COST EFFECTIVE SINGLE CRYSTALS

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Summary

The development by Rolls-Royce of a cost effective single crystal technology has required work in three key areas -

1. Single crystal casting technique
2. Alloy development
3. Orientation measurement.

The first has led to the adoption of the technically more difficult seeding technique as a result of its greater flexibility. The second has resulted in the development of a series of 3 alloys to meet specific turbine applications. The third requirement has been met by the development of a rapid and accurate orientation measurement technique (SCORPIO) suitable for the production environment.

Introduction

The history of the development of the gas turbine is characterised by many examples of materials research coupled with innovative design leading to major advances in power and efficiency. The successful introduction of new concepts requires the co-ordinated development of the supporting technologies.

Single crystal turbine components will allow both engine power and efficiency improvements by enabling the use of higher metal temperatures by either increased gas temperatures or reduced cooling air flow.

This paper describes three relevant technologies, namely casting, alloy development and orientation measurement, developed by Rolls-Royce to enable the cost effective production of single crystal turbine components.

Casting Technology

Rolls-Royce has had a long experience of investment casting, the process being introduced in the foundry during the mid 1940's for the production of nozzle guide vanes. Vacuum melting and casting were introduced in the early 1960's with the appearance of the stronger, more reactive superalloys.

In-house development of directional solidification (DS) began in 1968. To minimise the long term manufacturing cost of these components a purpose-designed plant was developed rather than the more obvious approach of modifying existing equipment by the addition of mould heating and withdrawal facilities.

Furnace Design

The Rolls-Royce DS furnace is based upon the withdrawal of an investment shell mould through a steep thermal gradient. For optimum directional solidification performance the thermal gradient in the casting should be as steep as possible (1). This implies, in the extreme, that single-shot blade casting, and hence a very small chill, would be most effective. Low cost, however, would be difficult to achieve with this configuration and therefore a careful compromise was developed to allow multiple blade casting while maintaining a satisfactory gradient resulting in the choice of 5.5 inch diameter chill plate. The size of chill permits, at the extremes, five civil HP turbine blades or 20 helicopter HP blades to be cast simultaneously as shown in Fig. 1.

A bottom run mould system was utilised to give controlled, predictable filling of the blade cavities and allowed the use of an integral ceramic filter ensuring very clean casting.

As a direct consequence of the chill size chosen, a charge weight of not more than 5kg needs to be melted. This is achieved by HF induction melting enabling the charge to be completely melted in about 2 minutes. One consequence of this technique is that the magnetic pinch effect keeps the molten metal away from the crucible walls allowing the use of inexpensive, disposable, refractory-fibre crucibles. Bottom pouring is achieved automatically by the melting of a preplaced metal disc by contact with the molten charge above it. This system provides a rapid melting and pouring

technique around which the rest of the furnace could be designed.

Fig. 1a Wax assembly for 5 civil HP turbine blades.

Fig. 1b Wax assembly for 20 helicopter HP turbine blades.

Fig. 2 Configuration of the Rolls-Royce DS Furnace

The developed DS furnace is shown schematically in Fig. 2 and consists of 3 individually pumped and valved vacuum chambers, namely an upper melting chamber, a central mould chamber and a lower withdrawal chamber. The furnace has duplicate crucible carriers and withdrawal chambers coupled to an indexing system which allows uninterrupted operation between casting cycles. The sequence of operation commences with the attachment of a crucible with charge to its carrier and the mould to the copper chill in the open withdrawal chamber. The furnace then indexes both the carrier and the loaded withdrawal chamber in line with the central chamber. Once a suitable vacuum is achieved in all chambers the vacuum valves are opened to allow the mould to be raised into the central chamber which is maintained at a temperature above the metal liquidus by a graphite resistance heater. Immediately after pouring the mould is withdrawn at a fully programmable rate into the cooled withdrawal chamber. The casting cycle is complete once the furnace indexes the next mould and crucible into place.

