DEVELOPMENT OF SINGLE CRYSTAL ALLOYS

FOR SPECIFIC ENGINE APPLICATIONS

D. A. Ford[1] and R. P. Arthey[2]

Rolls-Royce Limited
Metallurgical Research Laboratories, England

Summary

The wide range of applications within Rolls-Royce engines has led to the policy of developing single crystal alloys with specific targets. This has resulted in a comprehensive family of alloys which meets the requirements of particular engine applications. SRR99 is a high strength alloy to replace DS MM002 in applications where increased creep, tensile and fatigue strength are required. RR2000 has been designed for blades requiring low density or high impact resistance. RR2060 has been developed as a nozzle guide vane alloy, with exceptional resistance to environmental attack and thermal fatigue.

---

1. Rolls-Royce Limited, P.O. Box 3, Filton, Bristol BS12 7QE, UK.
2. Rolls-Royce Limited, P.O. Box 31, Derby, DE2 8BJ, UK.

Introduction

The DS process has been well established during the 1970's (1,2) and to date RR have accrued well over 1M hours of commercial flying time with DS turbine blades. During this time the principal advantages of increased creep life and resistance to thermal fatigue have been well demonstrated in terms of service performance. However, in order to improve turbine component capabilities further, it is necessary to adopt the single crystal process.

Alloys used for DS differ little in composition from conventionally cast alloys, as they need to contain elements that strengthen both the grains and grain boundaries. However, these elements give rise to phases, or regions of the microstructure, where the incipient melting point can be several tens of degrees below the γ' solvus temperature. It is, therefore, not possible to improve the material properties by removing the highly cored microstructure or refining the γ' precipitate by heat treatment.

Alloys developed to take advantage of single crystal processing are designed to be amenable to solution heat treatment. This is achieved by removing grain boundary strengthening elements (3) and balancing the matrix composition to optimise strength and obtain a practical heat treatment window. The homogeneity of single crystal microstructure resulting from solution heat treatment is illustrated in Fig.1.

Rolls-Royce gas turbine engines present a wide range of applications for single crystal components. This has led to the policy of developing a family of alloys each with specific property targets. A high absolute strength blade alloy is required for increasing component life or thrust rating in many engines, particularly where there are high stresses in directions other than along the blade axis. Other applications, such as unshrouded turbines in single engined aircraft, require high ductility and impact resistance to reduce the danger of complete loss of the blade set. In advanced, high rim speed turbines, a low density alloy with high specific strength is needed to keep disc stresses to acceptable levels. Nozzle guide vanes require less creep strength, but greater resistance to thermal fatigue and environmental degradation.

Alloy Development

The targets which were set for the development of single crystal blade alloys were a 30°C creep advantage over the equivalent DS alloys at high temperature and enhanced tensile and fatigue properties. The targets for the NGV alloy were equivalent strength to DS MM002 and greatly improved resistance to oxidation, corrosion and thermal fatigue.

The alloys were designed to give a good yield of defect-free, complex castings at economical withdrawal rates in the Rolls-Royce DS furnace and to have a practical heat treatment window in excess of 25°C.

High Strength Blade Alloy

Single crystal alloy SRR99 has been developed to replace directionally solidified MM002 in applications where increased creep, tensile and fatigue strength can be used to extend component life, increase engine thrust rating or improve fuel efficiency.

