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SNECMA EXPERIENCE WITH COST EFFECTIVE DS AIRFOIL TECHNOLOGY APPLIED USING CM 186 LC® ALLOY

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ABSTRACT

From a cost point of view SNECMA has found DS columnar grain manufacturing technology to be highly attractive compared to single crystal. CM 186 LC alloy exhibits enhanced mechanical and environmental properties and temperature capability compared to MAR M 200 Hf alloy; these properties are close to first generation single crystal alloys up to 982°C (1800°F). The alloy is shown to be amenable to various coating and brazing high temperature processes. The longer term creep-rupture/phase stability data base on the alloy has now been extended out to 8300 hours at 1038°C (1900°F). Castings for engine test have been produced using CM 186 LC alloy.

INTRODUCTION

The efficiency of gas turbines is dependent on thermodynamic criteria such as overall pressure ratio and turbine inlet temperature. During the last 30 years, turbine inlet temperatures have increased by about 450°C (810°F). About 70% of this increase is due to more efficient design of air cooling for turbine blades and vanes, particularly the advent of serpentine convection cooling with turbulators and pin fins and film cooling and thermal barrier ceramic coatings, while the other 30% is due to improved superalloys and casting processes. The greatest advances in metal temperature, stress and environmental capability for turbine airfoils has been the result of the development of directionally solidified, columnar grain (DS) and single crystal (SX) superalloy casting process and engine application technology pioneered by Pratt and Whitney Aircraft.

DS manufacturing technology (casting, solution heat treatment and inspection) can be less expensive than single crystal and the production of single or multi-airfoil vanes with large platforms can be more straightforward. MAR M 200 Hf alloy has been widely used for DS columnar grain airfoils and SNECMA has had good experience with the alloy in complex shape vanes and blades, in particular those with extended platforms. These comments relate to both manufacturing experience and turbine engine service performance.

However, the temperature and environmental conditions in new engine designs are becoming more severe, not only for vanes but also for the longer, low pressure (LP) turbine blades. This brings about the need for improved second generation DS superalloys. This class of alloy generally contains 3% Re, offers improved creep and oxidation performance but at the expense of some increased density. The second generation alloy studied in the paper is CM 186 LC [3] which is a nickel-base alloy containing 3% Re, 1.4% Hf and 67% of the coherent γ' precipitate strengthening phase.

The investigation work presented are:
- heat treatment evaluation
- initial environmental and mechanical property characterization
- industrialization
- a thermal fatigue technological test, and engine testing with a M53-P2 military engine used as a test vehicle.

This work is typical of a new alloy evaluation program at SNECMA. The data offer to design engineering the possibility of designing turbine airfoils with an alloy which may be useful for future engines.

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CHEMICAL COMPOSITION AND HEAT TREATMENT

Chemical Composition

The nominal composition of CM 186 LC is shown in Table 1, in comparison with René 142, PWA 1426 and MAR M 200 Hf, all of them being Ni-based DS superalloys.

Table 1
Chemical Composition (wt%)

	C	Cr	Co	Mo	W	Ta	Re	Al	Ti	B	Nb	Zr	Hf	Ni	
CM 186 LC®	0.07	6	9	0.5	8.4	3.4	3	5.7	0.7	0.015	-	0.005	1.4	bal.	8.70
René 142	0.12	6.8	12	1.5	4.9	6.4	2.8	6.2	-	0.015	-	0.02	1.5	bal.	8.6
PWA 1426	0.10	6.5	12	1.7	6.5	4	3	6	-	0.015	-	0.03	1.5	bal.	8.6
MAR M 200 Hf	0.13	8	10	-	12	-	-	5	2	0.015	0.9	0.02	1.75	bal.	8.5

Density (kg/dm³)

The first three alloys contain 3% Re. They are designated as second generation DS superalloys whereas MAR M 200 Hf is a first generation DS superalloy. Re is known to partition mainly to the γ matrix (roughly 80%), and retard coarsening of the γ' strengthening phase because it slows diffusion and increases γ/γ' misfit. Small Re clusters, detected in the γ matrix, act as efficient obstacles against dislocation movement. The remaining 20% of the Re partitions to the γ' thereby strengthening that phase [3]. These features provide significant improvement to mechanical and environmental properties. Re, Cr and Mo decrease metal fluidity during the casting operation. CM 186 LC has the lowest Re+Cr+Mo content.

All the alloys contain Hf to strengthen and improve the ductility of grain boundaries, thus improving transverse properties. This is particularly important for vane shrouds [4]. However, Hf is highly reactive with shells and ceramic cores and can be responsible for oxide inclusions in DS airfoil components.

The second generation alloys contain less W than MAR M 200 Hf. This element provides some improvement in high temperature mechanical properties but can be responsible for freckles, which are chains of small equiaxed grains formed during solidification of the DS airfoils, and instability problems in relationship with Hf. (The occurrence of platelets during HCF tests has led SNECMA to decrease Hf content from 2.1 to 1.75% in MAR M 200 Hf). Re-containing alloys can be sensitive to freckles. The (W+Re) content of CM 186 LC is slightly lower than the W content of MAR M 200 Hf, and CM 186 LC contains 3.4% Ta which is beneficial in relation to propensity to freckling. High W also adversely affects oxidation and hot corrosion resistance.

Interestingly from a cost point of view, CM 186 LC is a derivative of the CMSX®-2/-3/-4 family of single crystal alloys. This ensures the possibility of melting from virgin/CMSX-2/-3/-4 foundry revert blends [3]. Table 2 compares chemical compositions of two heats: one from 100% virgin material and another with 50% recycled CMSX®-4 foundry revert material.

These alloy features confirm SNECMA's strategy to evaluate CM 186 LC for future turbine engine applications.

In this paper, CM 186 LC alloy is directly compared to MAR M 200 Hf, which features 1.75% Hf and improved solutioning at 1240°C (2264 °F) (5°C below the incipient melting temperature). This specific heat treatment for MAR M 200 Hf results in a 10°C creep temperature capability improvement and also offers a significant decrease in property scatter compared to the original property performance of the alloy.

Table 2
Chemical composition of CM 186 LC alloy heats with or without recycled material (wt%, *ppm).

