DEVELOPMENT AND EVALUATION OF NEW INDUSTRIAL DS MONOCARBIDE REINFORCED COMPOSITES FOR TURBINE BLADES

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ABSTRACT

Two new industrially promising DS monocarbide reinforced composites (COTAC 74 and COTAC 741) for advanced gas turbines are evaluated. The major progress achieved lies in their exceptional stability under severe thermal cycling conditions. After 10 000 thermal cycles between 250 and 1070°C, the loss in subsequent creep strength for equivalent rupture lives is less than 15%. A Larson-Miller representation, as extrapolated from short duration tests, is not valid here and, for a better estimation of the real potential of these composites, long duration creep tests are necessary. Such tests, performed between 900 and 1080°C for over 2000 hours at each temperature, demonstrate a 100°C temperature gain along with a 30-40% strength increase over the best current superalloys. The successful realization of DS parts of complex shapes opens the way to industrial fabrication of cast to size blades and vanes with these composites.

Introduction

The trend for increasing efficiency of modern aircraft gas turbines has resulted in continuously higher gas inlet temperature. Evidently this increase in temperature leads to a reduction in specific fuel consumption and an increase in thrust. The present day advanced engines operate at a gas inlet temperature over 1300°C. The normal operating temperature of these superalloy blades is however not more than about 980°C which necessitates a highly efficient and sophisticated cooling of the high pressure first stage blades. Excessive cooling of these blades on the other hand will reduce the potential performance of the engine and it therefore appears that it might be interesting to develop new materials capable of working at higher temperatures rather than achieving a still more efficient cooling. From this standpoint the development of eutectic-like DS (Directionally Solidified) composites seems to be an elegant solution at least in the foreseeable future and places these types of materials at the forefront of the future high temperature materials for advanced gas turbines.

With these specific objectives in mind research work undertaken at ONERA led to the development of a family of composites having a DS cobalt or nickel base superalloy matrix reinforced with transition metal monocarbide fibers (TaC, NbC, TiC, HfC). As early as 1969, Bibring et al. (1 to 3) demonstrated the possibility of surmounting the narrow limits of pseudo-binary eutectic systems (Ni–NbC, Co–TaC, Co–HfC), and of directionally solidifying complex nickel or cobalt base systems by substantial additions of Cr, W, Mo, Al and other elements required for achieving particular properties. Among these composites COTAC 3* seemed to possess a set of properties, that placed it well above the best superalloys at least beyond 925°C.

However, extensive testing of this composite showed two drawbacks, one of which is its low strength in the range $700-800^{\circ}\text{C}$ as compared to γ' -strengthened nickel base superalloys. This particular limitation was at least partially overcome by a special heat treatment of COTAC 3 thus producing an exceptionally high resistant material up to 1100°C , designated COTAC 33 (4). The other defect of COTAC 3 was a drastic decrease in its stress rupture strength after a few thousand thermal cycles between 1070 and 250°C. Although the thermal cycling behaviour of COTAC 33 was found to be much better than that of COTAC 3 up to 1000°C , no significant improvement could be obtained at 1100°C .

The thermal cycling problem has a two-fold aspect. (i) If the maximum cycling temperature is rather low, the thermal expansion mismatch would cause some plastic deformation and the fiber rupture may take place solely due to this "mechanical" effect; however if the maximum cycling temperature is high the plastic deformation would also help the diffusion controlled degradation of the reinforcing phase through the formation of serrations. (ii) The particular effect of the solubility variation of the reinforcing phase in the matrix with temperature will be discussed below.

Under the light of these arguments research work was carried out at ONERA to directionally solidify nickel-base superalloy composites reinforced with niobium carbide fibers. The major advantage of this choice is that γ' hardening of nickel-base solid solutions offer an immense possibility of strengthening particularly at low and intermediate temperatures thereby increasing the flow stress of the matrix in a wide temperature range. It is obvious that such a strengthening would reduce the extent of plastic strain during thermal cycling and consequently the diffusion controlled degradation of the fibers. On the other hand niobium monocarbide fibers were chosen as the reinforcing phase in stead of tantalum carbide because of their higher volume fraction in nickel-base composites and lower density. These consideration sled us to the development of two new composites: COTAC 74 and COTAC 741, which were found to show little fiber degradation even after 10 000 thermal cycles between 1070 and 250°C. Among these two composites COTAC 741 seems to be particularly stable at least up to 1100°C under severe thermal cycling conditions.