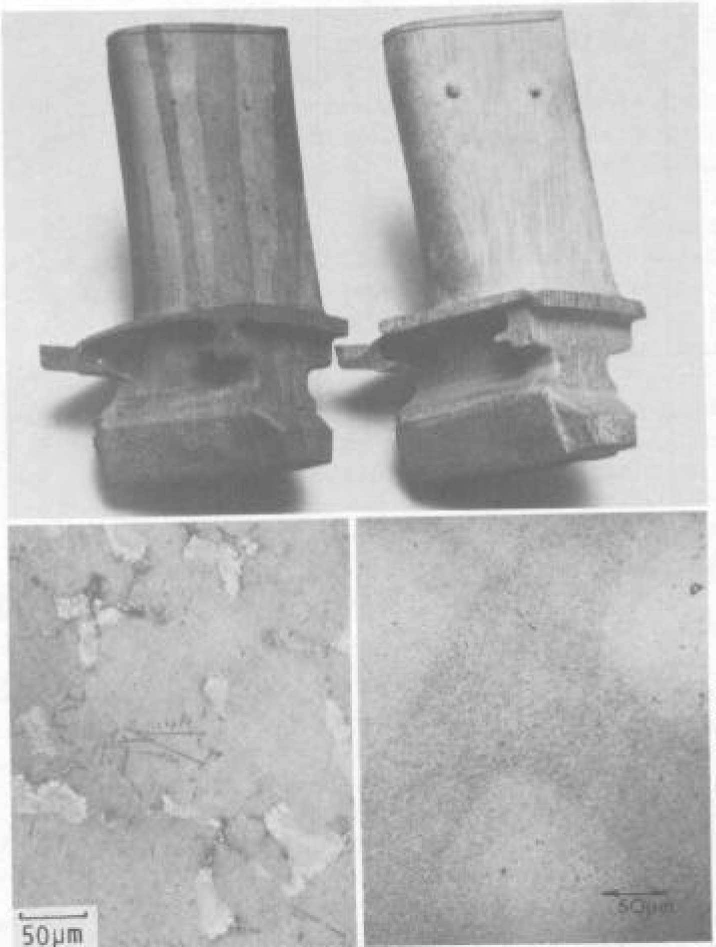
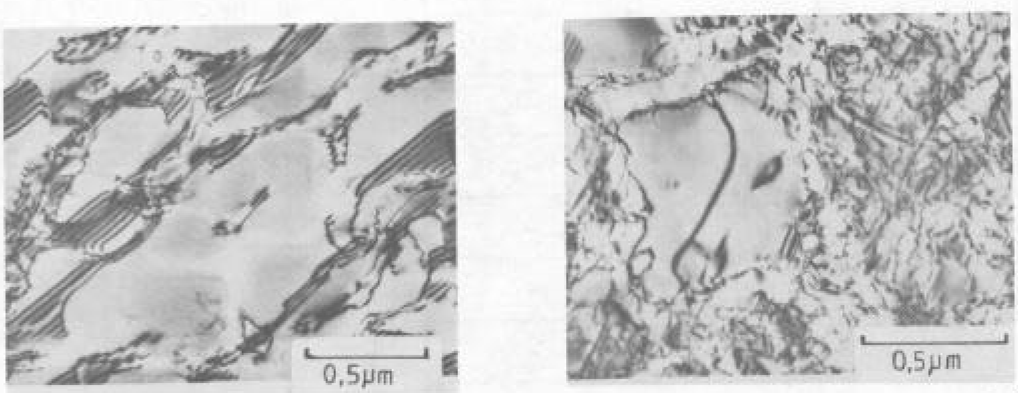


Figure 1. Microstructures and macrostructures of fully heat treated D.S. and single crystal turbine blades.

Figure 3. Complex cooled blade used as castability testpiece for single crystal alloys.



(a) (b)

Figure 2. Dislocation structures of superalloys after approximately 1% creep strain: (a) Stacking faults in γ' particles formed by the passage of a partial dislocation. (b) A pair of undissociated dislocations cutting a γ' particle and separated by an antiphase boundary.

Early trials on single crystal castings of alloys similar to MM002 showed that elimination of carbon, boron, zirconium and hafnium had the effect of raising the incipient melting point to above 1300 °C, giving a heat treatment window of some 20° - 30 °C. However, the creep advantage of the fully heat treated material over DS MM002 was very small, indicating that it is necessary to develop alloys specifically to gain maximum benefit from the single crystal process.

It was observed that creep in alloys like MM002 proceeds by one of two mechanisms, depending on the temperature. At temperatures up to about 850 °C, dislocations encountering the γ/γ' interface dissociate in the matrix and one of the partials shears through the γ', leaving a stacking fault behind it. The other partial remains in the matrix at the interface (Figure 2a). At about 850 °C the balance between stacking fault energy and antiphase boundary energy changes, and at higher temperatures it is more favourable for dislocations to pass through the γ' precipitates in pairs, separated by an anti-phase boundary of approximately 50Å in width (Figure 2b).

The individual dislocations themselves dissociate to an extent controlled by the stacking fault energy, which therefore influences the ease of cross slip.