In the production foundry, microprocessor control allows up to 12 furnaces to be operated by only two men; in addition all utilities are shared including the HF induction power supply. The multiplicity of units has a number of direct consequences:-

1. The capital cost of individual units is relatively low and capacity may be expanded easily to match market requirements.
2. Planned maintenance of individual units does not significantly reduce the overall plant availability and ensures a high level of plant reliability.
3. If unscheduled failures do occur the effect is limited, allowing production to continue on other units.

The high degree of control applied to the system ensures repeatability from furnace to furnace. It has been shown that this also applies to the transfer of work to subcontractors using identical units.

Single Crystal Component Casting

The DS furnace has proved to be very successful in production. The high thermal gradient achieved, typically 4000 K m^{-1} , allows the casting of single crystals without modification. The extension to single crystal technology only requires changes in mould design to ensure the growth of a single crystal. The simplest method is to use some form of crystal selector which is based upon competitive dendritic growth through a narrow passage, taking advantage of the $\langle 001 \rangle$ easy-growth direction of cubic crystals. Typical selector designs are shown in Fig. 3.

The crystal selector method, although perfectly satisfactory in its yield of single crystal castings, has a number of drawbacks, namely poor control of the longitudinal orientation, no control over the transverse orientation, restriction to casting components around $\langle 001 \rangle$, and it results in very fragile assemblies at the wax stage during mould manufacture. All of these disadvantages may be overcome by the technically more difficult technique of seeding. Rolls-Royce, through a unique approach (2), have engineered the technique to the stage where it can be reliably used for production. The technique is shown schematically in Fig. 4a compared to a top fed design Fig. 4b. The use of a side entry to the seed chamber ensures a consistent melt-back and is compatible with the preferred bottom running

and ceramic filtration techniques.

Fig. 3 Three single crystal selector designs

Fig. 4a Bottom run seeded mould design

Fig. 4b Top run seeded mould design

Alloy Design

A review of the likely applications of single crystal turbine components resulted in a varied set of requirements which could not be met by a single alloy.

Cooled turbine blades are subject to high creep stresses at moderate temperatures and require resistance to thermally induced strains. Oxidation and corrosion resistance are not a major consideration provided the alloy has adequate coated life. A typical first-stage uncooled turbine blade, in general, runs at lower stresses but higher temperatures than the previous example, putting greater emphasis on the coatability of the material as well as its required high-temperature creep strength.

In addition to the cases briefly discussed some applications require an alloy of improved creep and thermal fatigue strength but with the lowest possible density. These alloys cannot possess the same degree of absolute strength as the standard alloys but minimise disc loadings in advanced high rim speed designs. Alternatively some current engine applications can benefit from the substitution of a single crystal blade alloy of the same low density as the conventional alloy currently used, therefore avoiding any disc redesign.

Nozzle guide vanes were considered; for the case of a highly cooled HP NGV the major requirements are for very good oxidation and corrosion resistance combined with thermal fatigue resistance. Castability, creep and tensile strengths are of secondary importance. An uncooled vane has similar requirements in terms of oxidation and corrosion but is not subjected to the same thermal stresses as the cooled variant.

Table 1 summarises the property requirements for the identified applications. It can be seen that three types of alloy are required to meet these objectives. Alloy development has defined three compositions:-

SRR99 - a high strength, high temperature capability blade alloy (3)

RR2000 - a low density ($\rho = 7.9 \text{ Kg l}^{-1}$) blade alloy (4)

RR2060 - an oxidation and corrosion resistant NGV alloy (5)

The characteristics of these alloys are discussed more fully elsewhere (6)

	Creep Strength	Thermal Fatigue Resistance	Tensile Strength	Castability / Processability	Coatability	Low Density	Oxidation/Corrosion Resistance	Developer Alloy
Cooled HP Turbine Blade	**	**	*	*	*	-	-	SRR99
1st Uncooled Turbine Blade	**	*	*	*	**	-	-	
High Rim Speed Turbine Blade	**	**	*	*	*	**	-	RR2000
Cooled NGV	*	**	*	*	-	-	**	RR2060
1st Uncooled NGV	*	*	*	*	-	-	**	

