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SINGLE CRYSTAL SUPERALLOYS FOR TURBINE BLADES IN ADVANCED AIRCRAFT ENGINES

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Abstract

A number of high strength single crystal superalloys tailored for the casting of complex shaped blades and vanes have been developed in USA, Europe and Japan. Some of the recently developed European alloys also offer the advantage of relatively low densities allowing lower disc stresses. The stress rupture properties of selected single crystal superalloys are compared. The heat treatments are shown to play a crucial role in improving the creep resistance of these alloys. The use of high temperature gradients during single crystal solidification is shown to considerably improve the fatigue strength of single crystal alloys due to reduced casting porosity. HIP'ing is presented as an alternative technique for improving the fatigue resistance of low gradient processed industrial single crystals.

I - Introduction

The improvement of aircraft gas turbine efficiency is related to the increase in turbine inlet temperature (TIT). Turbine blade materials have been constantly improved through the development of superalloys with higher strength, new solidification techniques and optimized heat treatments. The average increase in TIT for the past twenty years or so has been on the order of 15°C per year, which includes the increase due to the contribution of materials, estimated to be about 7°C per year. The evolution of materials and cooling techniques illustrated in Fig. 1 and 2 (1, 2) has greatly contributed to increasing TIT in large engines but in smaller engines where advanced cooling techniques are more difficult to use, the development of better materials and processes has been even more pertinent. One of the important landmarks in the area of superalloy development is associated with the invention of vacuum induction melting in the late 1940's which allowed the casting of complex nickel based alloys with a substantial amount of reactive elements (Al, Ti, Ta...) required to increase the volume fraction of the strengthening γ' phase. The invention of the directional solidification technique developed by Versnyder and Guard (3) in the 1960's, who demonstrated the feasibility of making castings with a controlled directional structure, provided a major breakthrough in the precision casting of high strength cooled blades. This technique permitted to solidify a columnar grained structure with all the grain boundaries roughly parallel to the principal stress direction. Such an arrangement of the grain boundaries avoided the intergranular failures encountered in equiaxed grained turbine blades. Single crystal solidification is a further refinement of unidirectional solidification which permits the elimination of grain boundaries and allows to design new and simpler compositions which do not contain the usual grain boundary strengthening elements, such as C, B, Zr, Hf... (4). The suppression of these elements, which are also solidus depressants, considerably increases the incipient melting point and hence a complete solutioning of the γ' phase becomes possible.

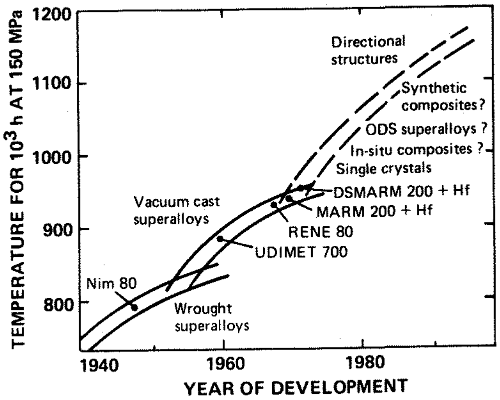

Fig. 1 - Temperature capability of gas turbine blade materials for 10^3 h life with a stress of 150 MPa displayed as a function of the year of introduction into service.

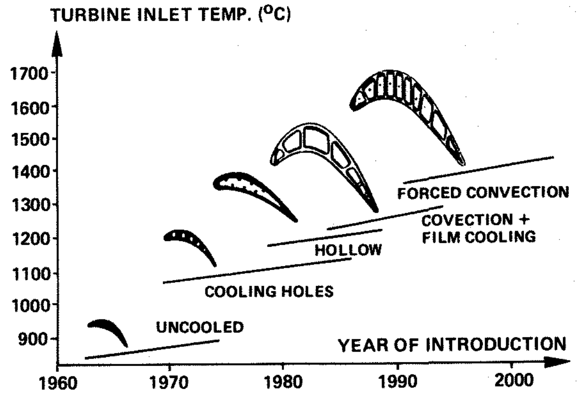

Fig. 2 - Evolution in turbine blade cooling technology.

