THE MANUFACTURE AND EVALUATION OF A LARGE TURBINE

DISC IN CAST AND WROUGHT ALLOY 720Li

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Abstract

The new generation of large high thrust aero-engines, such as the Rolls-Royce Trent, lead to ever increasing demands on materials. In particular as the requirements on turbine discs become more stringent traditional alloys such as IN718 and Waspaloy become less viable choices. To meet the more demanding requirements highly alloyed, high strength materials will be required. One such alloy is alloy 720Li, which is available in the powder or conventionally processed cast and wrought form. Recent developments in the manufacture of good quality Cast and Wrought billet at relatively large diameters (230mm and 250mm) has led to it being a cost effective choice for meeting turbine disc requirements.

A successful development programme has already been completed approving alloy 720Li billet and forging routes for a relatively small diameter turbine disc (450mm diameter). This paper will discuss the potential ability to scale-up the technology to be applicable to large civil engines. A large (840mm diameter) Intermediate Pressure Turbine Disc (IPTD) was selected for the exercise. The increase in the size of the forging is illustrated by comparison of the forging mult weight increase from typically 160Kgs to 500Kgs for the IPTD.

The manufacture and test of IPTD forgings will be discussed in detail. A key to the success of the evaluation was the use of numerical process modelling by the forgemaster. A number of tools were available to aid the design of the forging route, which not only enabled microstructural and property targets to be met, but achieved at the first attempt with confidence.

Two forgings were successfully manufactured meeting all of the release requirements normally defined for the alloy. One of the forgings was subsequently selected for full cut-up evaluation of macro/microstructure and

mechanical properties. The results from the macro/microstructural evaluation revealed the required structure had been fully generated, with a recrystallised grain size of ASTM 9-10. This was consistent with previous experience of the alloy. A full suite of mechanical testing was carried out from tensile testing through to the measurement of the crack propagation rate. In all cases the results were found to be comparable with previous experience for the alloy. The results will be compared to the forging manufactured in Waspaloy.

It was concluded that there was no debit in terms of mechanical properties, or degradation of macro/microstructure at the increased forging size, albeit with similar section thickness. The successful outcome of the programme has generated confidence that large disc forgings can be manufactured from existing cast and wrought alloy 720Li billet diameters.

Introduction

Alloy 720Li is a high strength nickel based alloy which has been identified as a turbine disc material to meet the ever increasing demands imposed by the new large, high thrust aero-engines. The alloy is available in both the powder form (1) and the conventional cast and wrought form. A successful development programme has previously been completed approving the alloy 720Li billet and forging routes for a relatively "small" diameter forging (450mm diameter) (2).

This paper will discuss the programme carried out to scale-up the technology to large turbine disc forgings. A large civil engine IPTD was selected as a suitable evaluation forging (840mm diameter) which is currently manufactured in Waspaloy.

The choice of this part led to an increase in billet input weight from previous experience (160 Kgs) to some 500 Kgs for the IPTD forging. This represented a significant challenge to

the forgemaster, particularly as the billet diameter was restricted to 250mm diameter. The use of numerical process models was key in designing the forging route, ensuring 'right first time' manufacture was achieved.

In addition to testing the forgemasters capabilities, the large forging represents a significant metallurgical challenge. A particular concern is the effect of quench cooling rate on the disc properties. It is known that a reduced cooling rate will decrease material strength, as shown in Figure 1. Additional areas of concern regard the generation of the required microstructure and achieving the desired levels of ultrasonic inspection.

A full metallurgical evaluation of the disc forgings was completed to allow comparison to the existing experience of the alloy. Any degradation in terms of macro/microstructure and mechanical properties as a result of the scaling-up in size would be determined. Furthermore, a comparison was made to the disc as manufactured in Waspaloy. The billet material for the evaluation was produced by Teledyne Allvac and the forging carried out by Wyman Gordon Ltd.

Figure 1: Effect of cooling rate from solution heat treatment temperature on ultimate tensile strength

Material

Alloy 720Li is a high strength nickel material, its composition is given in Table 1. The development of the alloy from a wrought blade alloy for land based turbine applications is well documented (3). Being a highly alloyed, high strength material it is inherently difficult to process through the cast and wrought route. Early attempts at processing the alloy centred on double melt (VIM-VAR) processing and was limited to small diameter billet, up to 160mm. The early material was prone to segregation showing a variable

microstructure. Disc forgings produced from such material showed very variable structures which failed to meet microstructural targets (4).