	C	Si	Mn	S*	Al	B	Bi*	Nb	Co	Cr	Cu	Fe	Hf
100% virgin	0.069	<0.02	<.001	4	5.68	0.015	<.2	<.05	9.4	6	<.001	0.027	1.4
50% recycled	0.07	<0.02	.001	2	5.7	0.014	<.2	<.05	9.4	6	<.001	0.047	1.4

	Mg*	Mo	N_2*	O_2*	Ta	Ti	W	Zr	Re
100% virgin	<80	.5	1	1	3.4	0.74	8.4	0.005	2.9
50% recycled	<80	.49	1	1	3.4	0.74	8.4	0.006	2.6

Heat Treatment

Solutioning

The majority of DS and SX alloys need a solutioning heat treatment to give a uniform precipitation of optimized 0.45 μm cubic γ' on subsequent aging to maximize creep-rupture properties. MAR M 200 Hf and René 142 require extensive solutioning to optimize their mechanical properties [1]. PWA 1426 has been developed to offer the mechanical properties of single crystal PWA 1480 while having higher casting yields normally achieved with DS alloys. This has been achieved with only partial solutioning [50%] of the γ' precipitates [2].

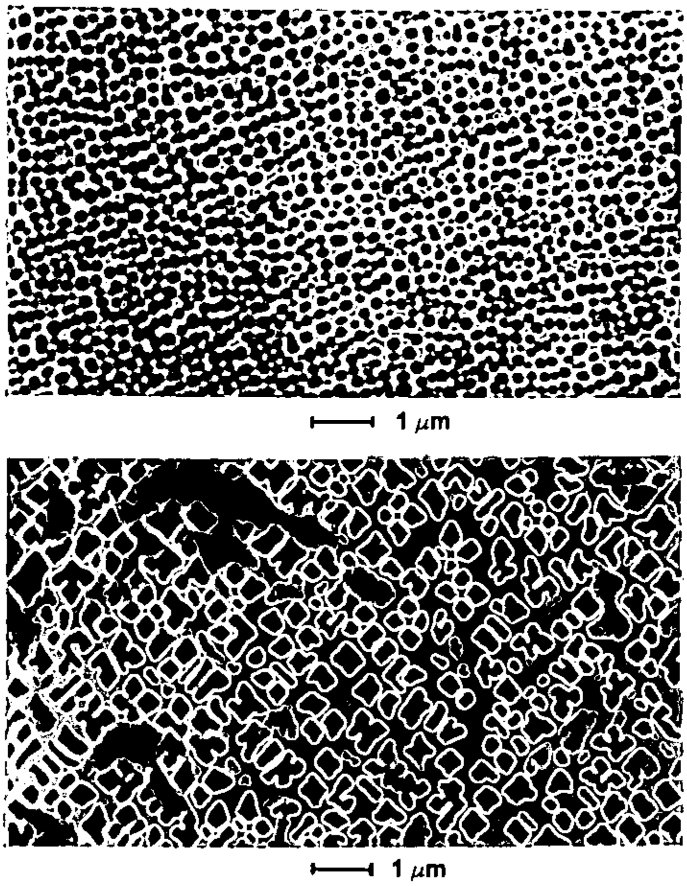
The development program goal of CM 186 LC was to provide longitudinal creep rupture properties in the as-cast plus double aged condition better than DS CM 247 LC® [5-6] and equivalent to CMSX-2/-3 [7] single crystals alloys up to 980°C (1796°F). This is interesting for vane applications since solutioning can result in recrystallization due to high residual casting stresses in transition areas between thick and thin sections of the part (for example, trailing edge areas near the shroud of an integrally cast, shrouded vane segment). Nevertheless, the possibility to improve the mechanical properties by performing a solutioning treatment has been investigated.

Liquidus, solidus and γ' solvus have been determined for CM 186 LC using a Differential Thermal Analysis method with a high temperature calorimeter. The liquidus is 1388°C (2530°F) and the solidus is 1326°C (2418°F). The γ' solvus is 1250°C (2282°F). In fact, SEM examination of samples treated at different temperatures showed that γ' solutioning begins at 1220°C (2228°F).

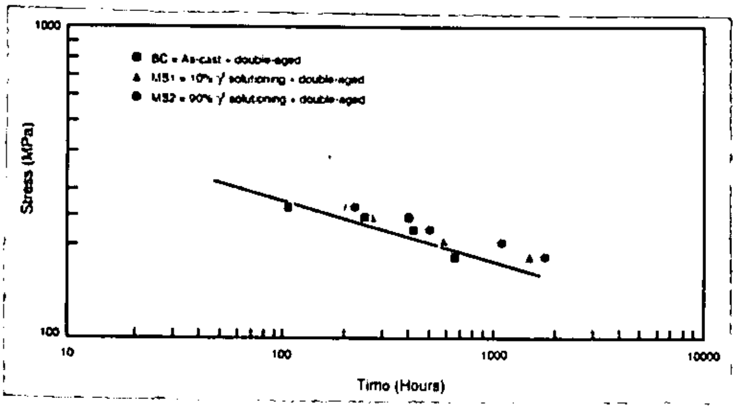
In the as-cast condition, SEM examination has shown appreciable areas of γ/γ' eutectic phase (Fig. 1). The γ' precipitates have a rather irregular cubic morphology : 0.5 to 0.75μm. Interdendritic areas have been found where the γ' is rather globular. This can be a result of microsegregation.

The first goal was to determine the incipient melting point. Samples in the as-cast condition were placed in a furnace at temperatures between 1250°C (2282°F) and 1300°C (2372°F). Incipient melting appears at 1275°C (2325°F), which is 20°C (36°F) higher than MAR M 200 Hf.

Different solutioning heat treatments have been tested and a solutioning ratio determined for each of them. Up to 90% of the γ/γ' eutectic phase could be solutioned. Stress-rupture tests were performed on samples in the as-cast plus double aged condition, "partially" solutioned (10% of γ/γ' eutectic phase) plus double aged condition and "completely" solutioned (90% of γ/γ' eutectic phase) plus double aged condition. Test results are presented in Figure 2.



γ' morphology in the as-cast condition
Figure 1



Stress rupture at 950°C (1742°F) of CM 186 LC partially or completely solutioned compared to As-cast and double aged condition.

Figure 2

Effect of Aging on Carbide Stability

The effect of aging in the range 1050°C (1922°F)-1200°C (2192°F) have been studied to address standard brazing and coating process thermal cycles. Image analysis techniques have been extensively used to study the effect of high temperature aging on carbide morphology and size.