Many advanced gas turbine engines use directionally solidified blades and vanes cast from high strength Ni-base alloys due to their improved temperature capability. The introduction of single crystal blades in the most advanced engines is expected to further improve the durability of the components by a factor of about three. A number of single crystal alloys have been developed in the past few years, both in the USA and Europe. These alloys contain about 70vol.% of the so-called γ' phase.

The purpose of this paper is to briefly describe some specific aspects of single crystal casting technology and to show the creep and fatigue potential of some recent single crystal superalloys. Particular emphasis is placed on the effect of parameters such as heat treatments, casting conditions and HIP'ing on the mechanical behaviour of a typical modern single crystal alloy, namely CMSX-2 (5) . It is anticipated that the general mechanical behaviour of this alloy will be representative of many other single crystal superalloys.

II - Casting technology of single crystal superalloys

The single crystal components are directionally solidified either by using a grain selector or a "seed" of desired orientation placed at the bottom of the mould. The molten metal is poured into the mould, which is withdrawn from the furnace at a constant rate. The temperature of the molten metal is about 200°C above the melting point of the alloy and the solidification occurs through a temperature gradient. The crystal selector method, as opposed to the seeded technique, has some drawbacks such as, no control of the secondary orientations, restriction of casting components only around ⟨001⟩ and rather poor control of ⟨001⟩ orientation. In industrial practice, the selector technique is still widely used since there is no clear evidence of the effect of secondary orientations on the mechanical properties of components. This technique permits the casting of blades and vanes oriented parallel to the ⟨001⟩ orientation, which is the natural growth direction of face centered cubic metals. This orientation has also the lowest Young's modulus, which helps improving the thermal fatigue behaviour.

For the solidification of single crystal components on an industrial scale, the furnace size is associated with the size of the water-cooled copper chill plate. Smaller furnaces offer the advantage of higher temperature gradients, allowing better foundry performance (absence of freckles, lower porosity, finer dendrite spacing...). However, the number of components which can be simultaneously cast is smaller compared to the capacity of bigger furnaces now more frequently used for columnar grained D.S. components. The temperature gradients prevailing at the solid-liquid interface are difficult to measure in industrial furnaces but estimations made from the dendritic spacings show that the gradients are low, typically on the order of 40°C/cm or less. The withdrawal rates for single crystal solidification are typically about 25 cm/hour.

The shape of the solidification front must be maintained slightly convex to avoid stray grain growth. When the withdrawal rate increases the shape of the solidification front tends to become concave, as predicted by heat transfer calculations (Fig. 3). At very high withdrawal rates, the solidification front moves downwards out of the susceptor causing the mould to be cooled from outside, resulting in solidification on the mould wall and hence the possibility of stray grain growth (6). The problem of stray grain growth in components is a very serious one due to the absence of grain boundary strengthening elements in modern single crystal superalloys. It is hence necessary to have a tight solidification control and to maintain the solidification front within the susceptor by controlling the withdrawal rate and susceptor temperature.

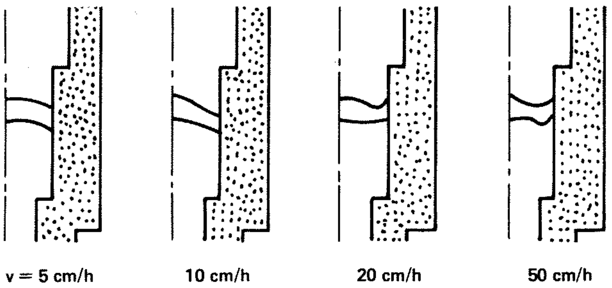

Fig. 3 - The shapes of solidification front obtained by calculation.

A number of single crystal superalloys have recently been developed in the USA, Europe and Japan. In the USA and Japan, the effort has been directed towards the development of high strength alloys, without giving a strong consideration to the alloy density (4, 7).