Table 1: Composition of alloy 720Li by weight %

	C	B	Cr	Co	Mo	W	Ti	Al	Zr	Ni
Nominal										
U720Li	0.15	0.15	16.0	15.0	3	1.25	5.0	2.5	0.03	Bal
Heat										
BT34-2	0.11	0.17	16.03	14.41	3.04	1.19	4.95	2.57	0.05	57.48

The development of conversion routes based on triple melt material (VIM-ESR-VAR) overcame many of the problems initially encountered. The addition of the ESR stage results in improved quality as well as a sound electrode to go into VAR. This in turn allows an improved VAR ingot in terms of structure and chemical segregation for final thermomechanical conversion to finished billet. The triple melt route also has the significant advantage of improving the cleanliness of the billet compared to double melt material (5).

The manufacture of good quality billet is key to the manufacture of acceptable forgings and is subject to continued development by the material suppliers. Figure 2 shows a macroslice from a 250mm diameter billet used to manufacture the IPTD. A featureless macrostructure is observed with no deleterious features evident.

The microstructure is typically ASTM 8 to 9, Figure 3 shows some grain size variation and banding of the γ' is also present due to persistent solidification segregation which has not been broken down through billet conversion. This standard of billet has previously been found to produce acceptable forgings.

Forging Route Development

Numeric Modelling Considerations:

The need to gain competitive advantage by reducing the 'development to market' cycle time in the forge industry has led to the introduction of a number of numerical tools for the forgemaster, which enable the simulation of both forge and heat treatment processes to be carried out with confidence, thus reducing or obviating the need for expensive and time-consuming prototyping trials. Each of these processes may be simulated to achieve various objectives, with increasing degrees of complexity:

- a) Forge modelling objectives:
 - i) Die fill / load prediction
 - ii) State variable prediction (temperature, strain, strain rate)

Figure 2: 250mm diameter billet slice after macro-etching
(immersion etched in acidified ferric chloride)

- iii) Microstructural prediction
(qualitative or quantitative)
- iv) Property correlation
- b) Thermal modelling objectives:
 - i) Cooling rate optimisation
 - ii) Quench stress reduction
 - iii) Property correlation
 - iv) Residual stress determination

A number of validated commercial packages are available to the forgemaster, and Wyman-Gordon Ltd use "Forge 2" for forge modelling (2-D axisymmetrical), and "Topaz" or "Nike" for thermal modelling.

However, accurate output is necessarily a function of the accurate input parameters, and Wyman-Gordon have developed in-house expertise at its Corporate Research and Development laboratories to generate the requisite parameters for both forge and thermal modelling. Validation of forge modelling predictions have been carried out on numerous component standardisation cut-up evaluations, over several alloy systems.

Rheological databases, which predict the flow stress behaviour over the hot-working process window, are developed for each alloy system under consideration via sub-scale isothermal compression testing. To optimise the accuracy of the flow stress data, which may otherwise be severely distorted by adiabatic heating effects, proprietary low friction lubrication processes have been developed which allow flow stress generation up to true strains of 1.0 - 1.2. Nevertheless, correction factors may still be required,

particularly at higher strain rates.

An extract from the Alloy 720Li rheology database is given in Figure 4. Although each forge process is carried out at a nominal fixed temperature, non-isothermal temperature effects need to be examined to incorporate both surface chilling (resulting from the die - workpiece or die - atmosphere thermal differential) and localised heating (generated adiabatically during the forging process), which may result in grain growth or secondary recrystallisation. The rheological database is thus determined over a wide temperature range, as well as strain rate range, to encompass the anticipated forge process window. In the case of Alloy 720Li, flow stresses were calculated over the following ranges:

Figure 3: Typical billet microstructure
(Etch: 10% bromine in methanol)

- i) Temperature: 1038 - 1148°C
(1900 - 2100°F)
- ii) Strain rate: 0.001 - 10.0/s
- iii) Strain: 1.0

Interrupted testing is carried out at several strain intervals, with the partially deformed samples being rapidly quenched to "freeze-in" the dynamically evolved microstructure, which can then be examined by metallographic evaluation. A simulated heat treatment cycle may be subsequently applied, to follow microstructural changes from static processes. These data may then be incorporated into the model (by either qualitative or quantitative means) to allow a measure of microstructural prediction. To achieve a fully recrystallised grain structure with Alloy 720Li, a high degree of strain at hot working temperatures is required.

