OPTIMIZATION OF THE HIGH TEMPERATURE, LOW CYCLE FATIGUE STRENGTH OF PRECISION-CAST TURBINE WHEELS

M. Lamberigts*, G. Ballarati**, J.M. Drapier**

* CRM, Liège, Belgium,
** FN-Formétal, Herstal, Belgium

Summary

The very high LCF strengths which some engine manufacturers now require for their most advanced integral turbine wheels cannot be achieved through purely conventional precision casting. The paper shows that, in the case of a particular IN 713 wheel, low cycle fatigue life mainly depends on carbide precipitation characteristics. The latter can be optimized by putting the low cost, proprietary "R" process into practice. Proper alloy selection could also be very helpful, the best master heats being those with a good castability, and low carbon and nitrogen contents. Fatigue life also depends on gamma prime fineness and homogeneity, grain boundary structure, and microporosity level. All those features can be improved by HIP'ing wheels cast under optimized conditions in such a way as not to affect the carbides. For thus cast and treated wheels, LCF performance is three times as good as it is for conventionally manufactured parts.

Introduction

The casting of integral turbine wheels has grown into a rapidly expanding field of activity for a number of foundries specializing in aeronautical applications. Most often, this manufacturing procedure is the only economically viable one in the case of small and medium size engines for which "fir tree" blade-to-disc mechanical attachment would be much too costly (1,2). Its unfortunate consequence is, however, that the microstructure is rather difficult to adapt to the locally variable service stressing conditions of such components. In fact, a relatively coarse grained structure is desirable in the aerofoils which must mainly resist high temperature creep, whereas fineness is expected in the sometimes very thick hub, where moderate temperature low cycle fatigue (LCF) is of prime importance.

The demand for improved turbine performance has led some engine manufacturers to require such high property levels for their most advanced integral wheels that they can hardly be achieved through conventional casting procedures. In most cases, the major problem comes from the hub LCF strength, and it is in that framework that the development of special foundry processes, aimed at creating a very fine grain structure in thick castings, must be replaced. Among those worth mentioning, inoculation (3,4) and stirring of the solidifying metal (5,6) have certainly assumed an outstanding position.

As it is speculated that even sophisticated foundry processes will not make it possible to satisfy extreme property requirements for future integral wheels, new design concepts are now being introduced, such as the so-called "dual-property wheel" in which DS or single crystal blades are bonded onto a P/M hub (7,8). This latest development is however outside the scope of the paper which only deals with more or less conventional casting processes.

Object Of The Work

Various advanced turbine wheels, a selection of which is shown in Fig.1, are currently cast at FN-Formétal in alloys such as IN 713 and Mar-M-247. Some of them are required to exhibit a combination of high tensile, creep, and LCF properties, so that the metallurgical problems mentioned in the introduction must be addressed very seriously. The foundry process to be used in each particular case must at the same time be a satisfactory technical solution, and as limited as possible a burden to production costs.

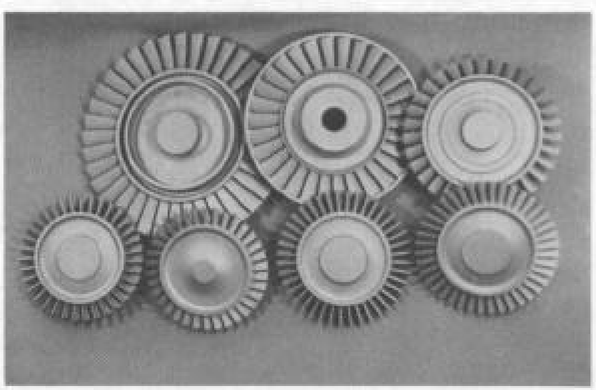
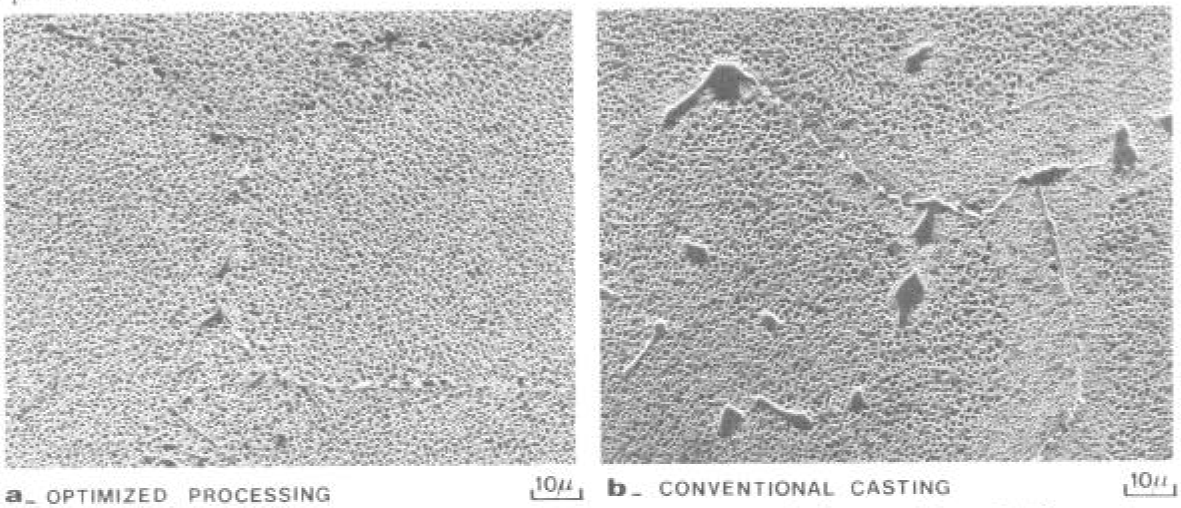