In Europe, both the "standard" density and the relatively "low density" alloys have been developed ; the latter alloys help reduce the disc stresses. In the U.K., Rolls Royce has developed a low density alloy, namely RR 2000 and a high strength low density alloy designated ONERAM-3 (density = 8.2 g/cm^3) has also recently been developed at ONERA. Among the most recent alloys developed in Europe, the SNECMA alloy AM 1 (developed through a joint collaboration between SNECMA, ONERA, ECOLE DES MINES and IMPHY SA (8), MXON (9), ONERAM-3 (10), SRR 99 and RR 2000 (11) are worth mentioning. The chemical compositions of some of these alloys are shown in Table 1.

Table 1 — Composition of some single crystal alloys.

Alloy	Element (WT. %)										Density (g/cm^3)
	Ni	Cr	Co	Ti	Al	Mo	W	Ta	Nb	V	
CMSX 2	BAL.	8	4.6	0.9	5.6	0.6	7.9	5.8	–	–	8.6
Alloy454 (PWA 1480)	BAL.	10	5	1.5	5	–	4	12	–	–	8.7
RENE N4	BAL.	9	7.5	4.2	3.7	1.5	6	4	0.5	–	8.5
SRR 99	BAL.	8.5	5	2.2	5.5	–	9.5	2.8	–	–	8.5
RR 2000	BAL.	10	15	4	5.5	3	–	–	–	1	7.8
MXON	BAL.	8	5	–	6.1	2	8	6	–	–	8.6
TMS-1	BAL.	5.5	7.5	–	5.2	–	16.6	5.1	–	–	9.16

III - Heat treatments

The heat treatments play a crucial role in increasing the mechanical properties of superalloys. In single crystal alloys their role is even more significant since the much higher melting points of these materials allow an almost total solutioning of the γ' phase and controlled subsequent precipitation. For alloys which contain a rather high volume fraction of the γ/γ' eutectic phase after casting, a proper solutioning treatment is of extreme importance. Work at ONERA has shown that in the case of Pratt & Whitney alloy 454 (PWA 1480) for instance, having a rather high amount of eutectic, a two-step solutioning treatment which results in the solutioning of a significant portion of the eutectic phase leads to a considerable improvement of the stress rupture properties (Fig. 4). The solutioning treatment can become an intricate problem from the industrial standpoint if the so-called "heat treatment window" (the temperature interval between γ' solvus and the incipient melting) is too narrow. A heat treatment window of at least 10°C is necessary to perform a one-step solutioning treatment in production vacuum heat treatment furnaces. The treatment time required for solutioning the eutectic is related to the dendrite arm spacing in the alloy. The use of high temperature gradients during the solidification process reduces this spacing and consequently, the γ/γ' eutectic islands are small. As an example, in the CMSX-2 alloy cast under a very high temperature gradient resulting in a primary dendrite spacing of 150 µm, the eutectic is completely solutioned after a 30-minute hold at 1315°C whereas in the case of low gradient solidification presently practiced in industrial furnaces (primary dendrite spacing $\simeq$ 450 µm) a 3 to 4-hour solutioning treatment is necessary. The solutioning treatment also partly homogenizes the dendritic segregation (Fig. 5a,b).

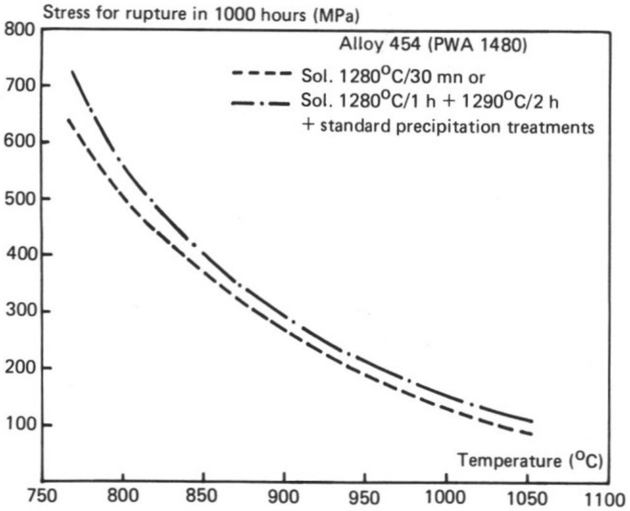

Fig. 4 - Improvement in stress rupture properties by a two-step solutioning treatment of alloy 454.

