A NEW TYPE OF ATTACHMENT FOR B/AL COMPRESSOR BLADES

R. Kochendörfer
Institut für Bauweisen-
und Konstruktionsforschung
DFVLR - Stuttgart, Germany

Abstract

The realization of the advantageous properties of composite materials in structural components is mostly limited by the attachment solution. For tension loaded structures used at elevated temperatures a shear load introduction type of attachment seems not to be an optimal design.

In the sense of a more fiber conform design a new type of blade attachment, which is even realizable with B/Al materials, will be demonstrated. In this design two blades are combined to a twin blade by a loop in such a way that most of the fibers are running continuously from one blade tip to the other. Bolts are provided for connection to the disk.

The technology to realize this twin blade design using B/Al, and tension tests of B/Al loop attachment specimens as well as first results of B/Al twin blade bending fatigue tests will be shown.

Introduction

Rotating structures like blades and disks are preferential applications for fiber reinforced composites. These structures are mainly loaded by centrifugal forces which lead to a predominant load path direction and allow consequently a high percentage of unidirectional composite arrangement. Under these conditions the outstanding properties of advanced composites, i.e., high strength and high stiffness to density ratio in fiber direction, can be exploited with maximum benefit.

Background information

Depending on the type of turboengine a substitution of existing metallic compressor blades by composite blades offers a total weight reduction between 15% and 30%, including the weightsavings of thereby influenced systems(1). These weight reductions of connected systems like disks and casings are not negligible. An essential FAA requirement is, that any blade lost by foreign object damage (FOD) or for other reasons must be contained within the engine nacelle so that neither nearby engines nor the cabin are penetrated by debris. Consequently current titanium fan engines have large steel rings around the fan stage which weigh as much as three to four hundred pounds. The reduced weight of composite blades would permit reduced weight of containment rings(2). In addition, the fracture characteristic of advanced composites should minimize the containment problem even more.

However, the mere substitution is only the first approach using composites as compressor blade material. The next step will be a redesign of blades which can lead according to Toth(3) to weight savings of about 30% either by reducing the blade thickness or the blade number per stage. The full potential of composites with the highest benefits can be achieved by a total system approach, i.e., designing an engine for the use of composites, fig. 1. That would be a time and money consumptive and risky way but there are some people who believe the use of fiber composite materials may be mandatory to make futural STOL aircraft feasible, which require engines with a thrust to weight ratio twice that of today's engines (2).

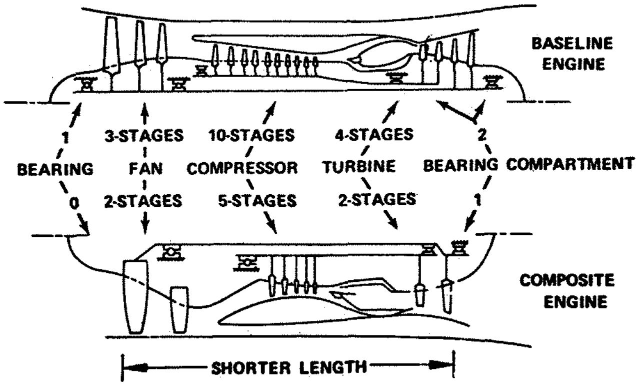

Fig.1: Benefits of composite design, after Siegel(3)(4)

To reach these goals the confidence of designers and project managers in composites as a blade material must be increased by hardware demonstration. Under all service conditions, including foreign object damage, the performance capability and the reliability must be demonstrated, a quality control and accept-reject criterias must be established and the cost efficiency factor of titanium must be reached.

Present situation

A lot of work is already done going this way. Almost every important company in the field of turboengines has composite activities, fig.2.

