Nickel Base Superalloys Single Crystal Growth Technology for Large Size Buckets in Heavy Duty Gas Turbines

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ABSTRACT

A larger size bucket with superior high temperature strength is required for future land based gas turbines. From the viewpoint of high temperature mechanical properties, single crystal alloys are rather promising. To grow larger sized single crystals of nickel base superalloys, a two stage heating and bypass process in which single crystal growth paths are incorporated into large cross sectional positions such as platforms has been developed. It results in successful single crystal growth of alloys for buckets with a total length of 170mm and large lateral cross section. Characteristics of single crystal buckets made by the bypass process and properties of an alumina mold prepared for a single crystal casting are described herein.

INTRODUCTION

Among approaches to improve efficiency of gas turbines, the best way is to increase gas inlet temperatures, which requires materials to be developed with superior properties at high temperatures. It is well known that columnar crystal buckets or single crystal buckets of nickel base superalloys, manufactured by unidirectional solidification, have superior high temperature properties. These materials have already been used as blades for jet engines, in which they provide good economical performance.

For power generation gas turbines, equiaxed crystal alloy buckets made by conventional casting have been used. Recently there has been an attempt to use columnar crystal buckets, but there has been no reported use of single crystal alloy buckets for power generation gas turbines. The reasons why single crystal alloy buckets have not been used can be summarized as follows:

1) The size of the buckets for power generation gas turbines is much larger than that of jet engines, and their shape is more complicated. At present the crystal growth technology for such larger buckets is not well established.
2) Due to the first reason, even when larger single crystal alloy buckets can be made, their manufacturing cost will be too high.
3) A nickel base superalloy for single crystal alloy buckets with almost the same corrosion resistant property as the conventional equiaxed alloy buckets is not available.

The single crystal growth technology for larger size buckets is becoming more important and necessary if single crystal alloys are to be applied to buckets for power generation gas turbines.

In this report the single crystal growth technology for larger size buckets and mechanical properties of a bucket made by it as well as the properties of an alumina mold for growing single crystals are presented.

EXPERIMENTAL PROCEDURE

Casting

Single crystal growth of nickel base superalloys was carried out by a mold withdrawal type unidirectional solidification apparatus, as shown in Fig.1. The mold heating furnace is divided into two stages, capable of giving a larger temperature gradient than the single susceptor type heating furnace. Table 1 lists the chemical composition of an alloy for the single crystal casting experiments. This alloy, with superior high temperature strength, was developed by Japanese National Research Institute for Metals. The liquidus and solidus temperatures are 1300 and 1363°C, respectively.

Fig.2 shows the bucket for single crystal casting experiments. The bucket total length is 170 mm, approximately the length needed for a 25 MW class gas turbine.

The single crystal alloy casting conditions were: upper zone mold heating temperature, 1520°C; lower zone mold heating temperature, 1530°C; and mold withdrawal rate, 10 cm/h. Starter and selector were used to initiate single crystal growth. The pouring temperature was about 1500°C. These casting conditions were determined according to fundamental studies in which small size single crystal alloy buckets with the total length of about 80 mm were successfully grown.

Mold

A cross sectional micrograph structure of the alumina mold used for the single crystal casting is shown in Fig.3. The mold was manufactured by a shell mold process. The materials for molding were colloidal silica as binder and alumina for filler and stucco.

Table 2 lists the molding conditions. It is well known that alumina is hard to fire, so using a silica binder was expected to give alumina powders which fired well with each other through formation of mullite particles, 3Al2O3•2SiO2, between those alumina powders. Alumina fillers were used to increase the mold strength. In Fig.3, the angular, darkened particles are alumina stucco, and the
TABLE 1. CHEMICAL COMPOSITION OF A SINGLE CRYSTAL ALLOY.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cr</th>
<th>W</th>
<th>Ta</th>
<th>Al</th>
<th>Ni</th>
</tr>
</thead>
</table>
| TMS12 | 6.6 | 12.8| 7.5 | 5.0 | Bal.