Fig.1. Various integral wheels cast at FN-Formétal

The paper deals with an IN 713 C wheel for which all mechanical property requirements could be met through conventional casting procedures, except for the low cycle fatigue performance of test pieces taken from the cored hub, very close to the central bore. Based on a literature survey, technical information from outside partners, and previous experience, it was recognized from the outset of the work that, in addition to a fine grain distribution and the absence of microporosity, the most desirable structure should be characterized by a low fraction, high density precipitation of fine and blocky carbides, thin and wavy grain boundaries, and a fine and homogeneous gamma prime distribution (9, 10, 11). Fig. 2 compares such an ideal structure to that currently achieved by conventional foundry procedures.



a_ OPTIMIZED PROCESSING b_ CONVENTIONAL CASTING

Fig.2. Comparison between ideal microstructure and that achieved through conventional casting.

It was the aim of the work to optimize alloy selection and casting parameters in such a way as to obtain the appropriate structure and satisfactory LCF performance without resorting to sophisticated processes similar to those described in the introduction. The effect of HIP on thus manufactured wheels was also to be evaluated.

Approach

Materials

Four virgin, and one fifty virgin-fifty revert master heats, supplied by three distinct alloy producers were involved in the study (Table I). They all meet the customer's chemistry requirements, even though some differences can be seen between carbide forming-and tramp-element contents. In that connection, it should be noted that the nitrogen levels of master heats 4 and 5 look relatively high.

With all their individual merits and shortcomings, those heats are well suited to help define alloy selection criteria, as they look likely to result in somewhat distinct microstructures (carbo-nitride precipitation,etc.) if subjected to identical solidification conditions. Furthermore, they have been shown to lead to satisfactory tensile and creep properties for the whole casting parameter range considered in this study; the comments hereafter have then been voluntarily restricted to microstructure and LCF performance.

Foundry Trials

In order to achieve very distinct solidification sequences, and ultimate microstructures and properties, experimental moulds were cast from heats 1 to 5 under a set of conditions corresponding to various wax pattern assemblies and corings, shell structures, mould insulations, mould preheating and metal pouring temperatures, and hot toppings.

Table I - Compositions announced by the alloy suppliers.

	Alloy suppliers				
	A (virgin)		B (virgin)		C(50/50)
	heat 1	heat 2	heat 3	heat 4	heat 5
% C	0.095	0.103	0.13	0.11	0.11
Si	0.0024	0.005	<0.2	<0.1	<0.05
Mn	<0.05	<0.05	<0.2	<0.05	0.01
Al	6.09	6.1	5.96	6.04	6.05
B	0.010	0.011	0.010	0.011	0.007
Nb + Ta	2.2	2.2	2.19	2.16	2.01
Co	<0.05	<0.10	0.15	<0.05	0.09
Cr	13.5	13.5	13.06	13.29	13.4
Fe	<0.05	<0.10	0.12	0.07	0.67
Mo	4.3	4.2	5.2	4.2	4.35
Ti	0.82	0.81	0.75	0.82	0.86
Zr	0.06	0.06	0.10	0.07	0.069
ppm Ag	<1	<1	<1 *	0.1	<0.1
Bi	<0.2	<0.2	<0.2 *	<0.1	<0.1
Pb	<1	<1	<1 *	0.5	0.2
Sn	<0.5	<0.5	<0.3 *	<2	<0.5
Zn	<1	<1	<1 *	2.2	
N_2	7	6	7 *	14	11
O_2	2	1	2 *	5	3

* as determined by FNF-CRM.

The thus obtained wheels were then subjected to the usual foundry quality control tests, including grain etch, FPI and X-radiography. All of them underwent the specified heat treatment which involves stabilizing at 954°C/1h, solutioning at 1149°C/8h, and stress relieving and ageing at 954°C/1h.

