THE PRODUCTION OF ADVANCED TURBINE BLADES

FROM P/M SUPERALLOY FORGING STOCK

I.C. Elliott[+], C. Cockburn[+] and S.W.K. Shaw[++]

[+] Inco Alloys Limited, Holmer Road, Hereford, U.K.
[++] Inco Engineered Products Ltd., Wiggin Street, Birmingham, U.K.

Abstract

Powder metallurgy nickel based superalloys are frequently used in advanced aero engine gas turbines, but nevertheless are becoming of interest to more down to earth applications where high material integrity and enhanced properties can also be cost effective. Thus, for instance, increasing quantities of corrosion resistant tubing and tool steels are being produced by P/M routes. Another area of interest is that of blades for land based gas turbines. This paper describes the development of the nickel based superalloy APK6, a modified P/M version of the corrosion resistant casting alloy IN792, which possesses creep rupture strength superior to cast IN792 at 650 to 750°C together with fatigue resistance over two times greater than IN738 LC at 600°C and equivalent to wrought NIMONIC* alloy 90.

* NIMONIC is a trademark of the Inco family of Companies.

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Introduction

The continual increase in the severity of gas turbine operating conditions has led to a progressive replacement of forged turbine blades from the first row of the high pressure turbine backwards to the lower temperature regions by cast blades in order to obtain increased creep and corrosion resistance and take advantage of the greater complexity of cooling passages which can be achieved in a casting. However, for the rear rows of blades, which in an industrial gas turbine can be very large, cooling is no longer necessary or even desirable and forged blades may then be preferred for their superior fatigue resistance, but forging such components from complex alloys presents certain difficulties.

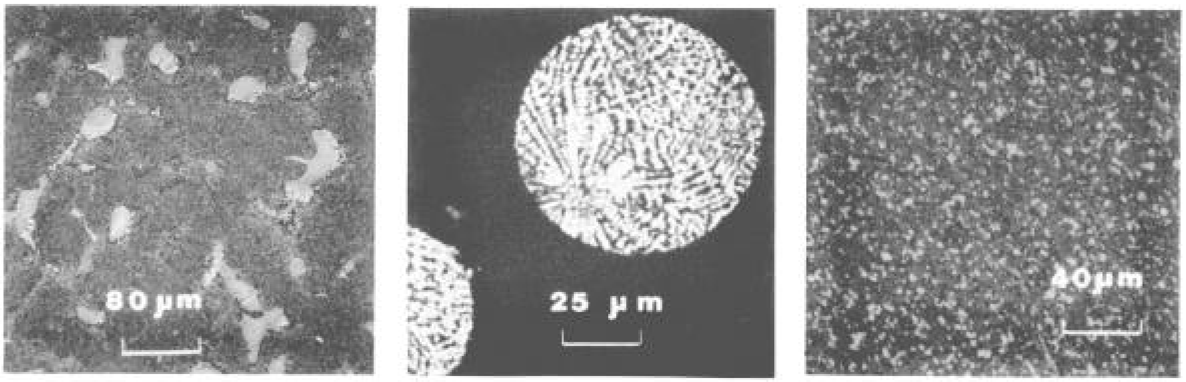
Similar problems have been encountered in the development of alloys for gas turbine discs, particularly for aero-engine applications. Increasing thrust and efficiency requirements demanded greater tensile and creep strength which could be achieved, initially, by moving from steels to wrought nickel based superalloys. Further alloying of these materials resulted in increasing problems of segregation and forgeability, such that radical changes in manufacturing routes became necessary.

The solution to these problems has been found in inert gas atomised powders, which on compaction provide homogeneous billets for disc forgings and for the same reasons a powder version of a highly alloyed nickel based alloy previously developed for casting applications is being studied for large forged turbine blades in the rear rows of industrial gas turbines.