The size, the morphology and the distribution of the ' precipitates are directly related to the precipitation heat treatment and these parameters can significantly affect the mechanical properties. It is widely accepted that in superalloys a fine γ' distribution, typically 0.2 to 0.3 µm in size, would result in optimum creep resistance. An investigation was undertaken at ONERA to determine the effect of different γ' sizes obtained through various precipitation heat treatments on the creep performance of CMSX-2 alloy at various temperatures. This investigation showed that the optimum creep strength in this alloy is attained with γ' particles having a size of about 0.5 µm. In view of these results, a detailed study of heat treatments was undertaken on the CMSX-2 alloy in order to develop a better understanding of the relationship between creep resistance and deformation microstructure. The deformation microstructures were studied, by transmission electron microscopy, essentially after the following two types of heat treatments :

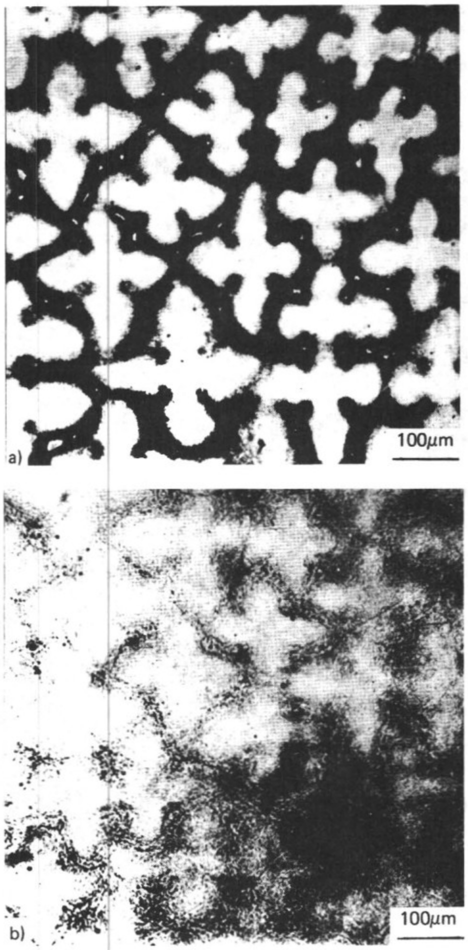

Fig. 5 - a), b) Effect of homogenizing heat treatment on dendritic segregation in CMSX-2.

Heat treatment T_1 : 1315°C/½ to 3 hours/A.C. +
980°C/5 hours/A.C. +
850°C/48 hours

Heat treatment T_2 : 1315°C/½ to 3 hours/A.C. +
1050°C/16 hours or
1100°C/4 hours/A.C. +
850°C/48 hours

The T_1 treatment, which was previously recommended by Cannon-Muskegon, results in the precipitation of irregular shaped γ' particles, about 0.3µm in size (Fig. 6). The T_2 treatment is the optimized ONERA heat treatment and it results in the precipitation of cuboïdal precipitates, about 0.5 µm in size (Fig. 7) ; the latter heat treatment leads to a two-fold improvement in rupture lives over the T_1 heat treatment. It has been clearly shown that the optimum creep resistance in many single crystal alloys is achieved by the ONERA-type heat treatment (12, 13). In fact, a γ' size of about 0.5 µm results in a very homogeneous deformation structure, which is responsible for an excellent creep resistance. The various deformation mechanisms observed during the creep of the CMSX-2 alloy have been analyzed in detail elsewhere (12).