In the as-cast condition, there are two types of carbides:

- "Chinese script" type, that is fine carbides whose morphology appears like chinese script, [MC_1]
- blocky carbides [MC_2]

The first type contains Ti, Hf, and Ta whereas the second type contains only Hf and Ta.

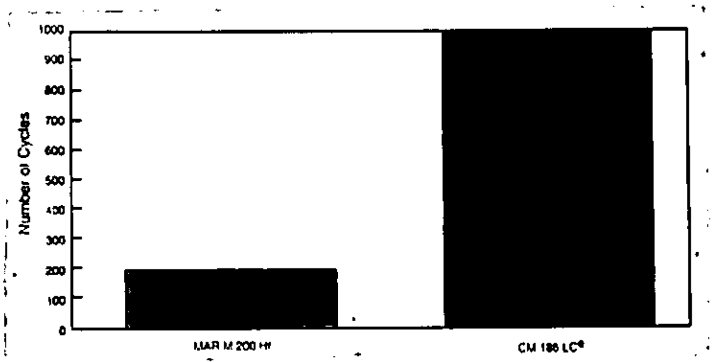
At 1050°C (1922°F), there is no modification on carbides up to 10hrs. For longer times, fine dispersed carbides form along grain boundaries and small lenticular and acicular carbides appear which contain Hf and Ta. [MC_2] At 1150°C (2102°F), grain boundary and "chinese script" carbides disappear after 10hrs and the lenticular and acicular carbides continue to develop. The same phenomenon occurs at 1200°C (2192°F) but at a faster rate.

STANDARD CONDITION CHARACTERIZATION

The standard study of cast superalloys for turbine airfoils at SNECMA consists of oxidation/corrosion testing to find if the alloy is suitable for jet engine applications and determine the type of coating needed. This is followed by physical and mechanical properties characterization.

Oxidation and hot corrosion (sulfidation) resistance

CM 186 LC, DS bare specimens have been tested in oxidation and hot corrosion (sulfidation). In oxidation, plates and bulk specimens of CM 186 LC have been tested at 1100°C (2012°F). The second generation alloy is much better than MAR M 200 Hf. Figure 3 shows the results in terms of number of cycles before catastrophic mass loss. Those tests also showed that CM 186 LC is sensitive to spalling at the edges of the specimens and life is dependant on geometry. It confirms that CM 186 LC needs a coating to avoid problems particularly at leading and trailing edges. At 850°C (1562°F) and 900°C (1652°F) in standard sulfidizing conditions, hot corrosion resistance of the two alloys are very similar. This fact led us to the conclusion that a C1A coating, consisting of chromizing and aluminizing, is necessary for turbine engine service.



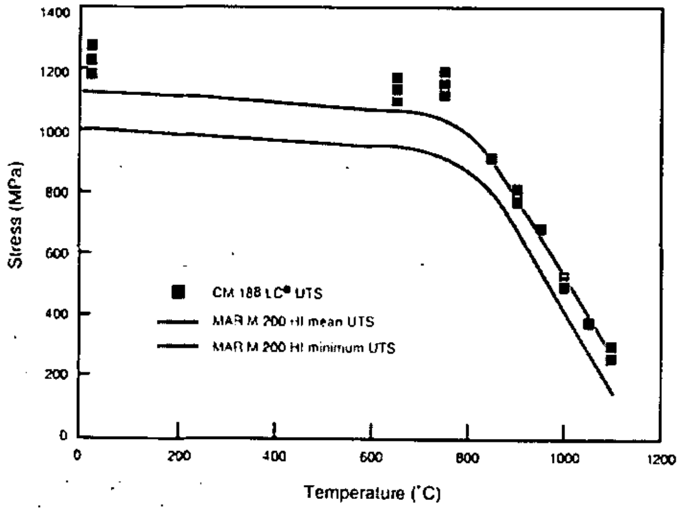
Oxidation resistance at 1100°C of CM 186 LC and MAR M 200 Hf
Figure 3

Mechanical Properties

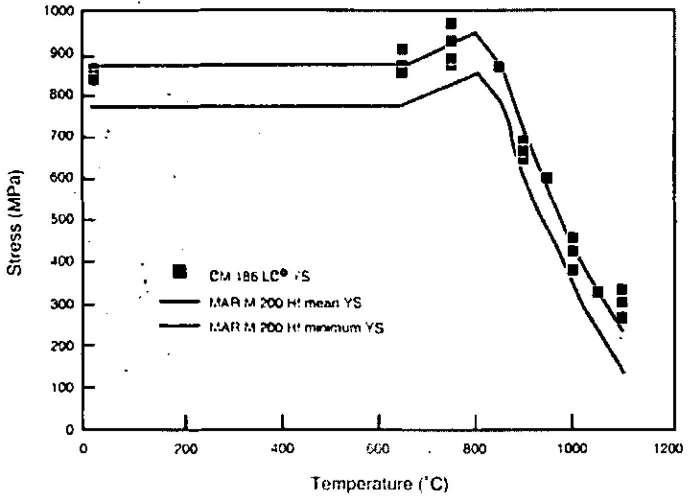
Since CM 186 LC is likely to need a coating, it was decided to conduct mechanical testing on samples with the following heat treatment: As-cast +1100°C(2012°F)/10hrs + 870°C (1598°F)/16hrs. The first part of the treatment simulates a normal C1A coating diffusion which is the most frequently used at SNECMA for DS or single crystal alloys. In fact, process parameters will be defined later, but then it will be necessary to evaluate the alloy's sensitivity to heat treatment. In all cases, it was necessary to characterize the mechanical properties in this condition.

Tensile Tests

Tensile tests have been performed at 20°C (68°F), 750°C (1382°F), 850°C (1562°F), 950°C (1742°F), 1050°C (1922°F) and 1100°C (2012°F) (Figs. 4-5). They show that the yield strength of CM 186 LC is similar to MAR M 200 Hf. A significant improvement is obtained for ultimate tensile strength.