The P/M Approach

Before describing the current blade alloy development, the advantages of the powder metallurgy approach will be considered in more detail. The inert gas atomisation process uses the kinetic energy of a high velocity stream of a gas such as argon to fragment a stream of molten alloy into spherical droplets. Due to their size, which is typically less than 250 microns in diameter, and the quenching effects of the high volume of cold gas the droplets solidify rapidly to give, in effect, very small, spherical, segregation free ingots. The refinement of microstructure due to the high solidification rate can be translated to the bulk form by a suitable compaction process such as hot isostatic pressing or extrusion, resulting in homogeneous, albeit highly alloyed forging stock. Indeed, in some cases the grain size of the compacts is so fine that the material is superplastic and is ideal for isothermal forging.

The structure of a conventionally cast nickel based superalloy IN792 (nominal composition 12.4% Cr, 9% Co, 2% Mo, 3.9% W, 3.9% Ta, 4.5% Ti, 3.1% Al, balance Ni) is illustrated in Figure 1a and shows a coarse dendritic pattern typical of this type of alloy. In the solute rich interdendritic regions which are last to solidify, areas of degenerate gamma - gamma prime eutectic form together with concentrations of primary carbides, and such highly alloyed and segregated structures are very difficult to hot work. In contrast, the same alloy produced as inert gas atomised powder shows a considerably more refined microstructure in the powder particles (Fig. 1b) which when



(a) (b) (c)

Figure 1 - Microstructural appearance of (a) as-cast (b) inert gas atomised powder and (c) HIP plus extruded powder alloy IN792.

HIPed and extruded results in an extremely homogeneous microduplex gamma - gamma prime structure (Fig. 1c) with none of the deleterious segregation features which are characteristic of the cast version. It will be shown later that this microduplex structure can be highly forgeable.

In order to take full advantage of refined microstructures that can be generated by the atomisation process, a high level of process development and quality assurance is required (1). Principally, the Inco Alloys Limited atomisation unit consists of a 500 kg capacity vacuum induction furnace mounted on top of an atomisation tower some 6 metres high. A feature of the powder handling equipment is the ability to prevent the powder coming into contact with air throughout the sequence from raw materials to finished compact. The atomised powder is cooled and stored under argon until all quality control checks have been performed. The powder is then sieved and blended before being transferred to the degassing unit. Here the powder is degassed under vacuum in order to remove any absorbed gases. Still under vacuum the powder passes into cans which are sealed when full, by means of a hydraulic crimp welder.

Perhaps the single most important factor which has emerged from the development of Ni-based atomised powders is the great importance that non-metallic contaminant inclusions have on the ultimate performance of products made from pre-alloyed powder. As most pre-alloyed powder development work has been directed towards the production of gas turbine discs the effect of these inclusions has been most apparent in reducing the fatigue life of the component (1), but this is also true for large turbine blades. The types of inclusions that may be found in pre-alloyed powder are both numerous and varied; the following is only a short list of the types and morphologies that can be found:-

i) fine (~ 20 um) stable oxide particles arising from deoxidation of melts.

ii) coarse (~ 50 um) stable oxide particles arising from furnace linings and raw materials.

iii) coarse reducible oxide particles arising from melting practices.

iv) varied inorganic particles arising from pollution of powder handling equipment for example rust, cement, weld slag etc.

v) varied organic particles arising from powder handling equipment for example vacuum seals, vacuum pump oils, plastic tubing.

vi) coarse metallic contamination from other alloy powders.

For the optimum properties in P/M alloys it is therefore necessary to control rigorously the content and size of inclusions. This is achieved by minimising the number of sources, thorough cleaning of equipment or the dedication of equipment, the sealing of equipment from environmental pollution, careful control of raw materials, material handling equipment, melting practice and indeed, the very design of the equipment in order to facilitate cleaning etc. The effects of the latter two points on the non-metallic inclusion content of a Ni-based P/M disc alloy NIMONIC alloy AP-1 as measured by the water elutriation technique is illustrated in Figure 2, following the installation of the atomisation equipment in 1976.