Table 1 - Rolls-Royce Single Crystal Alloys (wt%)

	High Temp. Alloys	Low Density High Ductility Alloys	NGV Alloys
C	0.015-0.05	0-0.05	0.015-0.05
Al	5.25-5.75	5.0-7.0	4.0-6.0
Ti	1.0-2.6	2.0-5.0	1.0-4.0
Cr	8.0-10.0	8.0-15.0	10.0-16.0
Co	3.0-7.0	5.0-15.0	4.0-16.0
Mo	-	0-8.0	2.0-4.0
W	8.5-10.5	0-8.0	0-2.0
Ta	2.5-3.2	0-8.0	2.0-8.0
Nb	0-1.3	0-2.0	-
V	-	0-2.0	-
Ni	BAL	BAL	BAL

Heat treatment windows = γ' solvus - incipient melting temperature

SRR99 - 28 °C
RR2000 - 50 °C
RR2060 - 30 °C

During alloy development trials it was observed that some single crystal alloys deformed in creep by the antiphase boundary method at temperatures down to 700 °C, and that these alloys were characterised by creep lives similar to those of DS MM002. Other alloys, with longer creep lives, exhibited stacking fault deformation at low temperatures. The overall creep behaviour of an alloy is therefore dependent on both the absolute and relative values of stacking fault and antiphase boundary energies. These in turn may be controlled by the composition of the alloy: increases in the titanium and niobium content have been observed to raise the antiphase boundary energy relative to the stacking fault energy, leading to an increased tendency for stacking faults to be formed at lower temperatures. Tantalum additions have a similar but much less marked effect.

Single crystal SRR99 has been formulated to ensure that the anti-phase boundary energy is high, so the stacking fault mode of creep deformation occurs at temperatures up to about 850 °C, and there is a good creep advantage over DS MM002. In addition it has been designed to have good castability in the Rolls-Royce DS furnace, a wide heat treatment window, and metallurgical stability. Alloy design has involved principally the balancing of the titanium, tantalum and cobalt levels (Table 1) (4)

SRR99 has achieved its high strength targets, with creep lives at least ten times those of DS MM002 at 1000 °C, and at least 15% improvement in yield and low cycle fatigue strength at 800 °C and above. It has been demonstrated to have the ability to produce, at economical rates, a high yield of defect-free complex component castings in the Rolls-Royce DS furnace, and has a heat treatment window of 28 °C.

Low Density Blade Alloy

Work carried out by Rolls-Royce during the 1970's to develop alloys suitable for directional solidification indicated that alloy compositions designed for densities less than $8 kg/dm^3$ and based on Al + Ti contents greater than 8%, possessed high intermediate temperature strength and high ductility. There are several applications where these characteristics offer distinct advantages over more conventional high temperature DS and single crystal alloys. Examples are high rim speed shroudless turbines requiring high specific strength and situations where wrought material replacement is required without loss of impact resistance for single engine aircraft.

The development of the low density DS alloys for single crystals resulted in alloy RR2000 (Table 1) (5). The principal features of its composition are:-

(i) Alloy hardening by a stable gamma-prime precipitate of the form $Ni_3(M)$ where M is Al,Ti,Nb,Ta,V. The combination of these elements is balanced to give minimum atomic mismatch with the gamma matrix.

(ii) Refractory elements W,Ta,Mo are limited to a combined maximum of 8%.

(iii) Corrosion resistance is obtained by Cr additions not less than 8%.

(iv) Co is added to balance the composition to maintain freedom from deleterious phases and to give additional matrix strength.

(v) The heat treatment window is improved by the addition of V.

This alloy is characterised by a wide heat treatment window; RR2000 has a practical window of 50 °C. In terms of creep strength RR2000 demonstrates a significant improvement over DS material at all temperatures and is particularly strong in the 850 - 950 °C temperature range. The specific strength is only slightly lower than SRR99 at high temperatures. In common with all single crystal alloys tested by Rolls-Royce, RR2000 shows an impact ductility trough in the 700 - 800 °C region, however the overall impact resistance is some three-fold greater than typical single crystal alloys and is in excess of wrought nimonic 115.

The addition of vanadium to these alloys has been found to be beneficial for strength and has the added advantage of widening heat treatment windows. It does, however, adversely affect oxidation resistance. Nevertheless, tests on single crystals containing up to 1% of this element show little difference in oxidation and corrosion resistance compared with DS material.