Some of the wheels cast under the most appropriate conditions for LCF performance optimization were also given a HIP cycle at 1200°C/100MPa/4h prior to the heat treatment mentioned above. Based on previous experience, HIP cooling rate was chosen so as to result in a homogeneous gamma prime distribution.

Evaluation

Two chordal LCF bars were ED machined from every fully treated experimental wheel. After lathe turning and stress relieving at 954°C/1h, they were low stress ground to dimensions and polished to remove all machining traces from their gauge lengths. Some confirmation wheels were also sent to the customer who machined similar test pieces under undisclosed conditions.

All those specimens were subjected to axial constant strain LCF tests at Mar Test Inc., Cincinnati, Ohio. The particular experimental conditions were as follows : 0.5% total strain range, 0 to maximum triangular wave form, 250°C. A given foundry procedure can only be considered satisfactory if it leads to a minimum logarithmic mean life of 23000 cycles, for a sample of at least four wheels. Moreover, the logarithmic standard deviation must be less than 0.366, and the minimum individual life to failure, over 8000 cycles. It must be noted here that such properties could not be achieved very easily, as conventional casting procedures applied to master heat 3 result in an average life of about 18000 cycles.

Metallurgical evaluation was based on grain size distribution along a diametral section in one wheel for each casting condition (Figure 3), and on extensive microstructure characterization in the heads of more than 40 LCF test-pieces, involving quantitative determination of dendrite arm spacing, and carbide-and eutectic-precipitation features (fraction, density, size and shape distributions, etc.) together with high magnification SEM observation and EDS local chemistry assessment.

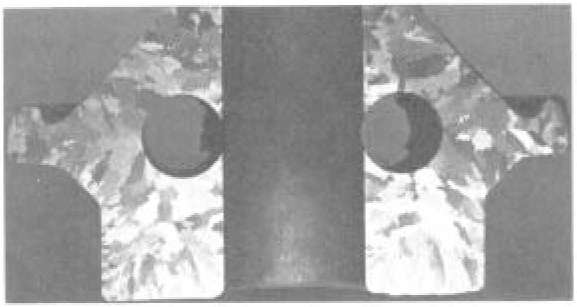


Fig.3. Typical hub grain structure showing locations of MFW-LCF test pieces on either side of central cored hole.

The fatigue properties and microstructural features achieved for each experimental group of castings were studied through a factor analysis procedure in order to determine which foundry parameters affect them most (12). This approach allows for numerous factors to be tested in a minimum number of foundry trials and also supplies significance thresholds for their eventual effects (F-tests). From such results, improved properties can then be sought along the so-called "path of steepest ascent", defining the most effective relative variations of statistically significant factors (12). The method was used to optimize manufacturing conditions in terms of fatigue life to failure and microstructure.

Results

Optimization Of Manufacturing Conditions

Applying the statistical evaluation method described in the last section above led to emphasize the dependence of LCF strength and microstructure on alloy quality, mould insulation, mould preheating and metal pouring temperatures, and hot topping.

In that connection, it was shown that master heats 1 and 2 give an average advantage of about 3500 LCF cycles to fracture over heat 3. This improved performance is associated with a decreased carbide fraction made of smaller, slightly more acicular, but more homogeneously distributed particles. Even though more detailed information is still needed to substantiate the conclusion, master heats 4 and 5 seem the worst of all, and this may be related to their particularly high nitrogen contents.

Optimizing the casting conditions of conventionally manufactured wheels still increase the carbide refinement effect of good alloy selection and result in another 4000 more cycles in fatigue life. However, putting the "R" process into practice is the most effective means to improve low cycle fatigue strength, as it prolongs life to failure by about 16000 cycles. This major effect is associated with further carbide refinement, which incidentally is less significant for master heats 1 and 2 than it is for master heat 3. Fig.4 illustrates the resultant consequence on carbide size distribution of all the processing parameters commented on here (S is the carbide individual diameter as measured in the section plane, $\emptyset_{eq.}$, the corresponding equivalent diameter, and Pr (S), the cumulated frequency).

Table II gives expected average structural features and fatigue lives particles, with all the beneficial carbide precipitation features being preserved. Grain boundaries were also made much finer than in conventionally cast and heat treated parts.

Those microstructural effects resulted in substantially improved LCF performance, as is shown by Fig.7 which compares the log-normal fatigue life distribution of the HIP'ed pilot batch considered here with that of the confirmation lot of cast wheels described above. It is seen that logarithmic fatigue mean life can be raised to 36330 cycles with a logarithmic standard deviation of 0.253. If the wheel one fatigue bar of which did not resist more than 9810 cycles (▲) might be considered an oddity, those figures would respectively be 40311 and 0.166.