Company	Engine	Compres. bladetyp.	Exempl. Aircraft	Composit material
General Electr.	TF 39	fan	C 5 A	CFRP BFRP
	J 79	1.stage	F 1o4	B/AL
	F 1o3/ CF6-50	fan	DC-10/ A-300	CFRP
Pratt and Whitney	JT 9D	fan	B 747	CFRP BFRP
	JT 8D	1.stage	B727,DC9	B/AL
	TF 30	3.stage	F111,F14	B/AL
TRW	F 1oo	3.stage	F 15	B/AL
	TF 41	fan	A 7	B/TI
Rolls Royce	RB211	fan	L-1011	CFRP

Fig.2: Composite blade activities for the cold part of turbojet engines

Most of these composite blades are already rig-tested even at elevated temperatures and at these tests two problem areas became apparent: FOD-resistance and root attachment.

These results were not surprising. The low impact resistance of composite materials related to titanium was known, and especially in the last few years an encouraging increase in impact resistance could be realized mostly for aluminum matrix materials by using the matrix ductility(5)(6). So it seems to become possible to fulfil the FAA-FOD-requirements with Boron/Aluminum first stage or fan blades.

However, no new root design philosophy can be seen. The root attachment of composite blades is more or less a modified dove tail type of the existing metal blades, fig.3. This may be an optimal solution for metal blading but that must not be valid for composite blades. If we want to take advantage of high strength and high stiffness to density values in the airfoil section of the blade, we may be forced to pay for that by redesigning the root section to use the full potential of composite with the highest benefit.

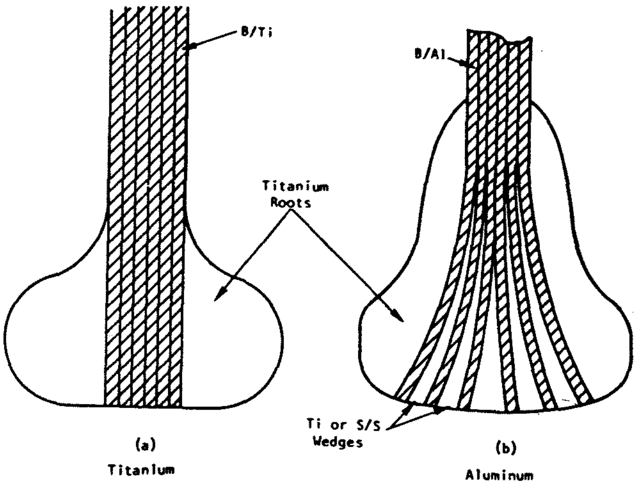

Fig.3: Wedge type root attachments(3) for composite blades

Objective of investigation

The overall objective of these investigations is to develop for B/Al compressor blades an alternative blade attachment to the already existing dove tail solution.

This blade root concept should be verified using the first stage compressor blade of the J79 engine as a demonstrator and proved in close contact with the German turbomachinery company MTU (Motoren- und Turbinen-Union), Munich.

Beyond this hardware demonstration the validity to transfer these results to more advanced compressor designs should be critically analysed.

Program approach

Because glassfiber/epoxy loop attachments showed their performance and reliability in high loaded structures it was intented to transfer this fiber conform loop design to compressor blades. Four years ago we published the twin blade concept based only on our experience with resin bonded composites(7). However we stated, the realization of this concept, where two blades are connected at the root end by a loop in such a way that all or most of the fibers are running continuously from one airfoil section to the other, should be possible using B/Al. We selected B/Al-material because it offers for this application advantages of temperature stability, erosion and FOD resistance compared to organic matrix composites.

Program tasks

The investigations can be classified in three sections.

- First, the verification of a simple B/Al loop with an acceptable joint efficiency factor was a premise of the whole program.

- Second, flanking activities should characterize the B/Al material in terms of static and dynamic mechanical properties (tension-tension and torsional fatigue), hot forming possibility, damping behaviour, erosion and impact resistance. Also a feasibility study about the applicability of the twin blade concept to advanced turbo compressor systems fits within these activities.
- Third, a hardware realization of the real size blade was necessary to prove and improve this loop attachment approach.