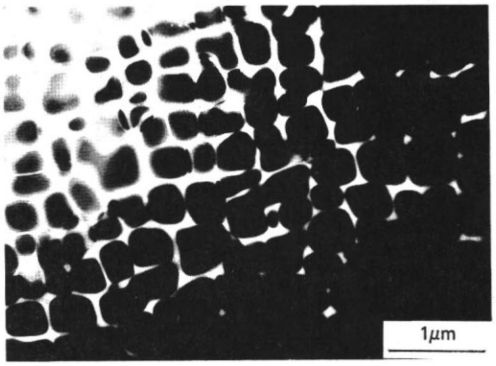

Fig. 6 - Morphology of γ' precipitates in CMSX-2 alloy after T_1 heat treatment.

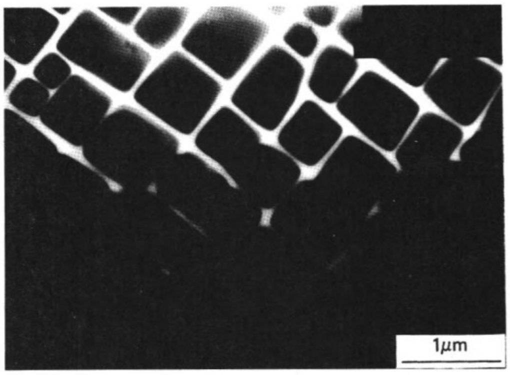

Fig. 7 - Morphology of γ' precipitates in CMSX-2 alloy after T_2 heat treatment.

IV - Creep behaviour

IV.1- Stress-rupture properties of modern single crystal superalloys

In turbine blades, creep is an important deformation mode due to the centrifugal stress. Even if in some modern complex shaped convection cooled first stage blades the stresses of thermomechanical origin are gaining importance, creep is still an important design consideration. Hence, for determining the temperature capability of a newly developed alloy it is common practice to compare its stress rupture strength with the best existing alloys. The creep strength of some ⟨001⟩ oriented modern single crystal alloys (PWA 1480, CMSX-2, MXON) is compared with that of the DS 200 + Hf columnar grained alloy in Fig. 8. The temperature advantage of such crystals over the DS alloy is clearly significant in the whole temperature range. The MXON alloy developed at ONERA shows the highest creep resistance in the high temperature regime and its strength is virtually equivalent to that of Cotac 744, a Ni-based eutectic also developed at ONERA in the late 1970's (14). The example of MXON illustrates the remarkable intrinsic creep potential of a titanium-free single crystal alloy with a fairly simple composition (Table 1). We have previously shown that the elimination of cobalt from this alloy, which makes the chemical composition still simpler, results in essentially the same creep resistance at high temperature as that of the 5 % cobalt containing version (9). The temperature advantage offered by MXON over alloy 454 (PWA 1480) at 1000°C is about 50°C.

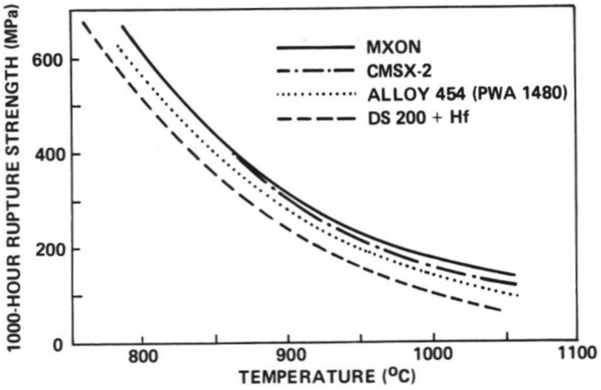

Fig. 8 - Stress rupture properties of single crystal alloys compared with DS 200 + H_f.

The density corrected stress rupture properties of some relatively low density alloys are compared in Fig. 9, in which the equiaxed IN 100 alloy is the well-known reference material. The RR 2000 alloy developed at Rolls Royce is a very interesting example due to its very low density. The ONERAM 3 alloy recently developed at ONERA is a high strength alloy, but has a slightly higher density. It is worth mentioning that both the creep resistance (time for a given creep strain) and the specific stress rupture strength of the ONERAM 3 alloy are at least as high as that of the CMSX-2 alloy. All these examples show that there is a real potential for the development of high strength superalloys tailored for specific applications (15).