TABLE 2. MOLDING CONDITIONS FOR SINGLE CRYSTAL CASTING.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Colloidal silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler</td>
<td>Alumina, mean particle size, 20 µm</td>
</tr>
<tr>
<td>Stucco</td>
<td>Alumina, 1st layer 100-200 µm</td>
</tr>
<tr>
<td></td>
<td>2nd layer 200-400 µm</td>
</tr>
<tr>
<td></td>
<td>3 to 7 layer 600-1200 µm</td>
</tr>
</tbody>
</table>

FIG. 1 UNIDIRECTIONAL SOLIDIFICATION APPARATUS.

FIG. 2. BUCKET FOR SINGLE CRYSTAL CASTING EXPERIMENT.

FIG. 3. CROSS-SECTIONAL MICROPHOTOGRApH OF AN ALUMINA MOLD.

Gray or white part is composed from slurry. The mold, about 8 mm thick, with a seven layer coating was further surface-coated by (Cr,Fe)₂O₃ to increase its radiation efficiency, and ensuring a casting growth with a large temperature gradient.

Differing from a conventional casting mold, a single casting mold needs to be much stronger at high temperatures, as the solidification time of a single crystal alloy bucket is far longer than that of a conventional casting. The high temperature strength of the mold was therefore estimated by lever type, four point bending creep testing. The distance of loading points and supporting points were 10 and 30 mm, respectively. For a comparison, a conventional casting mold, made of zircon, was also tested. The testing temperature was 1550°C for the single crystal casting mold, and 1450°C for the zircon mold. The specimen was 6 mm wide, 8 mm thick and 55 mm long.
Crystal orientation measurement

Crystal growth orientation significantly affects the high temperature strength. The crystal growth orientation was measured by a back reflection Laue method, in which a X-ray source was supplied by a synchrotron orbital radiation apparatus(SOR) installed in the Photon Factory of the National Laboratory for High Energy Physics, Japan. The intensity and irradiation beam size were 8 keV and 160 X 160 µm², respectively. The irradiation time was about one second for each measuring point.

RESULTS AND DISCUSSION

Properties of the mold

Fig.4 shows the X-ray diffraction pattern of the single crystal casting mold after firing under the condition of 1550 °C for 30 min. The mold is composed of alumina and mullite. The mullite seems to be formed by reaction between silica, used as the binder, and alumina, as expected.

![X-ray diffraction pattern of a mold](image)

FIG. 6. POLYCRYSTALLIZATION AT A SEAL-FIN.

Fig.5 shows the bending creep strength of the single crystal casting and conventional casting molds. Compared to the conventional casting mold, the single crystal casting mold shows two orders of magnitude lower creep rate, even though the test temperature is 100 °C higher. This lower creep rate is due to good mold heating during firing which is made possible by the mullite formation.

In order to study the reaction of the mold with molten superalloys, a rodlike single crystal was initially cast, and then, the interface between the mold and the casting was carefully analyzed by electron probe microanalyzer. Details of the result are not shown here, but no particular compositional change is seen. From these results, it is found that the mold composed of alumina and mullite has excellent properties for promoting single crystal growth.

Single crystal growth and bypass method

Non-single crystal growth at a large section

A single crystal casting of the bucket shown in Fig.2 was made by two stage heating in the furnace shown in Fig.1. Other crystals form at large sections such as the platform or seal-fin, as Fig.6 shows such an example in which polycrystallization occurs at a seal-fin.

This may be due to a small temperature gradient at the solid/liquid interface when the crystal grows from a small section to a large section. Unlike turbine blades for jet engines, buckets for power generation gas turbines generally have a more complicated shape and their size is several times larger. Therefore, it seems to be difficult to grow large single crystal buckets for power generation by the conventional unidirectional solidification method which has been successfully applied to jet engine blades.

Bypass method

In order to prevent other crystal formation at large sections, the "bypass method" was developed. As a result of this new single crystal growth technology, the large size bucket as shown in Fig.2 can be grown with a fully, single crystal structure.

Fig. 7 shows a schematic of the bypass method and an example incorporating the bypass at a seal-fin section. The bypass method allows a bucket to be grown with a fully single crystal structure at
a) Outline of bypass method.

b) Example of bypass.

**FIG. 7. BYPASS METHOD.**

large cross sections. In it, the edge of a large cross section is connected by a bypass to a part already grown as a single crystal.