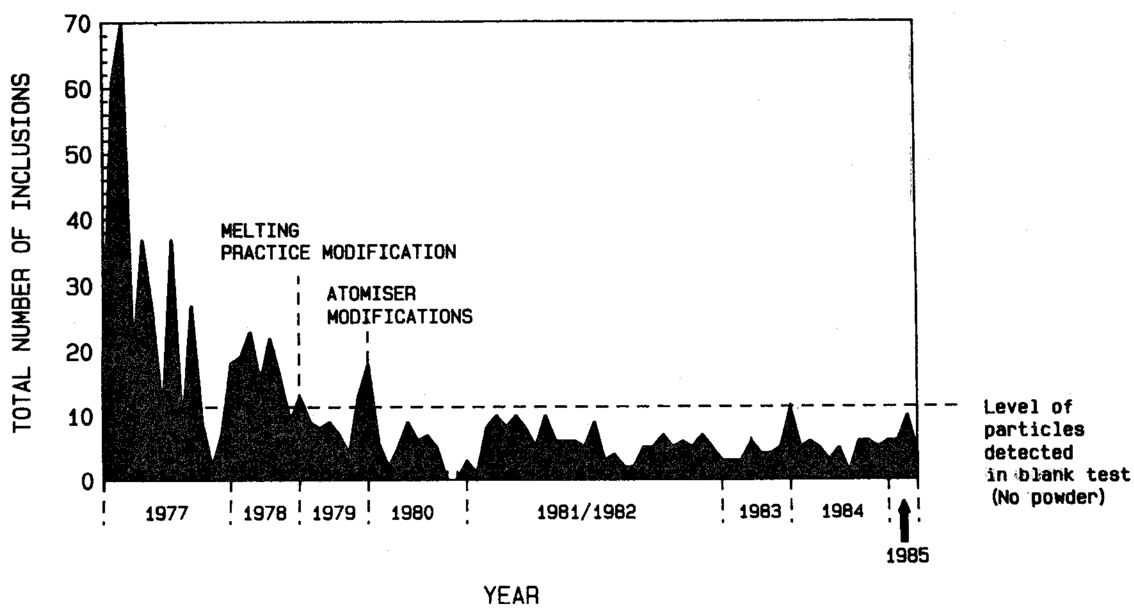


Figure 2 - Total number of inclusions found by water elutriation in the +106/150 micron fraction of a 0.5 kg sample of powder NIMONIC alloy AP-1 over the period 1977 to 1985, illustrating the effects of melt practice and atomiser modifications on powder contamination levels.

Similar reductions in inclusion content may be achieved by the introduction of such practices as melt filtration using reticular ceramic foam filters. This is particularly effective in minimising the number of fine inclusions arising from deoxidation (Fig. 3) as shown by the reduction in numbers of inclusions found metallographically in an extruded powder bar after filtration was introduced in 1982.

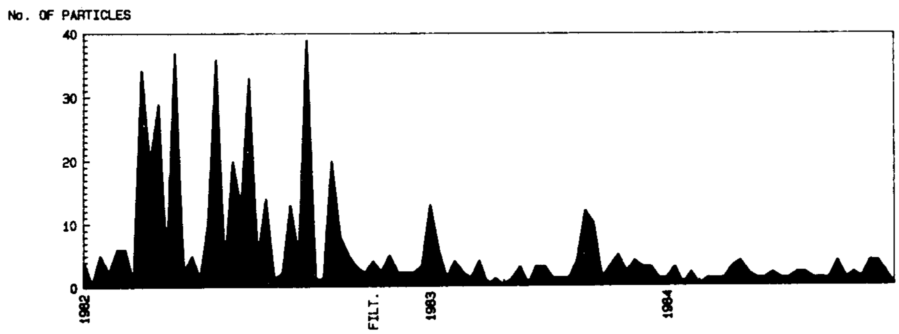


Figure 3 - Total number of particles less than 0.2 mm in length found metallographically in extruded power NIMONIC alloy AP-1 between the years 1982 and 1984, illustrating the effect of introducing melt filtration on powder contamination levels.