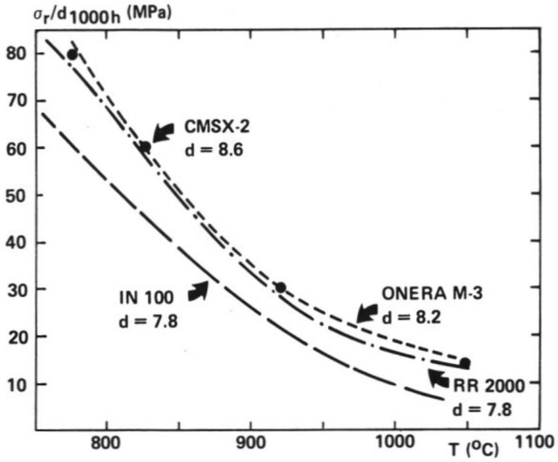

Fig. 9 - Density corrected stress rupture lives as a function of temperature of selected superalloys.

During creep at high temperature, the γ' precipitates coarsen in the form of rafts perpendicular to the stress axis. The kinetics of raft formation depends, among other factors, upon the testing temperature. At 1050°C under a stress of 120 MPa, the rafts form within a few hours (Fig. 10) ; the rafts have a high aspect ratio in T_2-type heat treated specimens in which the cuboïdal γ' precipitates are already aligned. The lateral extension of the γ' phase in the form of rafts causes the specimen to creep at a much lower rate compared with the creep rate of the material in which the γ' phase coalesces in more irregular manner. The alloys showing this type of rafted γ' morphology possess very long rupture lives at high temperatures. In these alloys, the misfit between the and γ' phases is found to be negative at high temperatures (15) ; in CMSX-2, the misfit at 1050°C is determined to be $- 3.3.10^{-3}$ (16). It has now been well established that a negative misfit is required for raft formation.

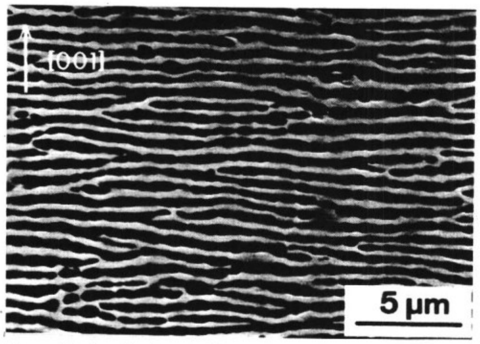

Fig. 10 - Oriented coalescence of the γ' phase in CMSX-2 after 20 hours of creep at 1050°C under 120 MPa (tensile stress axis is [001]).

IV.2 - Effect of solidification conditions and HIP'ing on creep

The effect of casting conditions and deviation from the [001] orientation on creep properties after the T_2 heat treatment is shown in Table 2. It should be noted that beyond 850°C neither the casting conditions nor the deviation from the [001] orientation (within the limit of about 15°) have any effect on the creep strength of the alloy. Conversely, at 760°C and 750 MPa, the higher is the deviation from [001], the lower is the creep strength. However, the decrease in rupture lives is small compared to that observed for Mar M 200 and Mar M 247 type single crystal superalloys (17, 18). Some creep results obtained on HIP'ed industrial single crystals of CMSX-2 are also included in Table 2. It is evident that HIP'ing, which results in almost total closure of porosity, only improves the creep strength at intermediate temperatures and high stress. At high temperatures (~850°C), HIP'ing does not affect the stress-rupture behaviour of this alloy.