COTAC 74 and COTAC 741 composites

Previous work at ONERA on nickel-base, γ' -strengthened matrices reinforced with tantalum carbide fibers (5) proved to be of considerable help in the development of COTAC 74 and COTAC 741 composites. The nominal composition of these two composites are :

COTAC 74 : Ni 20 Co 10 Cr 10 W 4 AI 4.9 Nb 0.6 C COTAC 741 : Ni 10 Co 10 Cr 10 W 5 AI 4.7 Nb 0.5 C.

^{*} Co-10 Ni, 20 Cr, 13.2 Ta, 0.78 C (weight per cent).

The matrices of both these composites are heavily solid solution hardened due to the presence of tungsten and precipitation strengthened by γ' -precipitates. The solution temperature of γ' precipitates is around 1060°C in the case of COTAC 74 and about 1140°C for COTAC 741. The higher stability and volume fraction of γ' precipitates in COTAC 741 directly results from a decrease in cobalt content (10%) and an increase in the aluminium content (5%). The incipient melting point of both composites is approximately 1330°C . Both composites have an acceptable volume fraction of niobium monocarbide fibers (\sim 6%) as measured on transmission electron micrographs. The density of COTAC 74 is 8.6 and that of COTAC 741 about 8.45. At least 10% chromium was considered to be a prerequisite for hot corrosion resistance; increasing the chromium content beyond 10% significantly increases the solidification range of the alloy, thereby rendering the solidification process more difficult. Finally, the solidification range of both COTAC 74 and COTAC 741 was measured to be around $10 \pm 2^{\circ}\text{C}$ by thermal analysis. The solidification was performed to obtain both 8 mm and 55 mm diameter bars. The temperature gradients in the liquid were measured to be about 200°C/c in the case of 8 mm diameter and about 120°C/c for 55 mm diameter ingots; the corresponding maximum solidification rates resulting in properly aligned composites were 2.4 and 1 cm/h. The mechanical testing was performed on specimens directionally solidified either at 1 or 1.2 cm/h.

Tensile tests

Tensile specimens of 3 mm gauge diameter and 30 mm gauge length with 7 mm diameter threaded heads were machined from 8 mm and 55 mm diameter directionally solidified bars. Some selective tests were run at 1070°C on both COTAC 74 and COTAC 741 composites in a Zwick tensile testing machine. Prior to testing the specimens were solution treated during one hour either at 1100°C (COTAC 74) or at 1160°C (COTAC 741) and then airquenched. The subsequent precipitation treatment was chosen to be 760°C–20 hours for COTAC 74 and 850°C–20 hours in the case of COTAC 741. The mean tensile strength of COTAC 74 at 1070°C was 300 MN/m² and that of COTAC 741, 350 MN/m². The detailed longitudinal tensile properties of COTAC 74, in the temperature range 20–1100°C along with some transverse values are listed in Table 1.

Table I
Tensile properties of COTAC 74

	L	Transverse specimens				
Temp. (^O C)	0.02% flow stress (MN/m ²)	Upper yield point (MN/m ²)	UTS (MN/m ²)	Elong. (%)	UTS (MN/m ²)	Elong. (%)
20	660	1260	1550	12.4	1080	0.16
700	_	1130	1240	7.5	_	_
800	786	960 — 1100	960—1100	7	798	2.5
900	_	680	680	7.7	_	-
950	449	580	580	7		-
1000	_	415	415	6.6	_	_
1100	85	287	287	5	81	23

Tensile creep tests

Creep tests were performed on thermally treated specimens which were identical to the tensile ones. Almost all the specimens were coated by the ONERA chromaluminisation technique (6); however some tests were also run at 1070°C on uncoated specimens of COTAC 74 and COTAC 741. All creep tests were performed in air. It was found that even at 1070°C under a stress of 120 MN/m², the rupture lives of both coated and uncoated specimens were equivalent for both composites.