Nozzle Guide Vane Alloy

The primary property requirements for an uncooled nozzle guide vane material are high temperature creep life, intermediate temperature tensile strength, and good resistance to hot corrosion attack. For a cooled vane operating at higher gas temperature, oxidation, hot corrosion and thermal fatigue resistance are most important. In addition to these features, ease of manufacture of complex-shaped components is necessary.

RR2060 has been developed to satisfy all these requirements. By adopting for the manufacture of vanes the seeding technique, which allows full, three-axis control of orientation, the low Youngs modulus <001> crystallographic directions can be aligned with the directions of greatest thermal strain, thereby reducing thermal stresses and conferring increased thermal fatigue resistance. The high creep ductility of single crystal alloys (approximately twice that of equiaxed material) also contributes to this advantage.

In order to keep process costs to a minimum and to ensure long component life without the need for repair, RR2060 has been formulated for good uncoated resistance to both high temperature oxidation and to hot corrosion at intermediate temperatures. This has been achieved by suitably high aluminium and tantalum contents for oxidation resistance, and a chromium level in excess of 10% for hot corrosion resistance. Good creep strength over the range of service temperatures is ensured by balancing the precipitation hardening provided by aluminium, titanium and tantalum, and the solid solution strengthening of tungsten and molybdenum. Cobalt once again is used to balance and stabilise the chemistry. The requirements for good castability and a practical heat treatment window have also been addressed in alloy design (Table 1) (6).

RR2060 has achieved the targets set for a single crystal nozzle guide vane alloy. It has a heat treatment window of approximately 30°C, and its creep and tensile properties are close to those of DS MM002. It has at least twice the thermal fatigue and oxidation resistance of DS MM002, and its hot corrosion resistance is superior to that of current NGV alloys such as C1023.

Properties of Rolls-Royce Single Crystal Alloys

Castability

Single crystal materials must not only show improved mechanical properties, but must also possess good processability in order that components can be produced economically and with guaranteed consistent properties. As described in Goulette's paper "Cost Effective Single Crystals: The Rolls-Royce Approach" (7), the Rolls-Royce DS furnace design features a high temperature gradient mould heater, which minimises thermal convection. As a consequence, a wide range of compositions can be considered without the risk of unacceptable chemical segregation. The criteria for good castability are freedom from stray grain and sliver formation, chemical segregation and porosity. The alloy must also be able to develop its single crystal structure at economical mould withdrawal rates.

In order to assess the castability of single crystal alloys a castability test piece based on a complex cooled turbine blade is used. This blade (Fig 3) is characterised by thin wall sections (0.030") with complex internal cooling passages. The test piece highlights tendencies towards microporosity, hot cracking, and stray grain nucleation at section changes. Alloys are assessed according to their freedom from defects using this test piece cast at economical rates. The Rolls-Royce alloys pass these castability criteria.

Heat Treatability

The heat treatment of single crystals is a critical operation. The process is essential to develop the full property potential of material, and design data is based on correctly heat treated material. Commercial heat treatment practice incorporates allowances for temperature excursions either side of a heat treatment band. The design of single crystal alloy compositions must allow for the inaccuracy of temperature measurement and achievable consistency of temperature control. The Rolls-Royce alloys are designed with a minimum heat treatment window of 25°C. This is defined as the temperature difference between the gamma prime solvus and incipient melting point obtained following commercial heat treatment practice. Details of the temperature windows are given in Table 1, together with the compositions of Rolls-Royce alloys.

Mechanical Properties

In general terms, the crystallographic direction that offers the best balance of mechanical properties is the direction of preferred crystal growth, <001>. The properties reported here are the results of tests performed on specimens with the stress axis within 10° of the <001> direction. The materials were in the fully solution treated and aged condition.

Strength. Both single crystal blade alloys, SRR99 and RR2000, offer significant improvements over DS castings with respect to creep resistance and tensile strength (Figs 4 and 5). The creep strength improvement is greatest at high temperatures ($\geq$1000°C) and SRR99 demonstrates a temperature advantage of up to 50°C over DS MM002 with a ten-fold improvement in creep life at these temperatures. This advantage in creep has been confirmed by engine testing. Fig 6. illustrates the difference in creep growth between DS and single crystal blades engine-tested at a high stator outlet temperature for the same period of time.