V - Fatigue behaviour

Another important property which must be considered while selecting a single crystal superalloy for turbine blade applications is the fatigue strength. The effect of solidification conditions, heat treatments and HIP'ing on the fatigue behaviour of the CMSX-2 alloy were therefore studied. Single crystals of this alloy were cast both under low and high gradient and then subjected to the high cycle fatigue tests in the repeated tension mode at 870°C ; the results are reported in Fig. 11. The fatigue resistance of specimens cast under high temperature gradient is much superior to that of the material cast under industrial conditions (19). The excellent response of the high gradient cast alloy in fatigue is directly related to the very small pore size (~10 µm). The single crystals cast under industrial conditions have a heterogeneous structure ; the interdendritic spacing and the level of porosity vary along the length of the bar. Specimens machined from the portion of the bar corresponding to the beginning of solidification show a better fatigue resistance compared with those corresponding to the end of the solidification process. Some fatigue tests were also performed on HIP'ed specimens cast under industrial, low gradient, conditions. Their fatigue behaviour has been considerably improved and their strength is now almost equivalent to that of the high gradient cast material (Fig. 11).

Strain-controlled fully reversed low cycle fatigue tests performed at 760°C confirm the much test, the higher is the deviation from the [001] orientation, the shorter is the fatigue life. It can be seen in Fig. 12a that, for a total strain range of 1.2%, the fatigue life is decreased by an

Table 2 – Effect of casting conditions, HIP'ing and deviation from the [001] orientation on the creep properties of T_2 heat treated CMSX-2 single crystals.

Test conditions		High gradient solidification			Low gradient solidification			
Temperature (°C)	Stress (MPa)	Time for 1% creep (Hrs)	Rupture life (Hrs)	Elongation (%)	Deviation from [001] (°)	Time for 1% creep (Hrs)	Rupture life (Hrs)	Elongation (%)
760	750	120	1138	21.8	6	89	759	12.5
		134	1117	13.9	15	124	664	11.8
					22	90	484	9.6
					5*	135*	939*	15*
900	380	75	227	37.1	12	78	212	19.7
		70	230	19.7	10*	82*	212*	12.9
950	240	142	370	24.5	5	130	341	10
		144	380	34.9	7.5	120	305	13
1000	200	73	177	34.3	8.5	67	162	–
		60	176	–	6	35	161	24
1050	140	160	266	20	15	163	255	11.4
		197	288	8.4	9*	145*	222*	5.4

*HIP'ed

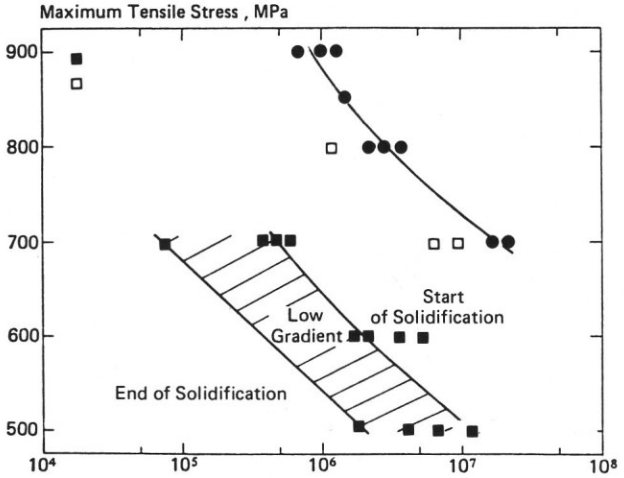

Fig. 11 - Effect of thermal gradient and HIP on the HCF behaviour of CMSX-2 at 870°C (frequency = 50 Hz).