Ultimately therefore one has to rely on the highest standard of production housekeeping and quality control testing to ensure the integrity of the finished component. To put the problems in perspective, current quality standards equate to finding one inclusion in about a hundred million powder particles. The techniques available include visual and metallographic inspection, water elutriation, electrochemical machining and ultrasonic testing.

Choice of Alloy

Since the application in this case is to be industrial gas turbine blades, the choice of alloy was based largely on the balance of corrosion resistance and high temperature strength. The detailed reasoning for the current alloy choice is given elsewhere (2). However, as many cast blades for this type of application are in IN738LC, the target is similar corrosion resistance at 650-750^{o}C but with a higher strength level than can be achieved by IN738LC (3). Alloy IN792, a Ni-Cr-Co casting alloy strengthened with W, Ta, Ti and Al, was identified as having the necessary balance of properties.

It has previously been demonstrated (4) that by moving to a P/M route for this alloy reducing carbon and correspondingly the carbide forming element Ta and Ti resulted in improved stress rupture properties. However, further enhancement was achieved by optimising the (Ti + Al) content (2) such that maximum intermediate temperature stress rupture strength occurs at a (Ti + Al) content of 8% (Fig. 4).

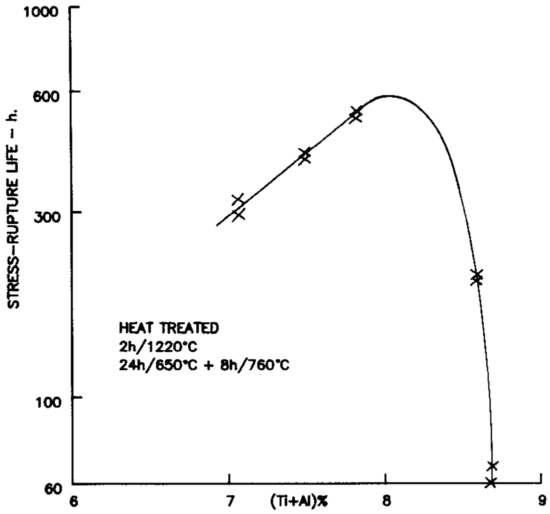


Figure 4 - Effect of (Ti + Al) content on S/R life of P/M IN792 at 740 MPa/700°C

0.03%C, 12.5%Cr, 9.0%Co, 2.0%Mo, 3.9%W, 3.0%Ta, 4.6%Ti, 3.4%Al, 0.10%Zr, 0.01%B, bal.Ni.

Table 1 - Chemical Composition of alloy APK-6

The resulting powder alloy, designated APK-6 therefore has the composition given in Table 1.

Production of Forging Stock and Blades

Laboratory extrusions of powder alloy APK-6 showed that high levels of ductility could be achieved with extrusion temperatures below about 1120°C (Fig. 5). The precise

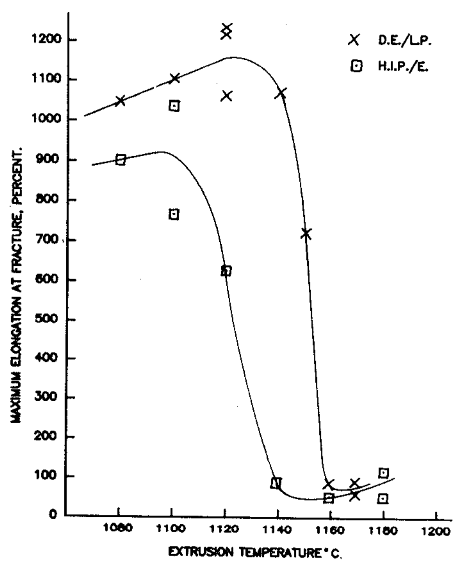


Figure 5 - Variation of maximum hot tensile elongation with extrusion temperature.