Up to about 900°C, the creep rupture strength of COTAC 74 is much higher than that of COTAC 3 and only slightly lower than that of IN100. Nevertheless, above 900°C, COTAC 74 has a much higher strength as compared to IN100 and is equivalent to COTAC 3.

Testing of COTAC741 specimens showed that the creep rupture lives were at least as good as these of COTAC 74 above 1000°C and better below this temperature: at 900°C under a stress of 260 MN/m², the average rupture life of COTAC 74 is only 150 hours, whereas in the case of COTAC 741 even under 270 MN/m², the failure of specimens occurs after about 230 hours. Similarly, at 950°C under 220 MN/m² COTAC 74 specimens break after about 40 hours, but in the case of COTAC 741, the average rupture lives are about 4 times longer (~ 152 hours). At this stage, it must be pointed out that in these composites, contrary to the monolithic superalloys, a slight decrease of the applied creep stress leads to an important increase in rupture life (Table II). It is obvious that it is impossible to estimate the real potential of these composite in service by a Larson-Miller representation obtained from short duration tests and it is proposed that stresses for at least 1000—hour rupture lives should be determined for each temperature in order to have a more realistic idea of the inherent strength of these composites.

Table II

Stress dependance of rupture lives of COTAC 74 and IN100 at 900°C

Material	Creep stress (MN/m ²) at 900°C for a rupture life of :			
Macorial	150 hours	1000 hours		
COTAC 74	260 MN/m ²	240 MN/m ²		
IN100	$290~\text{MN/m}^2$	210 MN/m ²		

These composites are certainly interesting for a long duration utilization under relatively low stresses and should be particularly suitable, for instance, in the case of low pressure uncooled first stage parts in advanced gas turbines. With this objective, the results of some long duration tests performed on COTAC 74 specimens machined from 55 mm diameter ingots are compared in Table III with those of IN100 and DS 200 superalloys.

Table III

Results of long duration creep tests performed on COTAC-74

Temperature	Creep stress	Rupture lives (hours)				
(o C)	(MN/m ²)	COTAC-74	IN100	DS200		
900	220	2600	~ 800	~ 2400		
950	140	> 8000 (no rupture)	~ 1100	~ 2500		
1040	90	3028	~ 160	~ 250		
1080	60	> 4000 (no rupture)	~ 160	~ 250		

At 900°C for stresses up to 220 MN/m², the creep life of COTAC 74 is at least as good as that of DS 200 and three times better than that of IN100. At higher temperatures the rupture lives of COTAC 74 are at least 10 times longer when compared to DS 200; practically, in long duration tests (\geq 2000 hours) COTAC 74 —as compared to best superalloys— offers a gain of 100°C for 30 to 40% increased applied stresses.

Thermally cycled creep tests

It has previously been shown that thermal cycling severely damages the carbide phase in certain nickel or cobalt base matrices reinforced with transition metal monocarbide fibers (7, 8). This results in a considerable decrease in the subsequent mechanical properties of these composites. In the case of COTAC 3 extensive thermal cycling tests performed at ONERA at high temperatures

showed a drastic decrease in its creep strength under thermal cycling conditions as compared to the isothermal tests (9). In view of this important problem of thermal cycling, it was decided that if a composite is to be considered for aircraft turbines it should yield equivalent stress rupture life under isothermal and thermally cycled creep conditions. The total time imposed for rupture lives was approximately 500 hours both under the isothermal and cyclic conditions. The hold time at the maximum temperature was 28 minutes, the total elapsed time for one cycle was 30 minutes and the minimum temperature was always around 250°C. All the specimens were self resistance heated. A comparison of temperature-cycled creep rupture lives and isothermal ones both in the case of COTAC 74 and COTAC 741 is shown in Table IV.

Table IV

Comparison of temperature-cycled lives with isothermal creep-rupture lives

	Temperature-c	ycled creep	Isothermal creep		
Composites	Cycle temp. (^O C)	Stress	Life	Temp. – Stress	Life
	maxi. — mini.	(MN/m ²)	(hours)	(O C — MN/m ²)	(hours)
COTAC-74	1070250	120	518	1070120	600
	1070—250	120	362		
	1100-250	100	395		
	1100—250	80	692		
COTAC-741	1070-250	120	524	1070120	786
	1070250	120	480	1070—120	523

^{(*) 30-}minutes cycles with 28 minutes hold time at the maximum temperature.