From a metallurgical viewpoint the bypass method is intended to take advantage of the growth characteristics of a dendrite. That is, when a dendrite growing vertically upwards with a growth direction of $<100>$ meets a mold wall, a dendrite side arm grows laterally with the growth orientation equivalent to $<100>$. This dendrite arm may meet a mold wall, then another dendrite arm grows again vertically with the equivalent orientation. By repeating this growing pattern, a single crystal can continue growing within the attached bypass.

There may be a coalescing location between a part growing from the main body and a part growing from the bypass. Consequently, it is important to know how the coalescing location solidifies or how crystals grow differently.

Fig. 8 shows the platform macrostructure of a single crystal bucket grown by applying the proposed bypass method. From the horizontal section structure the coalescing location can be clearly observed because the secondary arm spacing seems to be different due to the dendrite growing from the bypass and the dendrite growing from the main body. However, the longitudinal cross section structure shows almost no discontinuous growing region in the coalescing location, and it is also almost impossible to

**FIG. 8. MACROSTRUCTURE OF THE PLATFORM IN A SINGLE CRYSTAL BUCKET WITH A BYPASS.**

a) Measuring point

b) Growth direction
c) Vertical direction

**FIG. 9. DEVIATION OF CRYSTAL ORIENTATION AT THE PLATFORM.**
distinguish this region from other regions. Therefore, the discontinuous dendrite structure on the horizontal cross section seems to exist only at the surface region of a platform.

Fig. 9 shows the measured results of crystal orientation on the platform shown in Fig. 8. The measurement was carried out by SOR. Point Nos. 3 and 7 in Fig. 9 were taken as the reference point for growth orientation and for the normal direction to the growth direction, respectively, and deviation of the orientation was measured both from the growing direction, that is, on the (001) plane, and from the normal direction to the growing direction, that is, on the (115) plane in this bucket. The orientation deviation is only within 1° both on the growing direction and the normal direction. Such a small deviation in orientation does not seem to have any effect on a practical use of a bucket grown by the bypass method.

Fig. 10 shows the single crystal bucket with the bypasses at a platform and a seal-fin. As described earlier, it was impossible to grow a single crystal of this bucket using only the two stage heating, however, by adding the bypass method, this bucket size can be successfully grown as a single crystal.

**Tensile test.** In order to study how the dendrite structures at a coalescing location affect mechanical properties, tensile tests at a room temperature, 700 and 800°C were carried out. The test specimen size was 2 mm in diameter and 8 mm in gauge length. The specimens were taken out from a seal fin and a platform of a bucket with a bypass so that a tensile direction was normal to growth direction and the coalescing location was included in the gauge length part. For a comparison, specimens with the tensile direction normal to growth direction were also taken out near the coalescing locations from the main body. Before testing, heat treatment proposed to the single crystal alloy TMS 123 was given to specimens. This was; solution treatment, 1336°C for 4 hours plus water quenching, and after this, aging treatment, 980°C for 5 hours, gas cooling, and 870°C for 20 hours, gas cooling. The strain rate was 0.3%/min.

Table 3 lists the results of tensile tests. In this the tensile direction measured by a conventional back reflection Laue method is also shown. The symbols A, C, E, G and I are for specimens including a coalescing location, and B, D, F, H, and J are for specimens of the main body. Both the yield and ultimate strength increase as the test temperature increases. However, there is almost no difference in strength between the specimens including a coalescing location and specimens taken out from the main body.

From the studies with regard to the macrostructure, crystal orientation and tensile tests, the bypass method was found effective to grow the single crystal alloy bucket with a large cross section.

**Conclusions.**

In order to grow a large size bucket for power generation gas turbines, the bypass method has been developed. While developing this new method, the fundamental studies were carried out, and the following conclusions were obtained.

1) The alumina mold had superior high temperature strength, and was applicable to single crystal growth casting.

2) A single crystal bucket grown by the developed bypass method showed only a small deviation in growth orientation at the coalescing region growing from the main body and growing from an incorporated bypass.

3) By applying the bypass method, it was possible to grow a large size single crystal bucket with a laterally increased cross-section.
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REFERENCES