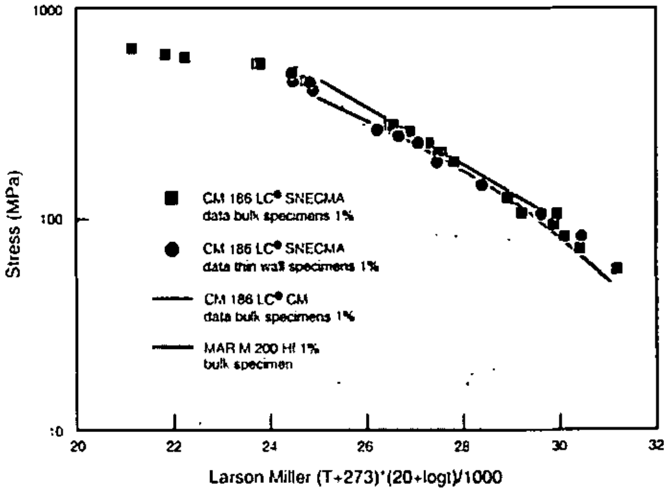
Ultimate Tensile Strength
Figure 4



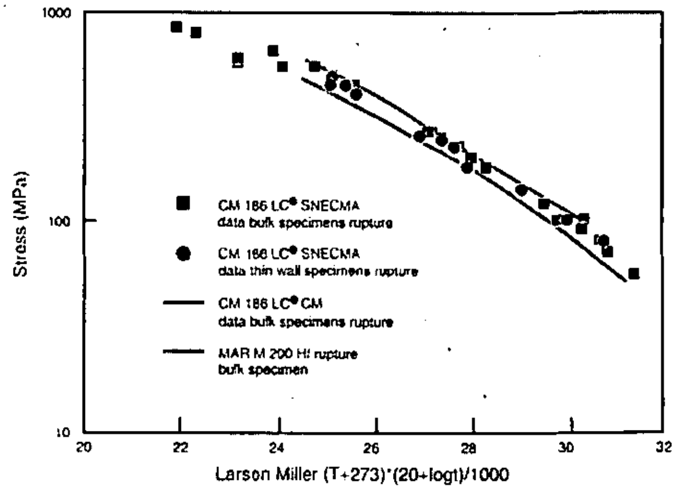
Tensile yield strength
Figure 5

Creep Tests

Longitudinal creep and stress rupture tests show marginal effects of heat treatment between the SNECMA heat treatment and the Cannon-Muskegon double age of 1079°C (1975°F)/4hrs + 871°C (1600°F)/20 hrs. (Figs. 6-7). Tests performed on thin wall specimens show no drop in mechanical properties. All these results confirm that even in the SNECMA standard condition, i.e., no solution heat treatment, CM 186 LC offers a creep temperature capability improvement of 20°C (36°F) compared to MAR M 200 Hf up to 1050°C (1922°F) and even more at higher temperatures. It seems that CM 186 LC is not very sensitive to aging heat treatment conditions. This beneficial feature is probably due to Re which slows γ' coarsening that occurs during the coating simulation heat treatment. The longer term creep-rupture/phase stability data base on the alloy has now been extended out to 8328 hrs at 1038°C (1900°F) with maintenance of the linear log stress-log stress-rupture life relationship.

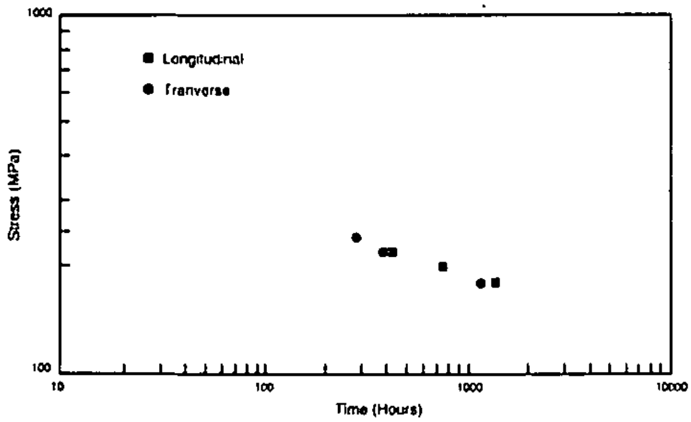


DS Longitudinal 1% creep properties
Figure 6

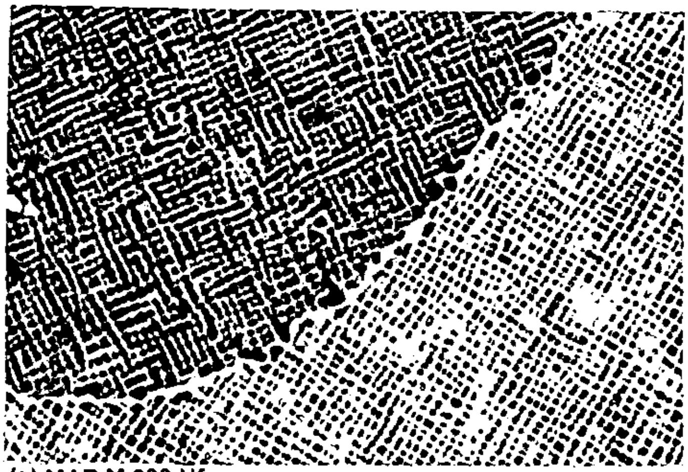


DS Longitudinal stress-rupture properties
Figure 7

Creep and rupture tests with stress perpendicular to grain boundaries on bulk specimens have been performed to test the transverse properties (Fig. 8). The results obtained are consistent with Cannon-Muskegon transverse creep data. Metallographic analysis was performed to compare the grain boundary grain microstructure of MAR M 200 Hf and CM 186 LC (Fig. 9). The carbide distribution for MAR M 200 Hf is more continuous compared to CM 186 LC which contains coarse γ' along the grain boundaries. Microchemical analyses using transmission electron microscopy with energy dispersive spectroscopy determined that the carbides in MAR M 200 Hf are $Cr_{23}C_6$ and are HfC in CM 186 LC (Figures 10 and 11, respectively). The copper identified is due to the maintaining grid in the TEM.