Both flow stress and structural effects of simulated die-chill can be evaluated in more detail by instituting a controlled rapid cooling cycle from the nominal forge temperature, and then performing in-situ tensile testing, and subsequently, metallographic analysis.

Individual quench facilities are characterised to determine local heat transfer coefficients for use with thermal modelling, which are validated via thermocoupled experiments. Residual stress modelling is validated via incremental depth measurements on as-quenched components.

Figure 4: Alloy 720Li, flow stress data [S/R=1.0/s] (uncorrected for adiabatic heating)

Forge Route Development:

Cast and Wrought Alloy 720Li billet to Rolls Royce specification is available in sizes up to 250 mm diameter. Although nominally recrystallised to an ASTM 10 grain size, unrecrystallised grains ALA ASTM 0 may be present. The forge route must be designed to eliminate or break down such microstructural features by designing intermediate forge operations that locally increase the strain level, such that the component ultimately achieves an overall high degree of

strain. Particular emphasis is placed on regions of the forging associated with the billet centre, where the highest proportion of large unrecrystallised billet grains are found.

The 250 mm billet diameter limitation resulted in an aspect ratio of 4.2:1, which necessitated a total of five forge operations to achieve the final shape.

To meet grain size, and associated mechanical property and ultrasonic inspection requirements, each forging operation is carried out at a sub-solvus temperature to prevent grain growth. Using the rheological database, the forge speed of each operation is chosen such that chill and adiabatic heating effects are balanced. To minimise flow stress increases and prevent chill cracking by forging at a "fast" speed, while preventing localised grain growth due to adiabatic heating (gamma prime dissolution & resultant grain growth) by forging at a "slow" forge speed. The Wyman-Gordon Ltd 30,000T and 9,000T hydraulic presses allow the use of controlled forge speed profiles, and a constant ram speed was stipulated for each of the five forge operations (overall, within the range of 25 - 80 mm/s). Examples of strain and temperature prediction, dominant factors in the microstructural evolution of Alloy 720Li are given in Figure 5. Over the range of forge speeds (chosen to balance thermal effects), strain rate effects on microstructural evolution of fine grain Alloy 720Li are minimal.

Heat Treatment Route Development

Heat treatment was carried out as per Rolls Royce specification. Thermal modelling was used to design the pre-heat treatment shape such that quench stresses are reduced to prevent quench cracking, yet cooling rates are high enough to satisfy mechanical property requirements. On-cooling quench stresses and average cooling rates for the IPTD are given in Figure 6.

Residual stress modelling has been validated by Wyman-Gordon for Alloy 720Li on a High Pressure Turbine Disc (HPTD) (6) and agreed with Rolls-Royce. Predicted residual hoop stresses (following quenching) are given in Figure 7. Although this technique is not as yet used as a forging route design criterion, it has been carried out to extend Wyman-Gordon's expertise in this area.

Figure 5: Predictions of strain and temperature generated on forging the IPTD

Manufacture:

A trial batch of two forgings was successfully manufactured to the following nominal parameters:

i) Starting Stock:

Nominal 500 kg @ 250 mm diameter
Cast and Wrought Alloy 720 LI
Supplied by Teledyne Allvac.

ii) Forge Process:

Five independent closed die forge operations (hot worked) on 9,000T and 30,000T hydraulic presses at Wyman-Gordon Ltd, Scotland
Process parameters assigned as per forge modelling simulations
Warm die philosophy
Sub-solvus forge temperature
Controlled ram velocity profiles

iii) Heat Treatment:

Pre-heat treatment shape defined via thermal modelling
Solution Treat: 4 hours @ 1105°C (2021°F); Oil Quench
Age: 24 hours @ 650°C (1202°F); Air Cool
Age: 16 hours @ 760°C (1400°C); Air Cool

Experimental Procedure

After forging and heat treatment, the forgings were machined to the final rectilinear shape to allow ultrasonic inspection. An integral test ring was also removed to allow release testing of the parts.

One of the forgings was then selected for cut-up evaluation. Forging macroslices were removed and surface ground to allow macro-etch inspection using acidified ferric chloride. Micro-specimens were prepared from locations throughout the forging. The samples were metallographically prepared and etched in bromine and methanol to reveal the general microstructure. The samples were then repolished and etched by means of electrolytic 10% phosphoric acid in water to reveal the γ' distribution.