It is apparent that the major progress achieved with the new composites COTAC 74 and COTAC 741 lies in the fact that they exhibit similar rupture lives under isothermal and cycled conditions and therefore seem to be quite insensitive to thermal cycling effects. The good thermal cycling behaviour of both these composites was confirmed in the maximum temperature range 800–1100°C. A possible objection to these type of tests is the relatively low number of cycles as compared to the larger number of cycles in real service. It was therefore decided to perform up to 10 000 rapid cycles in order to evaluate their influence on fiber degradation and the subsequent mechanical properties of the composite. A three minute cycle was chosen with a hold time of about 45 seconds at the maximum temperature. After thermal cycling the residual mechanical properties of COTAC 74 and COTAC 741 were evaluated both by tensile and creep tests at 1070°C. Prior thermal cycling tests were run either at 1070°C or 1100°C. In the case of COTAC 74, the loss in 1070°C ultimate tensile strength after 5000 prior cycles was about 18%; whereas the loss in tensile strength of COTAC 741 after the same number of prior cycles was found to be less than 15%. Metallographic examination of both composites after 5000 thermal cycles at 1070°C showed little degradation of fibers, which was expected in view of the above results.

COTAC 741 composite was further tested in isothermal creep at 1070°C (Table V).

<u>Table V</u>

Comparison of rupture lives of cycled and uncycled specimens of COTAC-741

Cycled specimens					Uncycled specimens			
Prior 3-m	in.cycles	Subsequent isothermal creep			Isothermal creep			
Temp.(^O C) max. — min.) Number of Temp. Stress Life n. cycles (O C) (MN/m²) (hours)		Temp. (^O C)	Stress (MN/m ²)	Life (hours)			
1070-250	5265	1070	120	149	1070	120	523	
1070-250 1100-250	9978 5738	1070 1070	120 120	200 141	1070	120	786	

The fiber morphology as shown in Fig. 1 (10 000 prior cycles and the subsequent creep test at 1070° C) illustrates the relative insensitiveness of this composite to thermal cycling.

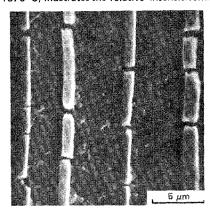


Figure 1 : COTAC 741. Fibers broken during a 200 hour creep test (1070°C/120 MPa) after 10 000 prior cycles at 1070°C.

SEM

It is inferred from these results that if equivalent rupture lives are to be obtained on previously cycled (up to 10 000 cycles) and uncycled specimens then the subsequent creep stress in the former case should be decreased by about 10% only. This realistic estimation is based on the stress dependance of creep rupture lives at any given temperature in these composites (Table VI). It is evident from Table VI that a stress decrease of about 14% at 1050°C increases the rupture life of the composite by a factor 10.

Stress dependance of rupture lives at 1050°C in COTAC 741

Temperature	Stress	Rupture lives		
(°C)	(MN/m ²)	(hours)		
1050	140	140		
1050	120	1452		

Thermal cycling phenomenon in DS carbide reinforced composites

It has been shown that although prior thermal cycling (up to 10 000 cycles at 1070°C) has only a slight effect on the subsequent creep strength of COTAC 741, fiber degradation is however not completely absent. In fact, if the maximum cycling temperature is raised to 1250°C, the fibers may undergo a rapid degradation, in contrast to the remarkable fiber stability of unstrained composites.

The practical implication of this observation is that the thermal cycling deleterious effect is displaced to very high temperatures and therefore the material may be used confidently up to at least 1100°C.

