow cooling is performed immediately after welding. The runner is allowed to stand after welding for the period required for the incubation of hydrogen-induced delayed failure to ensure that weld defects are not carried over to following processes.

5.3 Results of Production

Kawasaki Steel has to date manufactured a large number of hydraulic turbine runners. **Photos 4, 5 and 6** show, respectively, a Francis runner, Kaplan runner, and Pelton runner of 13Cr-3.5Ni steel produced by the com-

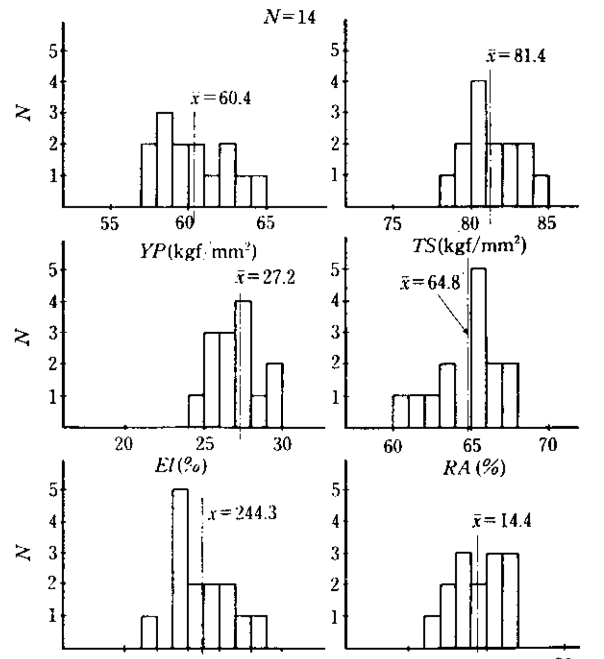

Fig. 24 Histograms of results from material testing of 13Cr-3.5Ni runner

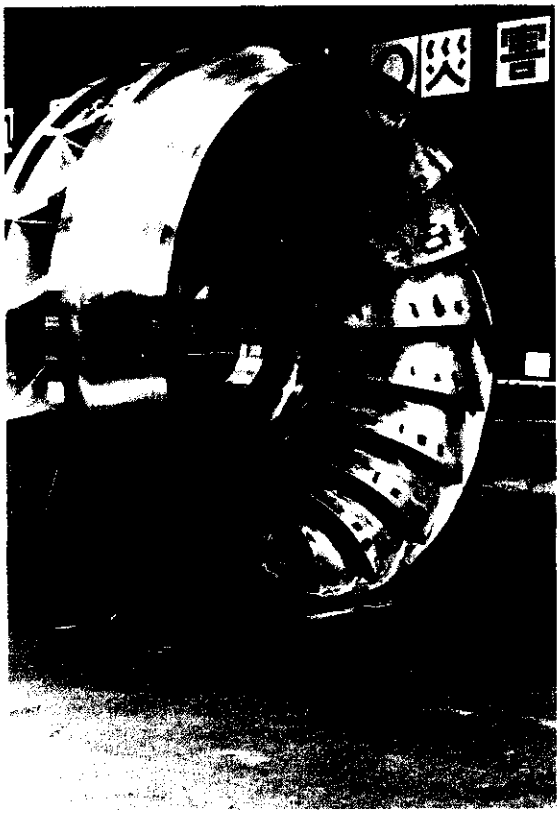

Photo 4 Francis runner

Table 3 Maximum weight and size

Products	Maximum weight (t)	Maximum size (mm)
Francis runner	25	3 500 ϕ
Kaplan runner blade	25	4 000 × 4 000
Pelton runner	25	3 500 ϕ

pany. **Figure 24** shows the results of material tests on specimens taken from a 13Cr-3.5Ni steel runner. These values sufficiently meet standard values. **Table 3** gives maximum weights and sizes of each of the types of runner manufactured.

6 Concluding Remark

The manufacture and quality of 13Cr-3.5Ni stainless steel hydraulic turbine runners were described. Kawasaki Steel has already established manufacturing techniques for all three types of runners, the Francis type, the Kaplan type, and the Pelton type, and has manufactured numerous runners for use. In recent years, the company has put into practical application a method for producing casting plans using its own solidification simulation system BACCAS and, as a result, is producing high-quality steel castings.

Photo 5 Kaplan runner

Photo 6 Pelton runner

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