Even though such an odd result elimination cannot be justified by any fractographic evidence, HIP still remains an appealing treatment, as it improves LCF strength without its jeopardizing the advantageous carbide precipitation characteristics achieved by the "R" process.

Discussion Of Results

The LCF performance of advanced IN 713 turbine wheels strongly depends on their Nb-Ti-Cr carbide precipitation. In actual fact, lives to failure increase very substantially whenever carbide fraction is made lower, density higher, and particles smaller and rounder. That goal can be achieved by optimizing manufacturing conditions, even without resorting to sophisticated casting processes, aimed at refining the grain size and involving inoculation or stirring of the solidifying metal. More precisely, LCF lives can thus be more than doubled, 20% of the improvement arising from good metal selection (castability, low carbon and low nitrogen contents), and 80% from applying the proprietary "R" process.

Gamma prime fineness and homogeneity, proper grain boundary structure, and low microporosity level are other beneficial features, though much less effective, as their imperfections do not prevent quite satisfactory fatigue lives, provided carbide precipitation is under control. When combined with the latter, however, they can make LCF performance even better, the cumulated result being a threefold improvement of average fatigue life as compared to conventionally cast parts. Such a global effect can in fact be achieved by HIP'ing the wheels directly after "R" processing. Figure 8 illustrates how improved the performance can be in each case.

Within the range of casting conditions considered in the study, grain size and dendrite arm spacing varied much too little for their eventual effects on LCF strength to be noticeable.

Conclusions

Substantially improved LCF performance can be achieved in the case of IN 713 turbine wheels by manufacturing them almost conventionally. The main point is to control carbide precipitation through the proprietary "R" process. The recommended procedure, which does not increase production costs substantially, also involves casting condition optimization. Results can be made even better if good master heat selection is put into practice, even though thus obtained microstructures are not ideal, as gamma prime distribution homogeneity is hampered by out of equilibrium solidification sequences.

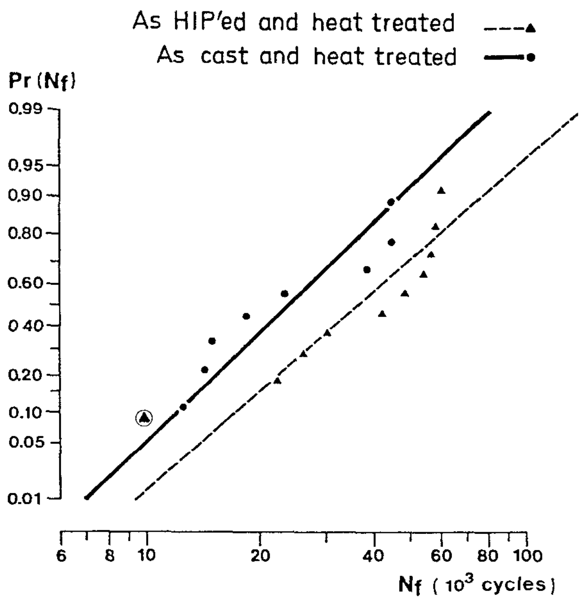


Fig.7. Comparative log-normality tests

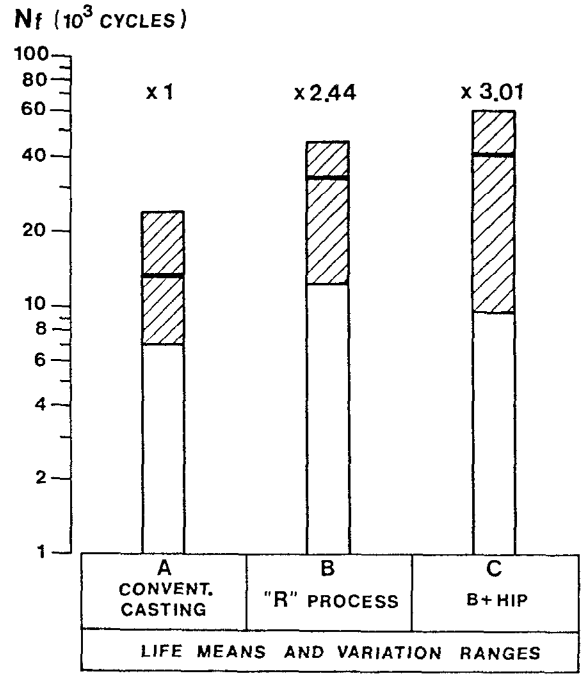


Fig.8. Dependence of low cycle fatigue performance on processing conditions.

Healing those defects and totally closing the residual microporosity through HIP carried out in such conditions as not to affect carbide precipitation leads to another increase in fatigue strength, the ultimate life being three times as long as that of conventionally cast parts.

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