conditions under which this maximum ductility occurs for a given extrusion temperature may vary depending on extrusion ratio (2). However, it is clear that under certain circumstances alloy APK-6 exhibits superplastic behaviour and that higher maximum ductilities are achieved with direct extruded loose powder than for powder initially consolidated by hot isostatic pressing prior to extrusion. This may be explained by the finer microduplex structure which forms by loose powder extrusion compared to a somewhat coarser structure in the case of HIP/ extrude generated from the HIP structure, in which initial recrystallisation of the cellular powder particles has already taken place during HIPing rather than on extrusion.

Full scale extrusion was therefore carried out using direct extrude, canned powder billets in a Loewy 5000 tonne horizontal press at 1120^{o}C and an extrusion ratio in excess of 30 to 1. The resulting bar was decanned, machined and ground to 30 mm diameter!

As with the laboratory extruded material high hot tensile elongations were observed.

Tests were carried out to determine 'm-values' using the step- wise technique with a few check tests at critical strain rates. A typical curve for hot ductility versus temperature is shown in Figure 6. Figure 7 illustrates the 'm-values' obtained at the temperature of maximum ductility (T) and at T plus and minus 40^{o}C. It is generally accepted that if the m-value approaches 0.5, then the material is superplastic. For these extruded bars of APK-6 values up to 0.64 have been recorded.

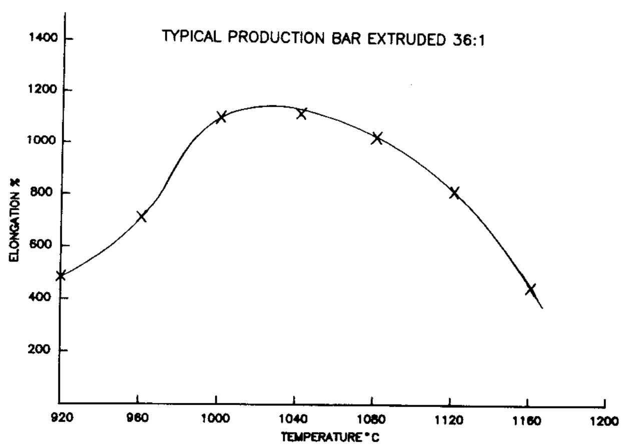


Figure 6 - Variation of hot tensile elongation of APK6 with temperature.

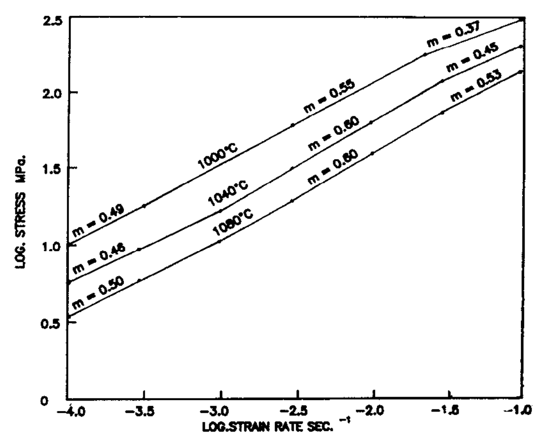


Figure 7 - Strain rate sensitivity of flow stress (m) for APK6.

While the ultimate aim of this development is to produce larger diameter forging stock for turbine blades 450-650 mm in length, the current intermediate phase was targeted on an existing rear row power turbine blade 180 mm long for a 5000 HP industrial gas turbine. Slug lengths of the 30 mm diameter APK-6 were therefore partially extruded to the preform for the aerofoil and root block of this blade. This is a critical step in the process, the main variables being forging temperature, speed and lubrication. The preforms were subsequently closed die forged to fully develop the aerofoil (Fig. 8).