Optical microscopy was carried out at each stage.

The bulk of the disc was then cut-up to provide specimens for the mechanical testing programme which is described in Table II.

Figure 6: Predictions of on cooling quench stresses and average cooling rates generated in the IPTD in heat treatment

Figure 7: Predictions of the residual hoop stresses generated in the IPTD on heat treatment

Table II: Mechanical test programme

Test Type	Position	No.	Test Detail
Room Temperature Tensile	Test - Ring	1	20°C
	Bore - Axial	2	"
	Bore - Tangential	2	"
	Web - Radial	1	"
	Rim - Tangential	1	"
	Rim - Radial	1	"
Elevated Temperature Tensile	Bore - Tangential	1	200°C
	Bore - Tangential	1	400°C
	Web - Radial	1	400°C
	Web - Radial	1	500°C
	Web - Radial	1	600°C
	Rim - Tangential	1	500°C
	Rim - Tangential	1	600°C
	Test Ring	1	650°C
Creep Strain	Test - Ring	1	625°C/730MPa
	Web - Radial	1	" "
	Rim - Tangential	1	" "
Plain Low Cycle Fatigue	Bore - Tangential	6	200°C
	Web - Radial	4	500°C
	Web - Radial	2	600°C
	Rim - Tangential	4	500°C
	Rim - Tangential	2	600°C
Crack Propagation	Bore	2	200°C
	Rim	2	500°C

Results

Release Testing

Normal release testing requirements were carried out on both forgings, the requirements being fully met in each case, results are given in Table III.

Good levels of ultrasonic inspectability were achieved in both forgings. Typical grass levels of -30dB or better were achieved against a No.1 FBH standard.

Both Macro etch and fluorescent penetrant inspection of the discs revealed no defects. These results were consistent with previous experience.

Table III: Results from release testing of forgings

Serial No.	Temp/°C	UTS/MPa	PS/MPa	%El	%RA
0001	20	1100	1581	16	17
0001	650	1058	1431	20	36
0002	20	1112	1594	16	17
0002	650	1041	1433	20	39

Macro/Microstructure

The etched forging macro slice is shown in Figure 8. An acceptable grain flow has been achieved. The macrostructure of the forging was consistently uniform across the full section, with no deleterious features evident.

The microstructures were found to be generally fully recrystallised uniform microstructure with an average grain size of ASTM 8-9, as shown in Figure 9. Some γ' banding with associated local grain size variation was visible. This microstructure resulting from the inhomogeneity associated with the cast and wrought route. This is an inherent feature of the cast and wrought processing, particularly of such a highly alloyed material.

Figure 8: Etched forging macroslice (Etch: acidified ferric chloride)

Figure 9: Representative microstructure from IPTD disc forging
(Etch: 10% bromine in methanol)

Some occasional (<1%) isolated unrecrystallised grains as large as ASTM1 were also identified, these grains were confined to the drive arm region of the disc forging. This corresponds with a relative low strain region of the forging as predicted in Figure 5. Modification of the forging route to locally increase the level of strain should eliminate such features. A typical example is shown in Figure 10. These features are typical of the process route and isolated examples are not thought to be detrimental. Figure 11 shows the typical γ' distribution found within the forging, the effects of the segregation discussed above are again evident in the γ' banding.

The macro/microstructure generated in the IPTD is consistent with previous experience for material forged via the hot die route. The IPTD disc forging

Figure 10: Typical microstructure showing isolated unrecrystallised grain
(Etch: 10% bromine in methanol)

shows a slightly coarser grain size compared to previous Rolls-Royce experience.

Tensile Properties

The tensile properties generated from the IPTD forging were compared against typical values for Waspaloy. As shown in Figure 12 the results from the IPTD forging compare favourably with previous experience for the alloy for both the ultimate tensile strength and yield strength. It is concluded that there has been no degradation in tensile properties in the scale-up to large disc forgings.

Considering the results from the IPTD alone, as would be expected there is some variation according to location within the disc. The rim area tending to have higher strengths than those from the bore. This largely reflects the different heat treatment response related to section thickness. The effect of grain flow during forging is also evident, the samples tested in the axial direction showing the lowest strengths.

The material showed good ductility across the temperature range investigated, all the values measured being greater than 15% for both reduction of area and elongation. These results are again consistent with previous experience for the alloy.