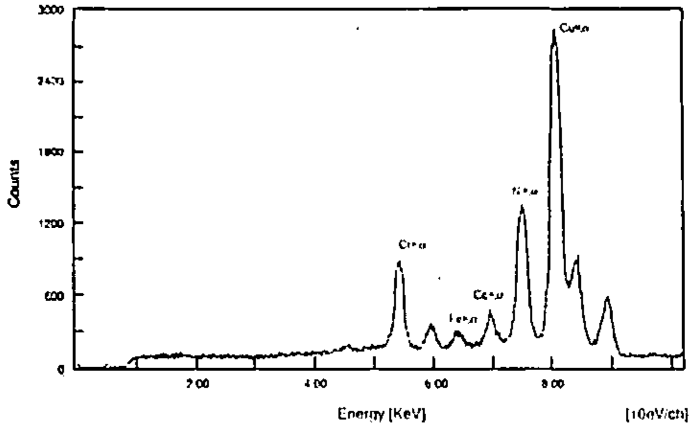
DS Transverse stress-rupture properties
at 950° C (1742°F)
Figure 8



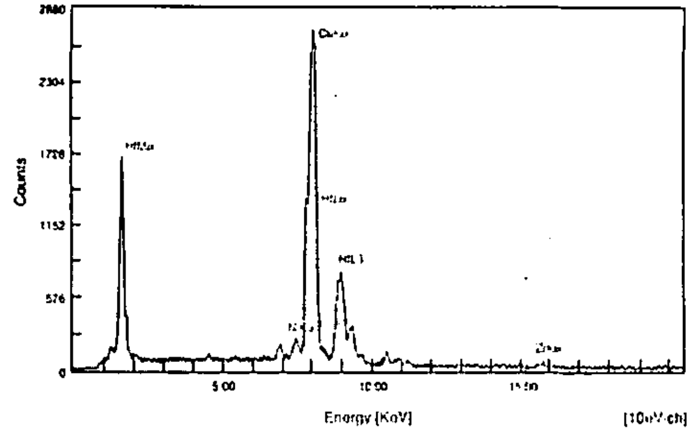
(a) MAR M 200 Hf ⟝——⟞ 10 μm

(b) CM 186 LC ⟝——⟞ 10 μm

Grain boundary structure of
(a) MAR M 200 Hf and (b) CM 186 LC
Figure 9



Carbide analysis of MAR M 200 Hf
Figure 10



Carbide analysis of CM 186 LC
Figure 11

Low cycle fatigue tests

Low cycle fatigue testing is also in progress. Results were not available at time of publication.

INDUSTRIALIZATION

In this section, the results of studies used to determine the manufacturing process parameters and the alloy sensitivity to processes needed for vane production will be presented.

Castability

Solidus and liquidus temperatures for CM 186 LC are 30°C (54°F) higher than for MAR M 200 Hf, but the castability range (liquidus-solidus) is wider in the case of MAR M 200 Hf (75°C (135°F) vs 52°C (94°F) for CM 186 LC).

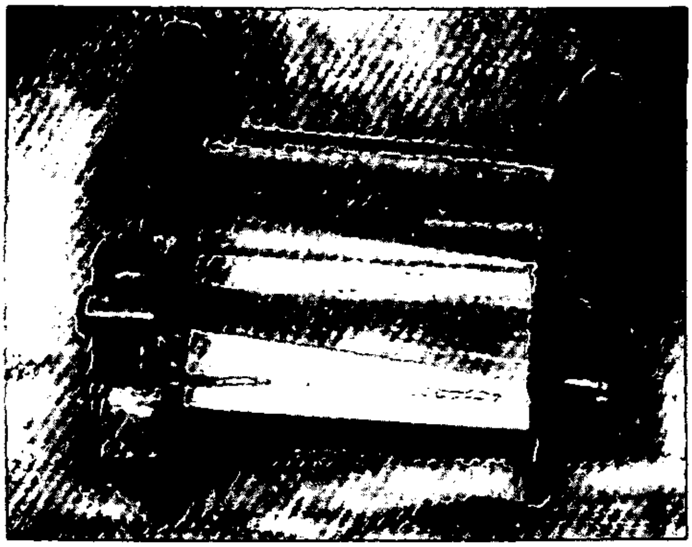
Samples of CM 186 LC have been melted under vacuum at 1530°C (2786°F) in two ceramic crucibles which represent the shell mold compositions that are used at SNECMA. The same trials have been performed with MAR M 200 Hf. Each button and crucible have been characterized visually and by chemical analysis of their surfaces and of a section in order to choose the most suitable ceramic system from a reactivity point of view. The reactivity behavior of the two alloys are very similar.

A few molds of CM 247 LC, CM 186 LC and René 142 have been cast to evaluate the alloys DS castability. The parts cast were:

LP turbine blade of CFM56-5C commercial engine.
HP turbine blade of M53-P2 military engine.
HP turbine vane of M53-P2 military engine.

For each mold, the normal DS casting parameters used for MAR M 200 Hf have been used. Fluorescent dye penetrant macroetch and X-ray inspection were performed. The results showed little porosity and good columnar grain morphology.

In view of the in-depth CM 186 LC evaluation, it was necessary to produce half a set of M53-P2 HP turbine vanes. Four molds have been cast to define casting parameters. The defects encountered have been freckles and grain morphology defects. No problems of reactivity or inclusions has appeared in production, but problems with freckles and grain morphology were confirmed. These problems are probably due to lack of experience and part geometry: the vane segment has a wide chord and is complex with large shrouds (Fig. 12).



M53-P2 HP turbine vane
Figure 12

Brazing

This study included parameter determination and mechanical property characterization. HP turbine vanes are assembled with Hastelloy® Alloy X cooling inserts and Haynes® Alloy 25 caps. Two filler metals can be used, depending on the gaps: one for gaps greater than 100 μm and another for less than 100μm. The configurations tested are the following:

CM 186 LC - Hastelloy Alloy X with a 300μm gap
CM 186 LC - Haynes Alloy 25 with a 300 and 40μm gap

Process parameters currently used for MAR M 200 Hf parts were first tested. The process is the following:

- brazing of cooling inserts
- visual and X-ray inspection
- brazing of external parts
- diffusion.

The parameter selection has been made by means of SEM examination of samples brazed and heat treated in order to take into account the combined effects of brazing, coating and final heat treatment on microstructure and properties. At this moment, it is not known which coating will be chosen, but the potential damage is due to microstructural changes which are controlled by process temperatures. Consequently, it was decided to coat at 1150°C (2102°F) for 3hrs, which is the highest temperature that could be attained, and then age at 870°C (1598°F) for 16hrs.

The micrographic examination revealed that:

- all gaps have been filled in
- no chemical reactions with the coating were apparent
- for high clearances, no eutectic phases have been met in the bonding area
- no major metallurgical transformations were seen in CM 186 LC.

Tensile tests have been performed on brazed specimens following the process described earlier. The results are reported in Table 3. These mechanical property results are excellent.