Table 1. Alloy property requirements for specific turbine components

Orientation Measurement Technique

The crystallographic orientation of every single crystal blade or test piece produced has to be measured. It was realised, during the early stages of single crystal technology development, that a simple deviation between the crystallographic and component axes was not sufficient to fully characterise the changes in mechanical properties with orientation and that a full, three-axis determination was required. A practical production measurement technique should be rapid (and ideally operate in real time to be able to cope with the large number of production turbine blades) and be capable of providing an accurate measurement of the orientation at low cost. Further to the above criteria, any system developed would have to be introduced into the production environment and therefore should be able to provide a pass or fail decision without the requirement for a technically qualified and skilled operator.

Fig. 5 Geometry for back-reflection Laue technique.

Traditionally the orientation of a single crystal is measured by the Laue X-ray diffraction technique. This impinges a collimated beam of white X-rays on to the surface of the crystal, and the position of discrete diffracted beams formed by the interaction between the incident beam and the crystal structure is recorded by a photographic film as an array of spots. The geometry of this technique is shown in Fig. 5. Exposure times of about $\frac{1}{2}$ hour are typical, after which the film needs to be developed and then analysed. The manual determination of the orientation from the film is a time-consuming operation, especially if the full 3-axis orientation is required.

A number of alternative techniques were extensively evaluated, such as ultrasonics, electron channelling patterns and optical reflectivity. All these techniques provide orientation-dependent responses but have serious drawbacks for the accurate measurement of crystallographic orientation. The ultrasonic technique was shown to be insufficiently precise and the physics of the acoustic response is not fully understood. The channelling pattern technique is a specialist scanning electron microscope method and was obviously not suited in any developed form for the production environment, however it remains a valuable research technique.

Fig. 6 SCORPIO orientation measurement technique.

The reflectivity of the etched surface was found to be a function of the orientation, however the practical difficulties involved and the imprecise nature of the results did not make this approach worthwhile. The Laué technique therefore was chosen as the method with the most potential and a development programme was initiated to reduce the analysis time.

The development of the Laué technique has proceeded in 3 phases. Phase 1 was directed to reducing the exposure time using the standard wet film and developing a computer-aided analysis routine. A reduction in exposure time to 2 minutes was achieved by modifications to the X-ray generator and camera-x-ray tube geometry. The adoption of bulk film processing methods significantly reduced the overall darkroom time. It is interesting to note that the use of instant film did not offer any advantages over wet film in this application, the major drawback being its significant cost penalty. The subsequent analysis was performed using the image processor coupled to a video camera. The film is viewed via the camera and the images analysed by an interactive programme overlaying a computer generated pattern. Once a match has been found the results are printed out as a set of characteristic angles, giving the full three-axis orientation of the crystal.

Fig. 7 Typical Laué pattern generated by SCORPIO

In phase 2 the problems of time, cost and inaccuracies resulting from the use of wet film were addressed. The ideal solution of a real-time detector was considered, but at the time the market was surveyed, in 1980, no suitable commercial detector existed. As a consequence a purpose-built detector was specified and manufactured which is capable of generating high quality patterns in less than 8 seconds. The adoption of a real-time detector requires an inclined geometry (7) as shown in Fig.6. The analysis of the pattern proceeds as before with a suitable modified programme and is capable of yielding a result in 30-40 seconds. Examples of a generated pattern and analysis output are shown in Figs 7 and 8.

Fig.8 SCORPIO analysis output

The final phase of development is aimed at eliminating human error in the analysis routine by producing a fully automatic programme requiring no interaction with an operator. Continuous operation would be facilitated with the incorporation of suitable automatic blade and sample handling. Such a system may easily be integrated as a quality control stage in the manufacturing lines of the production foundry.

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