Two parameters should be taken into account in order to gain some insight into the thermal cycling behaviour of carbide reinforced DS composites: 1) the first factor which may influence fiber stability is the solubility variation with temperature of the reinforcing phase or eventually the thermodynamic stability as expressed by the relative value of the carbide free energy of formation; 2) due to the large thermal expansion mismatch of the two phases considerably high internal stresses exist in such composites. The internal stresses may induce plastic deformation in the matrix during temperature fluctuations even in the absence of an externally applied load. At high temperatures the cumulative plastic deformation of the matrix may favour fiber degradation (serrations or platelets) through enhanced diffusion of the reinforcing phase in the matrix in the vicinity of the fiber-matrix interface. It was therefore decided to study, on one hand the variation of solubility of various monocarbides in cobalt or nickel base matrices and on the other hand the effect of strengthening the matrix on fiber degradation.

High temperature fiber solubility

The solubility of the carbide phase was determined by measuring the transition metal content in the matrix by electron microprobe analysis. The measurements were performed at room temperature both on the DS as cast as well as on solution treated specimens at temperatures 30 to 50°C below

the melting point and then water quenched, Table VII. The solubility variation of tantalum carbide is important in the case of COTAC 3 composite where the fibers are severely damaged after thermal cycling. On the other hand the solubility variation of niobium carbide in COTAC 74 or COTAC 741 is much less and both these composites exhibit little fiber degradation during thermal cycling. Furthermore the Ni,Cr—TaC composite seemed to be particularly interesting since there is no solubility variation of tantalum carbide up to 1300°C. Some specimens of this composite were thermally cycled in the range 250–1070°C: after 5000 thermal cycles the specimens were examined and the fibers were found to be damaged (Fig. 2). It is therefore concluded that a composite displaying no solubility variation is by no means secure from fiber degradation under thermal cycling.

Table VII

Transition metal content of the matrix in as DS as cast and solution treated composites

Composite	Solution treatment temperature	Transition metal content in the matrix (w %)			
Composito	(° C)	DS as cast		solution treated	
Co-HfC	1350	0.11 ± 0.09	Hf %	0.52 ± 0.08	
Co,Cr,Ni-HfC	1330	0.19 ± 0.02	Hf %	0.46 ± 0.05	
Ni,Cr-HfC	1250	0.24 ± 0.04	Hf %	2.30 ± 0.05	
Co-TaC	1330	0.80 ± 0.06	Ta %	3.77 ± 0.11	
COTAC-3	1300	1.76 ± 0.06	Ta %	3.12 ± 0.15	
COTAC 74	1300	0.75 ± 0.07	Nb %	1.02 ± 0.06	
COTAC 741	1300	0.50 ± 0.05	Nb %	0.76 ± 0.05	
Co-NbC	1330	0.31 ± 0.04	Nb %	4.11 ± 0.09	
Co,Cr-TiC	1280	0.39 ± 0.05	T i %	1.20 ± 0.05	
Ni,Co,Cr,Al-TiC	1280	2.39 ± 0.09	Ti %	2.77 ± 0.12	
Ni,Cr,W,Al-VC	1300	9.63 ± 0.12	V %	9.61 ± 0.16	
Ni,Cr-TaC	1300	13.2 ± 0.2	Ta %	13.0 ± 0.25	

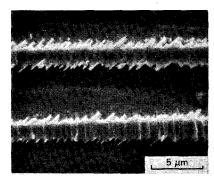


Figure 2 : Fiber degradation in a Ni,Cr—TaC composite after 5000 cycles between 250 and 1070°C.

SEM

This conclusion is further supported by our previous observation on COTAC 3. Some specimens of this composite were thermally cycled under an applied stress of 120 MN/m² in the temperature range 250–1070°C and some others in the range 700–1070°C. The high carbide solubility variation in the matrix remains quite equivalent in the above temperature ranges. Nevertheless, after tests conducted between 250 and 1070°C the fibers become serrated and the specimens break after a few hundred cycles (500 to 1000). On the contrary no fiber damage is observed even after 10 000 cycles performed between 700 at 1070°C.

This extremely different response of COTAC 3 when cycled in the range 700—1070°C as compared to the range 250—1070°C on the one hand and the good thermal cycling behaviour of composites COTAC 74 and COTAC 741 on the other hand as compared to the fiber degradation in the Ni,Cr—TaC composite displaying a still lower monocarbide solubility, falsevidently to be accounted for by

solubility variation. The role played by the cumulative plastic deformation of the matrix has to be considered.