Due to the fact that processing parameters have a large influence to the obtained values the evaluation and improvement of fabrication methods to verify this concept was necessary throughout the program.

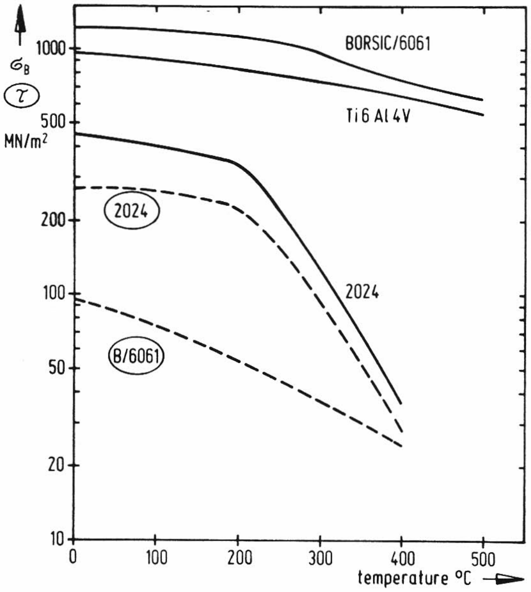

Fig.4: Short time values for unidirectional reinforced B/Al and for metals versus test temperature

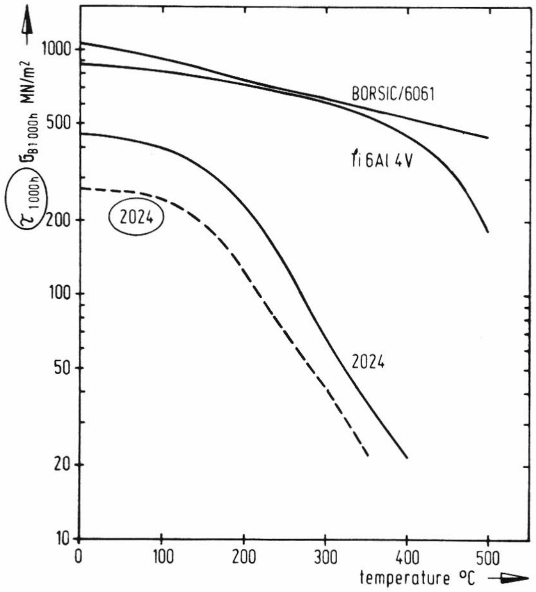

Fig.5: Stress rupture properties (1000h) for unidirectional reinforced B/Al and metals versus test temperature

Simplified loop attachment

The main advantage of a dove tail composite blade root is the interchangeability with existing metal blades for testing purpose. However, as in most airframe applications, the requirement to substitute metal parts by composite parts implies also in the case of compressor blades a restriction in utilizing the full amount of fiber material potential, because that means a shear load introduction type of attachment. Fig.4 clearly demonstrates the tremendous differences in material behaviour under tension and shear load conditions, especially for temperature applications. Compared with these short time values the differences at long term loading, which is a more representative design criteria for a blade are even more aggravated because of creep effects, fig.5.

Contrary to a dove tail blade root, with a loop attachment the fiber controlled high tension strength should be utilizable at least up to 350°C, which seems to be a temperature limit for B/Al application due to thermal cycling fatigue. The first goal was therefore to fabricate and test simplified loops to gain basic informations for the twin blade concept.

Fabrication

The selected loop, fig.6, stands for a simplified twin blade where the airfoil sections are verified by two flat plates positioned under an angle of 25°. These two plates are connected by a circularly curved loop. The loop radius R = 16 mm is adequate to the minimum curvature of the original size blade loop. The cross section of the entire loop is constant, 60 mm wide and 1.8 mm thick. The unidirectionally arranged fibers are running continuously from one plate tip to the other.