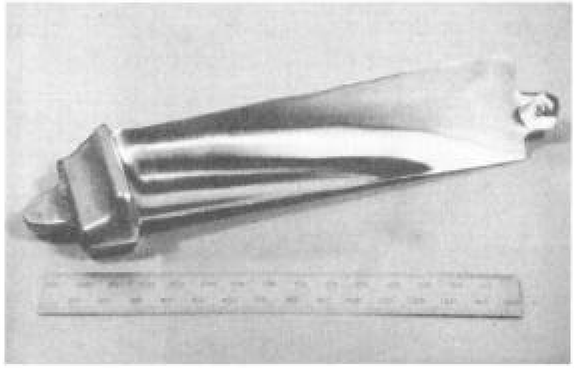


Figure 8 - 180 mm long forged APK-6 turbine blade for rear row of an industrial gas turbine.

Mechanical Properties of APK-6

Only a limited number of turbine blades were available for cut-up testing at this stage, as a considerable number are required for an engine test. Furthermore, it is only possible to machine a few small samples from each blade. The main property database has therefore been generated using slab forged starting stock. 85 mm long slugs of the 30 mm diameter APK-6 were side forged at 1080°C to produce slabs 13 mm thick, from which test samples were machined.

The gamma prime solvus temperature of APK-6 has been determined as 1205°C. A heat treatment was developed using a ramped solution treatment including a 2 h period at 1220°C. The reverse ageing heat treatment employed for NIMONIC alloy AP-1 discs of 24 h/650°C + 8 h/760°C has been used as the temperature of application is similar, although it is doubtful if this is optimum. Comparative long time stress-rupture results at 700°C for an earlier 7% (Ti + Al) alloy and APK-6 are given in Figure 9 which suggests that a target life of 50,000 h at 450 MPa can be met. APK-6 is compared with conventionally cast (C-C) IN-792

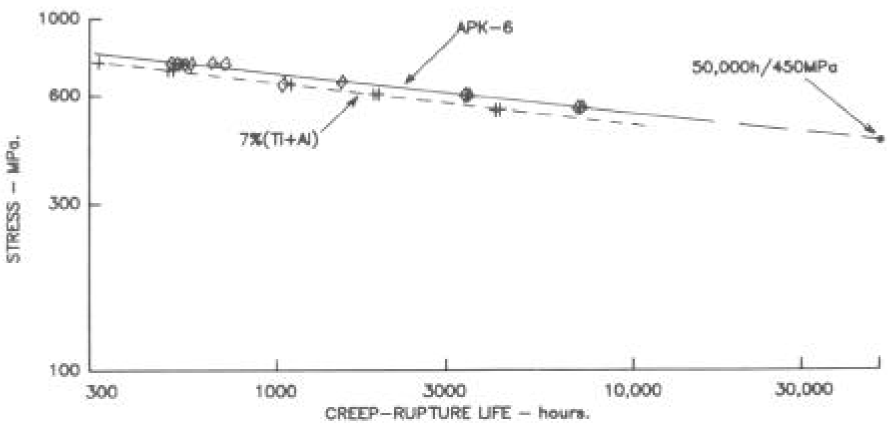
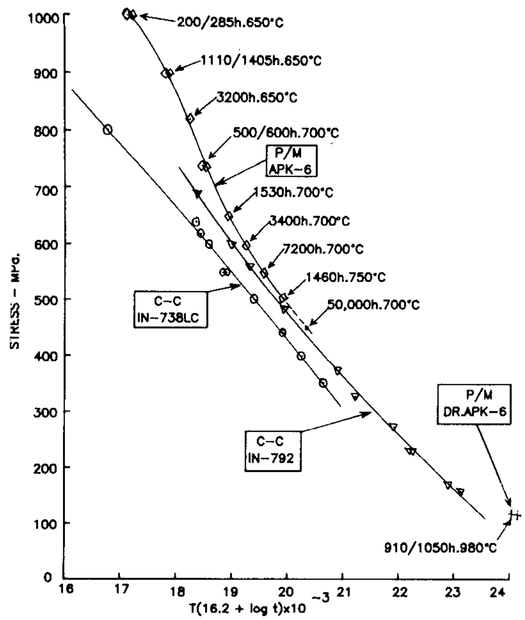