Table 3
Tensile properties

Specimen	Yield strength (MPa)	UTS (MPa)*	A%
CM 186 LC/Hastelloy X (300μm)	138	147	6.8
Hastelloy X minimum		105	
CM 186 LC/Haynes Alloy 25 (300μm)	209	236	9.5
CM 186 LC//Haynes Alloy 25 (40μm)	209	230	9.5
Haynes Alloy 25 minimum	125	230	

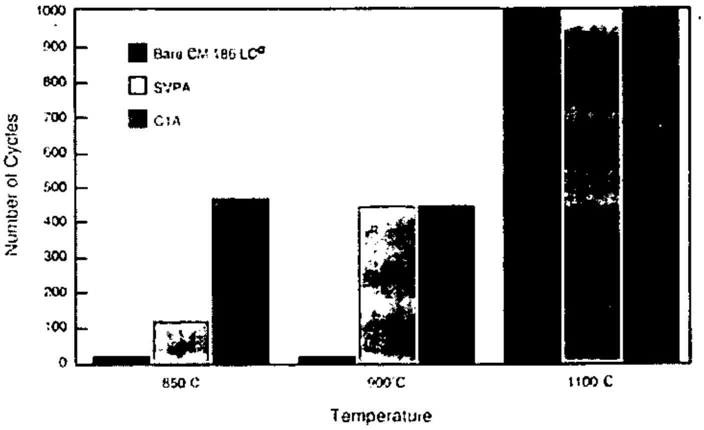
(*UTS=Ultimate Tensile Strength)

Coating

The process parameters were to be chosen among the following possibilities:

- aluminizing by a SNECMA process (SVPA)
- CIA (chromizing and aluminizing)

Micrographic examinations have been performed but didn't show any major differences between the different coating processes. Due to this fact, the only way to select the best process was to test specimens coated in the different conditions in oxidation at 1100°C (2012°F) and hot corrosion at 850°C (1562°F) and 900°C (1652°F) (Fig. 13). The



Corrosion and oxidation tests at 850°C (1562°F), 900°C (1562°F) and 1100°C (2012°F)
Figure 13

performance of CM 186 LC in the oxidation test was so good that no improvement from standard coatings was observed. The corrosion test showed that C1A was clearly better at 850°C(1562°F); both coatings performed the same at 900°C (1652°F).

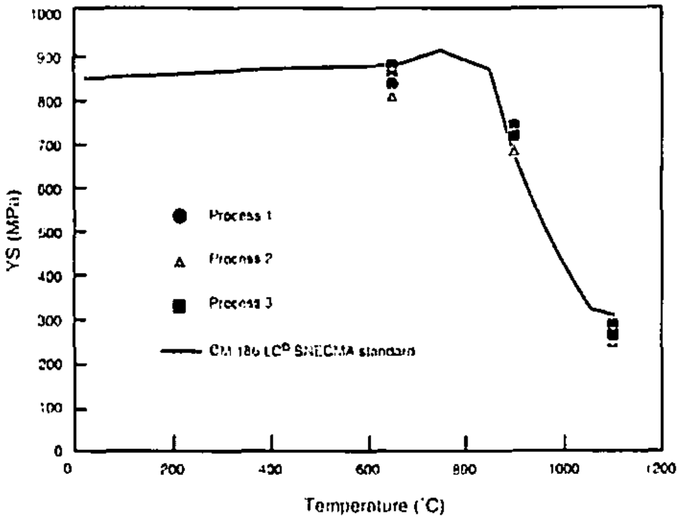
Process Effects On Mechanical Properties

The goal of this study was to compare tensile and creep properties of CM 186 LC heat treated following three different vane processes to standard CM 186 LC properties.

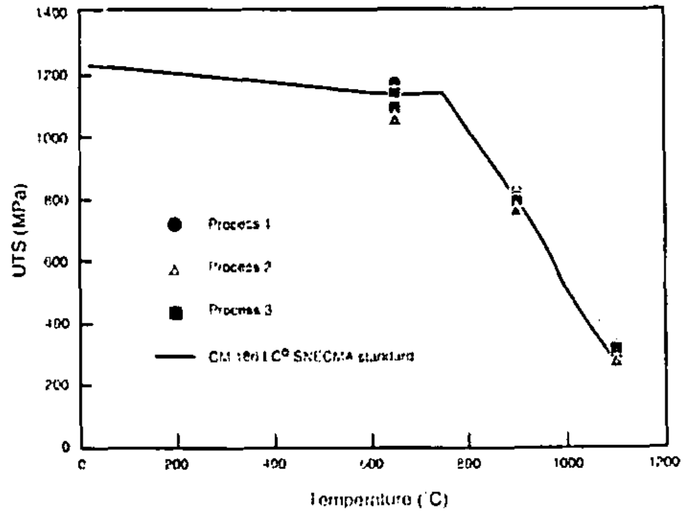
process 1: brazing-diffusion-SVPA 1100°C (2012°F)/5hrs.
process 2 : brazing-diffusion-C1A 1100°C (2012°F)/10hrs.
process 3 : brazing-diffusion-C1A 1100°C (2012°F)/5hrs+
1150°C (2102°F)/3hrs.

All these parameters are possible for engine application. In addition, the test material from each process was aged at 870°C (1598°F)/16hrs prior to testing.

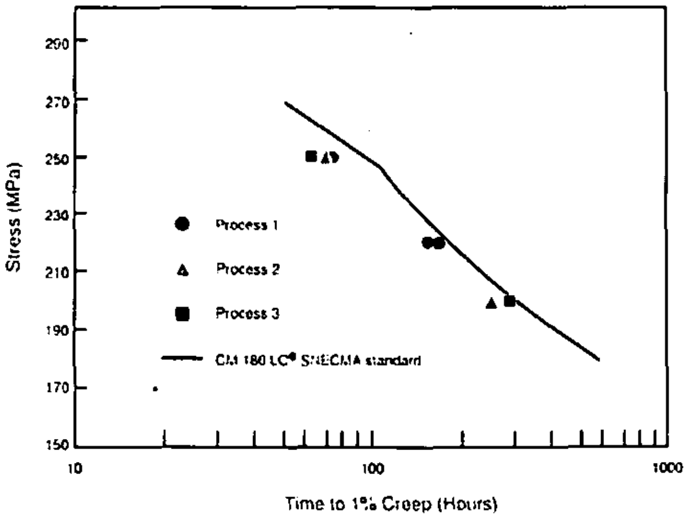
The tests conducted were tensile test at 650°C (1202°F), 900°C (1652°F), and 1100°C (2012°F), and creep test at 950°C (1742°F). The results are shown in Figs. 14-17.