RR2060 has not been developed for maximum strength, as the chemistry has been selected for corrosion and thermal fatigue resistance. Nevertheless the creep strength of this alloy approaches that of DS MM002 material.

Fatigue. Low cycle fatigue, vibration and thermal fatigue resistance of the blade alloys are all improved by at least 10% compared with DS material. This is due to a combination of crystal structure and the removal of microstructural crack initiation sites. The NGV alloy has twice the fatigue life of DS MM002 when tested under thermal cycle conditions using a turbine combustor heating rig (Fig 7).

Impact Ductility. Impact resistance is not normally considered a design feature by alloy designers, however, there are special applications where the loss of impact strength could affect the reliability of an aircraft. For such applications RR2000 is the preferred alloy, as it can match more conventional alloy compositions for intermediate temperature strength, but has impact strength equivalent to or better than wrought

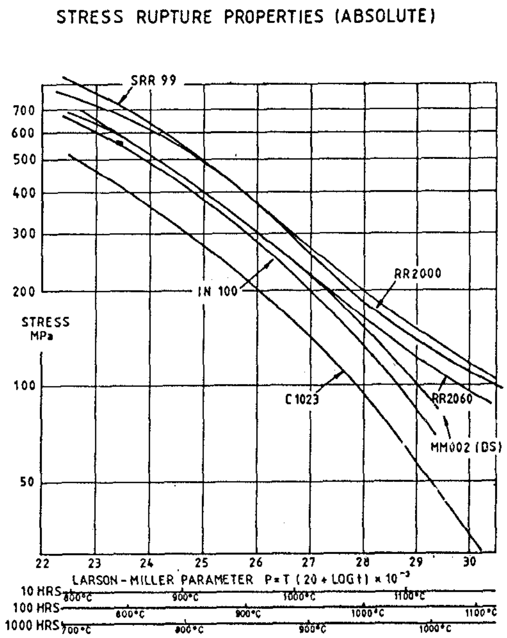


Figure 4. Larson-Miller parameter curve comparing the stress rupture lives of directionally solidified and single crystal alloys with conventionally cast alloys

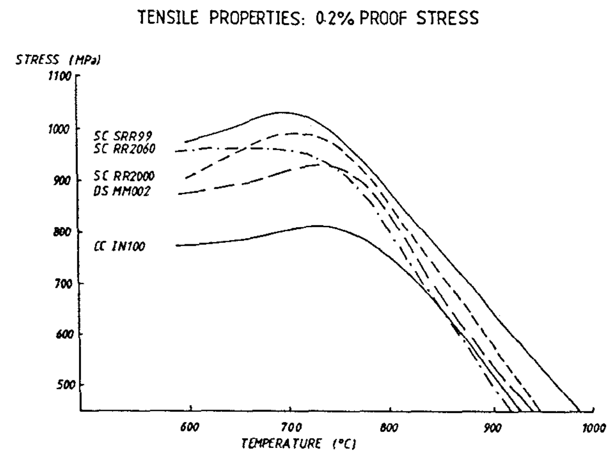


Figure 5. Comparison of the 0.2% proof stress of directionally solidified and single crystal alloys with conventionally cast IN100.

superalloys. Fig 8 compares the impact resistance of RR2000 to wrought nimonic 115, and conventionally cast, directionally solidified and other single crystal alloys.

Surface Stability

In general it has been the experience of Rolls-Royce that single crystal materials are inherently better in oxidation and corrosion resistance to the equivalent composition in DS or equiaxed form. This effect is due, at least in part, to the increased homogenisation of the microstructure and the absence of grain boundaries.

For blade applications the compatibility of the base alloy with oxidation resistant coatings is of significant importance. The performance of aluminide coatings on SRR99 and RR2000 is compared in Fig 9(a) with that on DS MM002 and equiaxed IN100, showing the advantage of the single crystal alloys.

The uncoated oxidation and corrosion resistance of equiaxed C1023, DS MM002, and single crystal SRR99 and RR2060 are also compared in Figure 9(b)&(c). As expected, the resistance of SRR99 is very similar to that of MM002, but that of RR2060 is far superior to that of the other alloys.

Single Crystal Blade/D.S.Blade
Fig 6. D.S. and single crystal blades engine tested at high stator outlet temperature showing difference in creep growth.