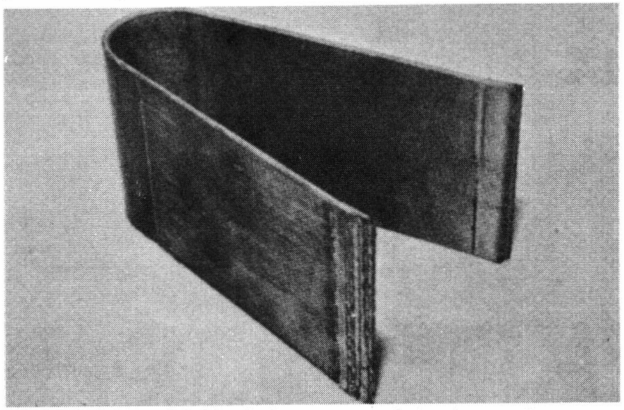

Fig.6: Simplified loop as fabricated

The selected tape material is fabricated by a French company, Sociéte Nationale des Poudres et Explosifs (SNPE). The B_4C coated boron fibers with 100 Ø µm are spaced on a 6061 foil and plasmasprayed with 6061 powder. The broad goods were characterized in acceptance tests according to fig.7.

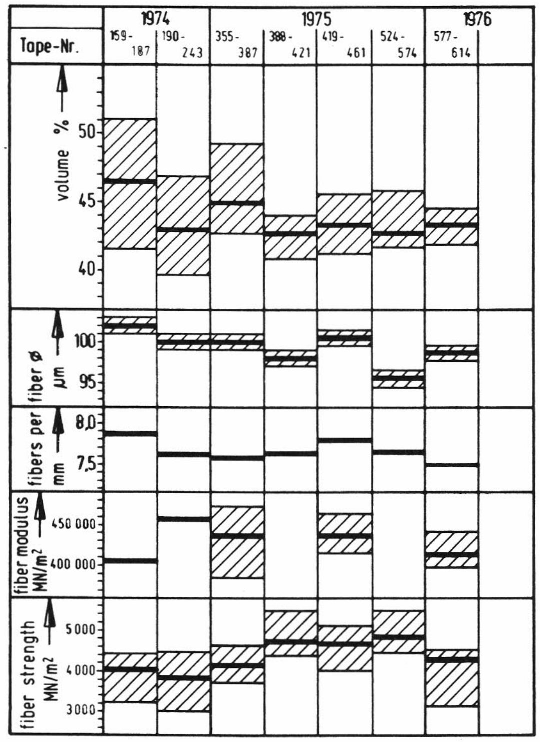

Fig.7: Characterization of SNPE-material $BB_4C/6061$

The fabrication of the loop was performed under argon atmosphere using a hydraulic press with the main hydraulic cylinder in the vertical axis. The main parts of the die are shown in fig.8. The monolayers were cut to size and clamped to the plunger before composition of the mold. After inserting the die in the cold press it was heated to pressing temperatures of 620°C to 640°C with a heat-up rate of 150°C/h. To realize the first pressing sequence the plunger was pressed by the horizontal cylinder into the loop mold until the loop area was completely pressed to the desired thickness. This can be done without fiber fracture because the monolayers at the loop flanks are not yet pressed and can move according to the loop consolidation.

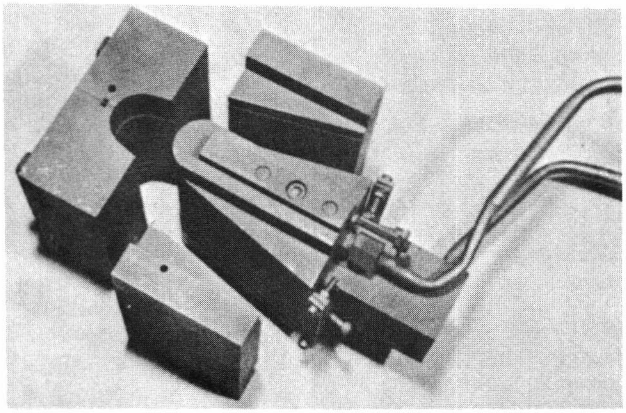

Fig.8: Pressing tool for fabrication of the simplified loop

In the second sequence these loop flanks are consolidated by pressure application with the vertical main hydraulic cylinder. This hot pressing and consolidation period, which lasts about 30 min, is followed by a cooling down period of two hours.