Role of plastic deformation of the matrix

The cumulative nature of plastic deformation during thermal cycling was first portrayed by El Gammal (10) and the steady state, reached after the first cycle, is schematically illustrated in the stress-temperature diagram, Fig. 3. The matrix is supposed to exhibit a perfectly elastic-plastic behaviour and the fibers to be perfectly elastic. The plastic strains resulting from the properties of the component phases, the heating and cooling rate and the initial state of residual stresses has also recently been analyzed by Garmong (11) in detail. Garmong illustrates with some concrete examples of simple composites that the width of the hysteresis loop in dilatometric curves is a rough indicator of the composite plastic deformation during temperature variations. This width should be useful in predicting the susceptibility of a eutectic composite to the thermal cycling damage in terms of plastic deformation. Garmong further shows that the hysteresis loop of a stress-temperature plot is usually stabilized after only a few thermal cycles and the matrix undergoes constant strain-amplitude tension-compression fatigue during subsequent thermal cycles. This conclusion is in perfect agreement with that of El Gammal.

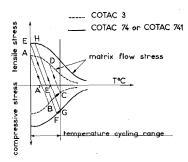


Figure 3 : Schematic illustration of the matrix flow stress in composites during a thermal cycle.

In the stress-temperature diagram of El Gammal, the temperature dependance of the shear flow stress in the matrix, resulting from the three-dimensional stress state is schematically represented by the dashed curve. The thermal cycle defined as AA'BCDA for example depicts a particular situation where the matrix has a rather low strength (COTAC 3 matrix for example). The temperature dependance of the shear stress in the matrix within the portions AA'B and CD is calculated by the theory of elasticity (10). When the specimen is heated, the fibers and the matrix undergo an expansion and the internal stress in both these phases progressively decreases till point A'. At A', the real shear stress is zero in each phase and till B, the matrix deforms elastically, in compression. The shear stress then follows the portion BC and the matrix undergoes plastic deformation in compression. During the cooling half cycle, the shear stress first follows the portion CD and then DA. The matrix undergoes extensional plastic deformation along the portion DA. The hysteresis loop defined by the complete cycle would, in other words, increase the dislocation density during repeated temperature variations.

On the other hand if the matrix of the composite has a very high yield strength, the hysteresis loop would be extremely narrow and this new situation is represented by the full-line loop EE'FGHE. This is supposed to represent COTAC 74 (or COTAC 741) which has a much stronger matrix than that of COTAC 3. For a similar temperature range, the width of the hypothetical hysteresis loop of COTAC 74 as projected in Fig. 3 being much smaller than that of COTAC 3, the expected damage in terms of plastic deformation during thermal cycling should be much less or insignificant, in the former case. This was found to be true by the experimental evidence of the excellent thermal cycling behaviour of COTAC 74, under stress, as compared to the alarming response of COTAC 3.

The cumulative nature of plastic strains produced during each cycle may lead to a high dislocation density especially near the fiber-matrix interface. The existing thermodynamic equilibrium may therefore be locally disturbed due to the presence of these dislocations and the fibers may tend to "dissolve" locally to establish new equilibrium conditions. Moreover, the higher the temperature the higher would be the diffusion rate of the elements constituting the carbide phase. The carbide platelet growth from the fibers was found to occur in deformed regions near the fiber-matrix interface. Nevertheless, the cumulative plastic strain of the matrix may also result in a stress concentration against the fibers—possibly through a dislocation pile-up mechanism (12)—sufficiently high to break them before their "chemical" degradation. In order to collect some more experimental evidence of

the important role played by the plastic deformation of the matrix in fiber degradation some specimens of COTAC 3 composite were deformed till about 8% in tension at room temperature. In such tensile strained specimens, the fibers are broken throughout the gauge length (Fig. 4a). If such a specimen is afterwards isothermally treated at 1100°C during 15 hours, the scanning electron micrograph shows that the small fragments of tantalum carbide are no longer smooth but have a serrated appearance (Fig. 4b) and resemble fibers of a thermally cycled composite. Some of the fragments have completely globulized. It should be recalled that in the absence of a prior plastic deformation, no change in the fiber morphology is observed after isothermal holds. These observations show that at high temperatures the fiber damage is caused by accelerated diffusion of the "fibers" in the presence of a high dislocation density near the fiber-matrix interface.