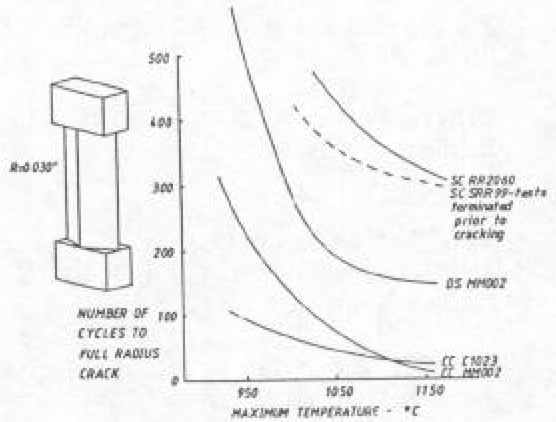


Figure 7. Comparison of thermal fatigue rig performance of conventionally cast (C.C.) directionally solidified (D.S.) and single crystal (S.C.) alloys.

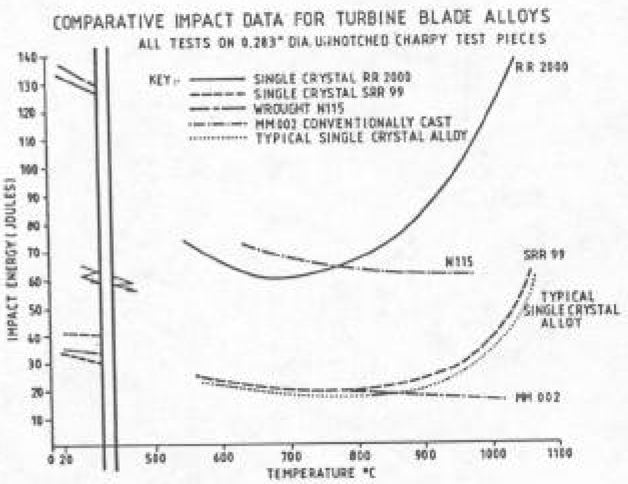
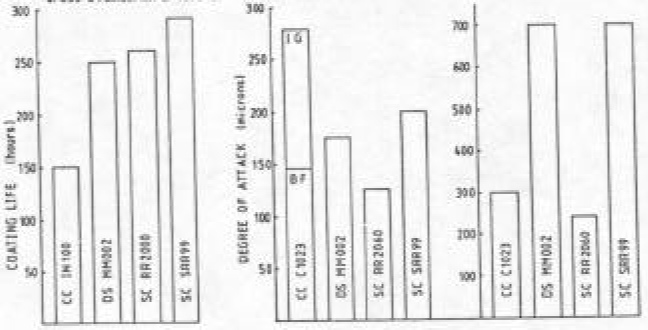


Figure 8. Comparison of impact strength of wrought, conventionally cast and single crystal alloys.



(a) (b) (c)

Fig 9. (a) Life of 45micron pack aluminide coating on conventionally cast, D.S., and single crystal alloys. (b) Salt promoted oxidation attack (I.G = inter-granular, B.F = broad front). (c) Corrosion controlled attack.

REFERENCES

1. B.J.Piearcey and F.L.VerSnyder, Journal of Aircraft, Vol 3, No.5, 1966, p.390.

2. F.L.VerSnyder and M.E.Shank, Materials Science and Engineering, Vol 6, No 4. 1970, p.231.

3. F.L.VerSnyder and M.Gell, Fundamental Aspects of Structural Alloy Design (ed R.I.Jaffee and B.A.Wilcox, Plenum Press, New York) 1977, p.209.

4. G.W.Meetham, M.J.Goulette, R.P.Arthey and R.G.Roome, UK Patent Application 8,223,353 (Publication number 2,106, 138A) US Patent Application 303,581.

5. A.D.Hill, D.A.Ford, M.J.Goulette and R.P.Arthey, UK Patent Application 8,223,815 (Publication number 2,105,369A) US Patent Application 416,008.

6. G W.Meetham, M.J.Goulette and R.P.Arthey, UK Patent 2,073,744, US Patent Application 528,844.

7. M.J.Goulette, R.P.Arthey and P.D.Spilling, to be presented at the Fifth International Symposium on Superalloys, Champion Pa. (AIME 1984).