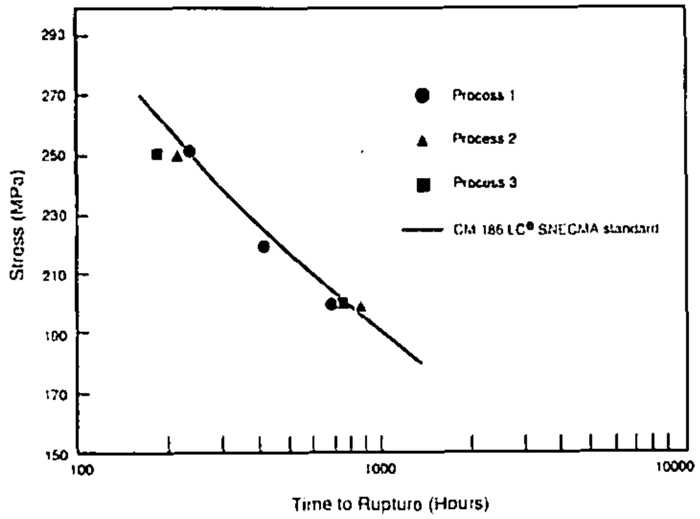
Yield strength
Figure 14



Ultimate Tensile strength
Figure 15



1% Creep 950°C (1742°F)
Figure 16



Stress-rupture 950°C (1742°F)
Figure 17

No significant drop in the mechanical properties have been observed except in creep. Metallurgical changes in γ' morphology have been observed after the treatment at 1100°C (2012°F)/5hrs+1150°C(2102°F)/3hrs. So despite the fact that we didn't see any clear mechanical improvement of 1100°C(2012°F)/10hrs compared to 1100°C (2012°F)/5hrs+1150°C (2102°F) /3hrs., the chosen process is the following:

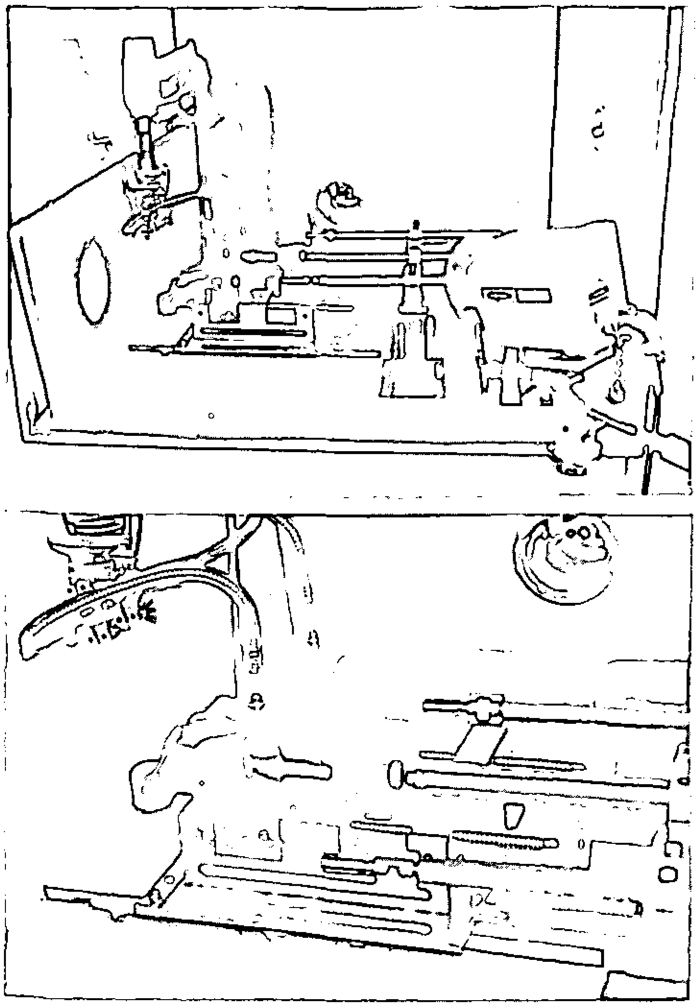
- Brazing
- Diffusion
- Chromizing 1100°C (2012°F)/5hrs } C1A
- SVPA 1100°C (2012°F)/5hrs } coating
- Aging 870°C (1598°F)/16hrs

TECHNOLOGICAL THERMAL FATIGUE AND ENGINE TEST

Technological Thermal Fatigue Test

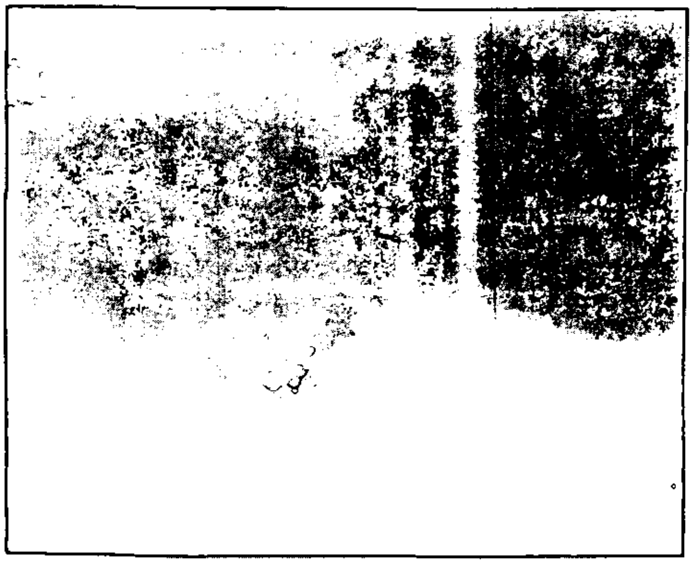
Since the thermal fatigue properties of DS alloys are highly dependant on their crystallographic orientation because of elastic anisotropy, it was interesting to test MAR M 200 Hf and CM 186 LC in conditions as close to reality as possible (except for environment). The intent is to evaluate, by comparison with engine tests results, the importance in service of high temperature properties and oxidation/hot corrosion resistance.