Figure 9 - Creep rupture properties of APK-6 at 700°C

and IN738LC in Figure 10 where it is seen that at high stresses and temperatures up to 750°C APK-6 is superior to C-C IN-792.



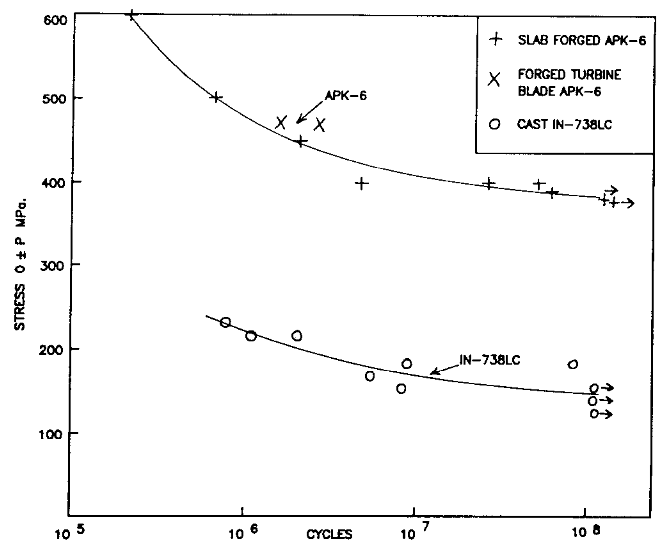


Figure 10 - Comparison of stress rupture properties of cast IN-738LC and APK-6

Figure 11 - Fatigue properties of APK-6 and IN738LC at 600°C, 0 +/- P

The main reason for considering P/M superalloys for forged rear row blades is for fatigue resistance, in combination with high stress-rupture strength and corrosion resistances. The latter 2 could nearly be provided by a C-C blade if satisfactory investment castings could be produced in so large a blade in the very difficult to cast, strongest alloys such as IN-792, but the fatigue resistance of C-C materials is always markedly inferior to those of forged materials. Figure 11 compares the fatigue resistance at 600°C, stress O +/- P of IN738 LC C-C in ideal carrot-shaped test bar blanks with those of APK-6 extruded and slab forged. Duplicate results are also shown for fatigue specimens cut from a 180 mm long forged blade of APK-6 showing that the forged blade possesses slightly superior fatigue resistance to the slab forgings which themselves equalled the fatigue resistance of the highly fatigue resistant forged alloy NIMONIC alloy 90.

Conclusions

1. The high quality standard production routes developed for inert gas atomised powder aero engine disc alloys can be applied to powder alloys for other components where high integrity is required, such as turbine blades.

2. A P/M superalloy, APK-6 has been developed from the casting alloy IN-792 which provides an improved combination of mechanical properties and hot corrosion resistance.

3. Extrusion compaction of powder APK-6 produces a forgeable alloy which under certain circumstances exhibits superplastic behaviour.

4. A forging route has been developed for a 180 mm long rear row turbine blade for a small industrial gas turbine. Development continues to produce forging stock for 450-650 mm long blades.

5. The stress-rupture strength of APK-6 is superior to cast IN 792 at 650^{o}C to 750^{o}C and from extrapolation of tests out to 7200 hr at 700^{o}C appears likely to meet a target life of 50,000 hr at 450 MPa/700^{o}C.

6. The fatigue strength of extruded and forged APK-6 is at least 2 1/2 times that of conventionally cast IN-738LC.

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