In comparison to the current IPTD disc material Waspaloy, the Alloy 720Li IPTD shows a 25-30% increase in strength. This would be expected in terms of alloy composition and grain structure (Alloy 720Li forging ASTM 9 or finer, compared with ASTM 5-7 for the Waspaloy forging).

Figure 11: Typical γ' distribution
(Etch: electrolytic - 10% phosphoric in water)

Figure 12: Tensile strength measured from IPTD forging compared with typical data for Alloy 720Li and Waspaloy

Creep Strain Testing

Creep strain testing was carried out on three locations within the IPTD forgings, the results are given in Table IV. In each case the results met the target requirements and were consistent with previous experience for the alloy.

Table IV: Results from creep strain testing

Location	Temp/°C	Stress/MPa	TPS(%)
2	625	730	0.036
4	625	730	0.025
6	625	736	0.010

Low Cycle Fatigue Testing

Plain load control LCF S-N curves were generated at 200°C and 500°C. All tests were carried out at 15 cycles per minute with a O-maximum stress cycle (R=0). Figures 13 and 14 show the LCF curves at 200°C and 500°C respectively. In both cases the material shows good resistance to fatigue under these test conditions. The results are consistent with previous experience for the alloy, although only limited data is available at 200°C. At 600°C the curves appear very 'flat' and small increases in the applied stress can produce a much reduced life. The results can also be grouped into two 'families' dependent upon the location from where the samples were manufactured. The specimens manufactured from the rim location showing improved performance compared to those from the web of the disc. This may be indicative of the relative degrees of structural refinement observed in those areas.

Investigation of the fracture surface of the failed specimens typically showed

that the initiation site was a titanium rich nitrides/carbonitrides. Figure 15 shows an SEM micrograph of a representative feature. These discrete titanium nitride/carbonitride were usually in the size range 10-40µm and are an inherent microstructural feature, and do not compromise the LCF life of the material.

Comparing these results to typical Waspaloy data, the Alloy 720Li shows a greater resistance to fatigue at both 200°C and 500°C. This behaviour is again as would be expected partly due to the compositional and structural differences between the alloys.

Figure 13: LCF behaviour at 200°C for IPTD forging compared with typical alloy 720Li and Waspaloy data

Crack Propagation Testing

Crack propagation testing was carried out at 200°C and 500°C and specimens prepared from the rim and bore of the disc. The results for the testing at 200°C are given in Figure 16, and it can

Figure 14: LCF behaviour at 500°C for IPTD forging compared with typical alloy 720Li and Waspaloy

Figure 15: Sub-surface initiation site within failed LCF specimen.

be seen that the results are comparable to previous alloy 720Li experience. In comparison it can be seen that the Waspaloy shows a greater resistance to crack propagation than the Alloy 720Li. The coarse grain microstructure being the dominant feature, outweighing any differences in alloy composition.

The results from the crack propagation testing at 500°C, Figure 17, compared favourably with previous Alloy 720Li experience and was similar to Waspaloy behaviour.

Summary

Two large IPTD forgings have been successfully manufactured from 250mm cast and wrought billet. This represents a significant scaling-up in size from previous manufacturing experience. The forgings met all of the requirements specified in terms of macro/microstructure and mechanical properties. Excellent correlation was

achieved with previous experience, an indication that there was no degradation in material performance in scaling up the forging size. The successful outcome of the evaluation demonstrates that alloy 720Li has the potential to meet future requirements for high strength large disc forgings.

The use of numerical forge and heat treatment models has been critical in designing the forging route, production standard forgings being produced at the first attempt. The design cycle has been significantly reduced from the traditional trial and error techniques. This successful design philosophy can be extended to other component geometries, and is not restricted to Alloy 720Li alloy.

Figure 16: Results from crack propagation testing on IPTD forging at 200°C compared to typical alloy 720Li and Waspaloy data

Figure 17: Results from crack propagation testing on IPTD forging at 500°C compared to typical alloy 720Li and Waspaloy data

Further Developments

Further developments of the manufacturing route have been identified by this study. The developments will lead to the definition of a cost effective production route for large forgings. In particular, the need to develop larger billet diameters whilst maintaining the current structural

standards. This represents a stern challenge for the billet manufacturer, who have already come a long way in developing the current manufacturing routes to produce the current standard of Alloy 720Li billet.

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