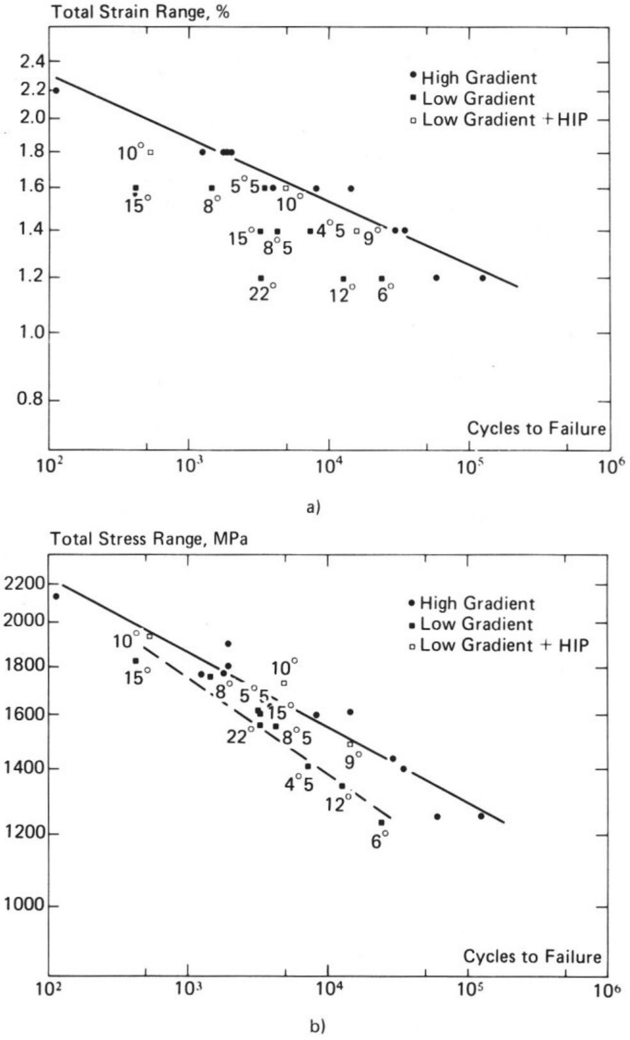

Fig. 12 - The effect of processing conditions, orientations and HIP'ing on the LCF behaviour of CMSX-2 at 760°C (frequency = 0.33 Hz). The degrees represent the departure from the [001] orientation.

order of magnitude when the crystal orientation, relative to the [001], moves away from 6 to 22°. The decrease in fatigue life is a consequence of the increase in stress level through the increase of elastic modulus. Since the plastic strain component at 760°C is small, the results can be quite reasonably plotted as total stress vs. number of cycles to failure (Fig. 12b). In this representation, the effect of crystalline orientations on the fatigue life of the industrially processed single crystals does not appear and all the results of low gradient single crystals can be represented by a single curve.

The examination of fracture surface shows that the cracks are initiated at microporosity, which proves that these "defects" (microporosity) (Fig. 13), are of prime importance in determining the fatigue life of this alloy. The size of microporosity in "industrial" single crystals can be as large as 80 µm but hardly over 10 µm in single crystals cast under the very high temperature gradient. The adverse effect of microporosity is also indirectly confirmed by the results obtained after HIP'ing of single crystal bars solidified under the low temperature gradient. Indeed, the fatigue strength of single crystals cast under low gradients after HIP'ing can be restored to that of the high gradient processed crystals (Fig. 12a,b).

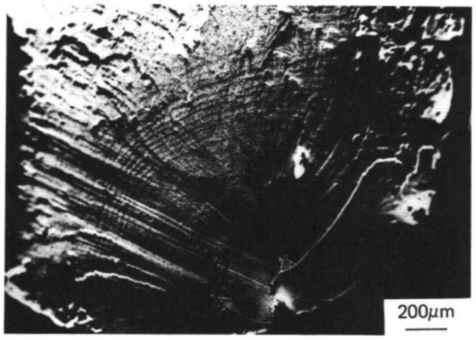

Fig. 13 - Crack initiation at a large pore in a low gradient processed single crystal (HCF at 870° C).

VI - Conclusions

Various single crystal superalloys have been developed to cope with the increasing turbine inlet temperatures in advanced aircraft engines. Research work in U.K. and in France has led to the development of a number of single crystal superalloys including some relatively low density materials which can be possibly used in certain critical applications due to reduced disc stresses. Work on heat treatments has clearly shown the importance of both solutioning and precipitation heat treatments in optimizing the creep strength of single crystal superalloys. Proper heat treatments can improve the temperature capability of the alloy by almost 30°C.

Microporosity is identified as the single important source of fatigue crack initiation. High gradient solidification which minimizes the amount and size of pores greatly improves the fatigue resistance. HIP'ing of single crystals processed under industrial, low gradient, solidification conditions leads to a considerable improvement of both the high cycle and low cycle fatigue resistance of modern single crystal superalloys.

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