The test configuration is shown in Fig. 18. Two vanes are tested at the same time: one each of MAR M 200 Hf and CM 186 LC. The vanes were processed to the conditions chosen in the previous section (i.e., C1A-coated). The temperature was determined by an optical pyrometer which had been checked with two other parts containing thermocouples. The cooling air inside the vanes was 100°C (212°F). The cycle, as measured by the optical pyrometer at the leading edge of the MAR M 200 Hf part, was 670°C (1238°F) to >1150°C (2102°F) in 10s, 1150°C (2102°F) to 670°C (1238°F) in 10s. There was no hold time in the heating and cooling cycle.

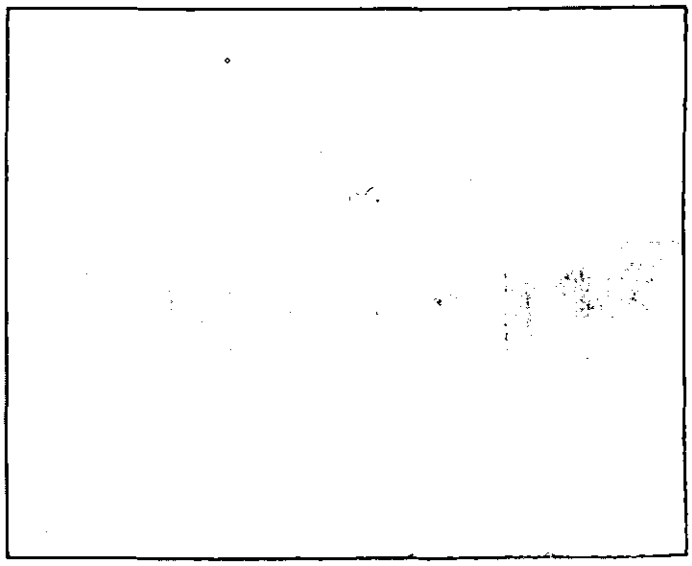


Test facility and configuration
Figure 18

Because of air flow heterogeneity in the test facility, the maximum temperature seen by CM 186 LC was 1180°(2156°F). The two parts have been submitted to 5000 cycles. Figure 19 shows the induced damages, and Figure 20 compares the oxidation effects near the major defect on each part. It can be seen that the interface between the coating and the part is much more oxidized for MAR M 200 Hf. Since oxides have a greater volume than normal constituents, they force the coating to crack which explains the larger defect on MAR M 200 Hf.

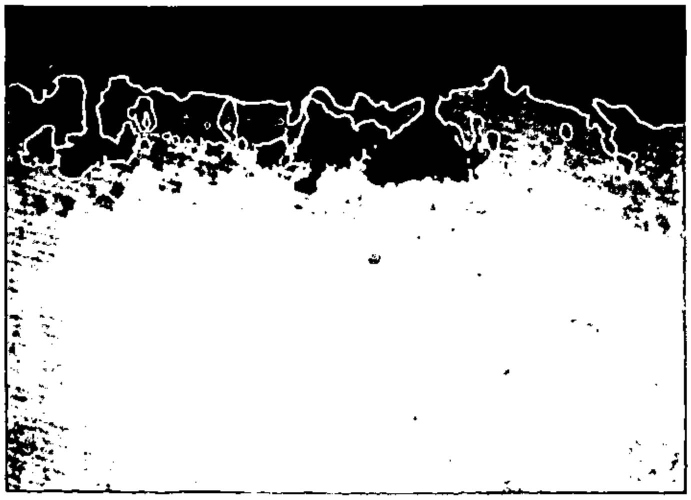


(a) MAR M 200 HF

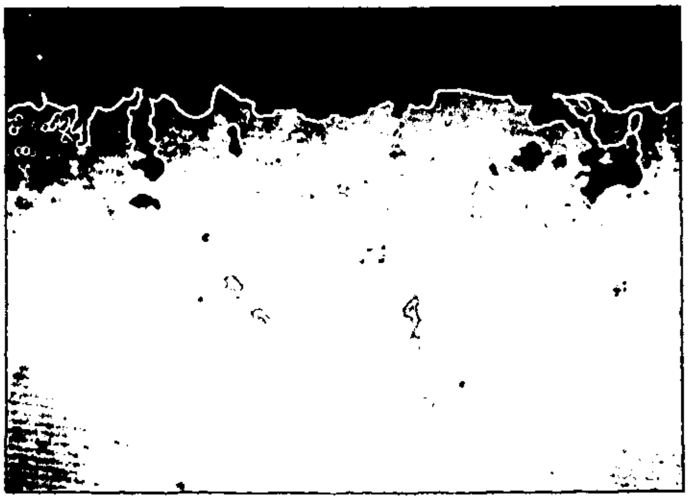


(b) CM 186 LC

Leading edge damage from technological thermal fatigue test (a) MAR M 200 HF (b) CM 186 LC
Figure 19



(a) MAR M 200 Hf



(b) CM 186 LC

Oxidation pattern at leading edge from technolgical thermal fatigue test (a) MAR M 200 Hf (b) CM 186 LC Figure 20

Engine Test

An endurance test on a M53-P2, a military engine, will be completed by mid 1996. Three HP turbine vane materials will be tested: Mar M 509, MAR M 200 Hf and CM 186 LC. The results of this test were not available at the time of publication.

CONCLUSIONS

Mechanical, oxidation and hot corrosion tests of CM 186 LC in SNECMA standard conditions show that this alloy is a good candidate for applications in future engines.

All the processes for vane and blade production have been developed (brazing and coating) to save time in an engine development program. The technological thermal fatigue test has confirmed the improved properties of CM 186 LC in oxidation and thermal fatigue and that C1A coating is well suited for CM 186 LC. Engine testing will be performed this year.

DS airfoils using CM 186 LC could be a cost effective alternative to single crystal components for many high temperature applications in advanced turbine engines. Although Re-containing second generation DS alloys offer only a small raw material cost reduction compared to first generation single crystal alloys, DS castings are easier to produce and have lower manufacturing costs. In the foundry process, grain defect rejections are lower and production of vanes with large platforms is easier. Elimination of solution heat treatment with CM 186 LC is an important advantage compared to other DS alloys and avoids the risk of recrystallization.

For all of these reasons, CM 186 LC can find application in parts which do not require single crystal properties, but do exceed the capability of first generation DS alloys.

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