Testing

Prior to testing the simplified loop was cut parallel to the fibers into four loop sections with a width of 10 mm. According to fig.9 these loop sections were tension loaded in the as-fabricated condition, i.e., without any heat treatment prior to testing. The crosshead movement was 2 mm/min for room temperature tests and o.1 mm/min for tests at 250°C.

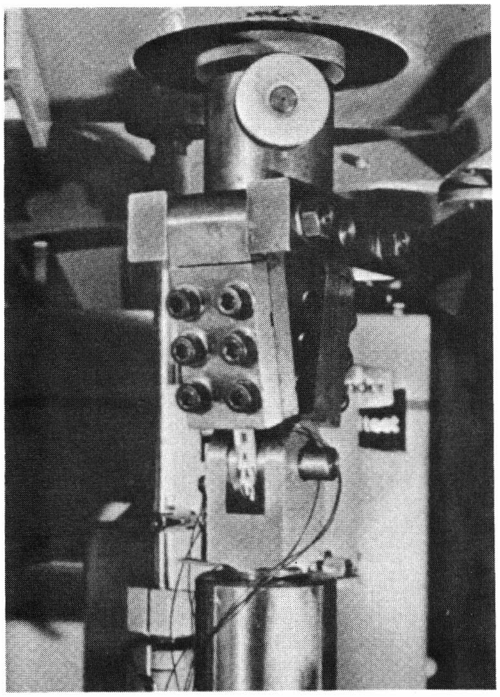

Fig.9: Tension testing of the simplified loop section

Test results and discussion

The test results are summarized in fig.10. According to the loop radius and the fiber diameter a certain amount of fiber potential cannot be utilized to carry external load due to the inherent fiber bending stresses. This penalty of the loop attachment concept has been calculated by normalizing single filament bending stress to a 50 vol% composite. In the present case this leads to stresses in the order of 525 MN/m^2. The columns above this platform signalize the maximum amount of tensile stresses which can be introduced in this loop by external forces. According to the marked number each column represents one to four test values. The failure mode was fiber fracture within the loop area without any delamination or creep effects even at elevated temperatures.

Comparing the RT values it can be seen that the stress levels could be increased up to 1100 MN/m^2 by refining the technology.

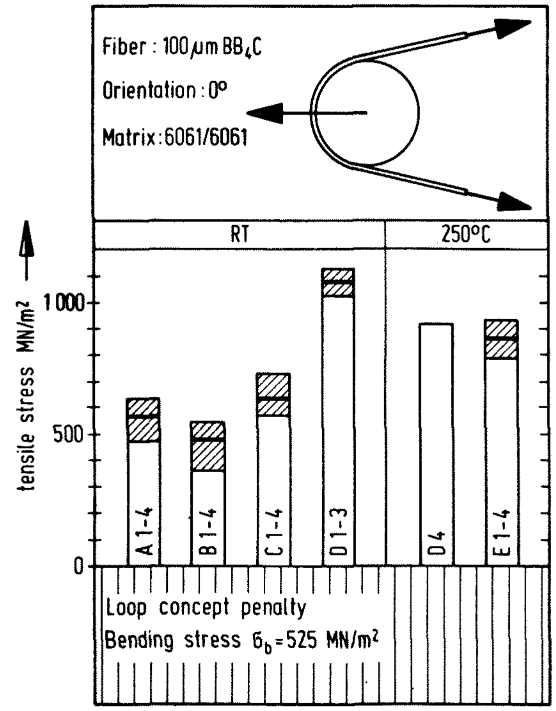

Fig.10: Fracture stresses measured in loop tests at RT and 250°C (short time values)