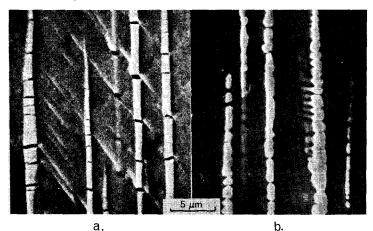


Figure 4:
COTAC 3. Fibers
in a specimen deformed 8% in tension
(left) and subsequently isothermally
treated at 1100° C
during 15 hours
(right).

SEM

Other porperties

The other mechanical properties and particularly fatigue, shear creep and impact strength of these composites are generally better than those of conventional materials. For the most part, the tests were simultaneously conducted on IN100 superalloy:

- The tension-tension fatigue behaviour of COTAC 74 is found to be superior than for IN100, especially in the temperature range 700–800°C. For instance the 10^7 endurance limit is 700 MN/m² (360 \pm 340) at 700°C and 500 MN/m² (260 \pm 240) at 800° C. The rupture surface examination shows that about 70 % of the area is typical of fatigue.
- Shear creep tests performed on COTAC 74 parallel to the fiber direction at 700°C, under a shear stress of 400 MN/m² show that this composite exhibits a much higher rupture life (90 hours) as compared to IN100 superalloy (1 hour 20 minutes) tested in the same conditions.
- The impact behaviour of both notched and unnotched specimens of COTAC 74 at 20, 700 and 1000° C is superior than for IN100 if the impact is normal to the fiber direction (Table VIII). The notched impact behaviour of transverse specimens (notch parallel to the fibers) is equivalent to that of IN100 at 1000° C.

Table VIII
Fracture energy of COTAC-74 and IN100 (J/cm²)

Temp.	Unnotched specimens		Notched specimens COTAC-74 IN100		Transverse specimens COTAC-74 notched ^(*)
20	77–110	57-120	25–31	14–28	67
700	37.5-40	43	21–23	12	8.3–8.7
1000	48–50	25	25–26	11	13–14

^(*) Notch parallel to the fibers.

- The ballistic impact tests at 1100°C show that COTAC74 has a much better behaviour as compared to IN100.
- The oxidation and hot corrosion resistance of uncoated specimens is better than for IN100 superalloy up to 1100°C. Tests performed on COTAC 74 protected with recently developed ONERA coating showed that the coated composite was at least as good as the coated IN100.

Industrial feasibility

In spite of the difficulty to control the directional solidification of large size composite ingots, 55 mm diameter, 100 mm long bars were successfully aligned and some blades and vanes were machined from these ingots for engine testing.

Moreover, some complex shapes with regions of rapid change in cross section have also been successfully solidified under the plane front conditions and the microstructure in these areas was hardly disturbed. The "skin effect" in these as-directionally cast shapes is also found to be much less pronounced than expected. Work in progress on directionally cast to size tensile and creep specimens for testing without any subsequent machining allows to evaluate the relatively slight influence of the skin effect on the mechanical properties.

Thus, the eventual casting to size blades or vanes by directional solidification, entailing only little ulterior machining seems to be feasible and could save time and labor in the practical application of these high melting point composites.

Conclusions

The new industrial composites COTAC 74 and COTAC 741 developed at ONERA exhibit creep properties equivalent to the superalloy IN100 up to about 900°C. Beyond this temperature, both these composites posses much higher creep strength as compared to the best currently available superalloy.

The major progress lies in the high temperature thermal cycling behaviour of COTAC 741 which exhibits only 10 to 15% loss in the subsequent creep strength at 1070°C even after 10 000 prior cycles at the same temperature.

Extensive creep testing has clearly proved that the potential of these composites can best be exploited by performing long duration creep tests. In this respect COTAC 74 and COTAC 741 seem to be challenging candidate materials for replacing the sophisticated cooled blades by more simple shapes or even solid ones from now onwards. This last use seems to be particularly attractive in the low pressure turbine stages of advanced turbofan engines (blades and vanes) which are expected to operate in the near future at temperatures over 1000°C.

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