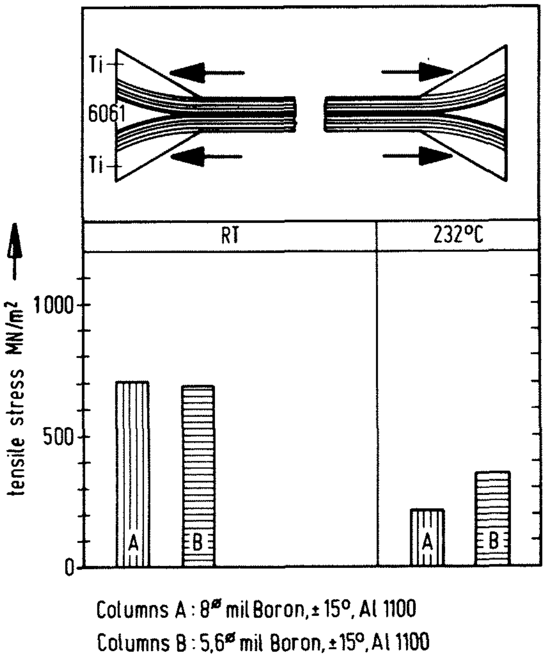

Fig.11: Failure stresses measured for B/Al wedge roots at room temperature and 232°C (short time values)

These are quite acceptable values, especially compared with the highest stresses of about 80 MN/m^2 in an operating blade due to centrifugal forces(8). A full consolidation of B/Al material in the airfoil section area could be demonstrated by bending tests. The specimens for these separate tests were cut out of the loop section flanks after loop testing. The obtained bending stresses range between 1900 MN/m^2 and 2300 MN/m^2.

The measured values at elevated temperatures are very interesting. Stress levels as high as 80% of the room temperature values could be sustained by the loop attachment during these short time tests at 250°C. It can be deduced from results of stress rupture tests at elevated temperatures, fig.5, that if the loop attachment proved its usefulness at 250°C, the stress level which can be sustained during long term loading at 350°C would be about 20% less with probably no change in failure mode.

Similar tensile tests, using specimens with wedge root attachments at each end, were conducted in a TRW program to increase the FOD resistance of B/Al(5). This type of tensile test specimen proved its ability also in our own tests, measuring the joint efficiency of wedge type blade root designs in carbon/epoxy since 1972(7)(8)(9). The results Melnyk and Toth found during the TRW-program are summarized in fig.11, where each column represents one test.

Because these design concepts were optimized to FOD resistance, fiber diameter, fiber orientation and matrix material are representing a different B/Al material. However, the large influence of test temperature is obvious, not only regarding the obtained different stress levels but also the change in failure mode.

Whereas the RT test specimens failed by fiber fracture, all specimens tested at elevated temperatures failed by shear. Even during this short time tests with constant crosshead speed of o.5 mm/min the specimen elongations by creep effects were up to 7%. The location of the shear failure points out another problem area of the wedge type root design. The shear failure starts at the interfaces between B/Al composite and the outer Ti-wedges. These Ti-wedges seem to be necessary for a real blade application, fig.3, due to high contact pressures and fretting effects in connection with the disk. Unfortunately during the diffusion bonding process the formation of a brittle reaction zone between the aluminum and titanium surfaces cannot be prevented, which decreases the shear transfer capability even more.

Intermediate balance

Comparing the results of the wedge-root and the loop-root design it can be stated for B/Al material, that the wedge type solution may be applicable for first stage and fan blades but restricts elevated temperature applications, whereas the loop concept allows to take advantage of the high temperature potential of B/Al in realizing compressor blades at least up to the third stage.

Flanking activities

The results of the first section demonstrated a possible realization of the twin blade concept. Concerning the flanking activities one main aspect was a study about the problems which may occur due to the blade disk interface. The other main aspect was the evaluation of material properties.

Part I: Feasibility study

The loop attachment may be an optimal design for composite blades but the advantages may be more than balanced by possible disadvantages on the disk side. These problems were evaluated in a feasibility study by MTU, Munich. The basic configuration was a modern concept of a three stage low pressure compressor. All components including the blades were built in Ti6Al4V. This basic Ti-configuration was redesigned, according to the requirements of B/Al blading, with different root concepts, i.e., wedge type single blade and twin blade concepts with either bolt attachment or saw tooth shaped fittings. With the assumptions that the B/Al blades will fulfil all requirements and do not need midspan shrouds and without fiber reinforcement in disks and casings (containment rings), the possible weight saving for all three attachment types was about 25%, fig.12.

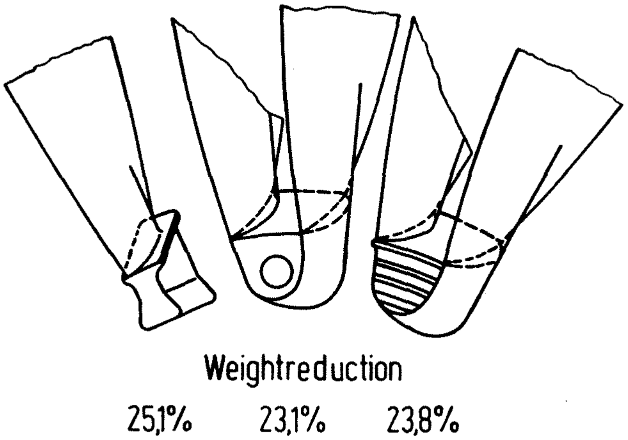

Fig.12: Possible weight saving of B/Al blades with different root designs

First economic considerations showed that the fabrication cost (without material cost 14oo DM/kg(280$/lb)) of a B/Al twin blade in a serial production can be 4oo DM(160$) without, or 700 DM(280$)with a cost efficiency factor of 15oo DM per kg weight saving(3oo$/lb). This seems to be realizable(3).

The results of this feasibility study can be summarized as follows:

- The change in rotor design was not as pronounced as expected in fitting twin blades to the disk instead of single blades.
- The even number of blades which is necessary to realize the twin blade concept is already a reality in a lot of modern compressor concepts as CF6-50, ATF3, ALF5o2, JT1OD.
- The possible weight saving of about 25% compared to a titanium stage for almost the same cost makes it worthwhile to continue the way toward a hardware realization of the twin blade concept.

Part II.: Materials evaluation

This second part of flanking activities does not deal with static tests to control the effects of variations within the processing parameters. The main aspect of these testseries is to gain own experience about material behaviour under conditions which were representative for a compressor blade application.

Dynamic behaviour Beside the impact behaviour the most interesting material property for this application is the fatigue behaviour. We started two series of investigations to evaluate the torsional fatigue and the tension-tension values for B/Al.

The torsional fatigue behaviour is essential for the leading and trailing edge area, because the torsional layers in a composite blade are normally cut there. The results for BB$_4$C/6061 are summarized in fig.13. All specimens were 50 mm long, 9 mm wide and 3 mm thick. The lay-up sequence was for curve(A) 26 layers 0°, for curve(B) $+45^\circ$, -45°, 22 layers 0°, -45°, $+45^\circ$. The torsional axis was in 0° fiber direction. Tests were running at 25 Hz, a 5% stiffness drop was defined as a failure. Contrary to the hitherto experience with composite materials it seems to exist a real fatigue limit in this dyn. torsional loading case. The obtained stress levels are lower for 0°- laminates but the ratio dynamic shear stress to static shear stress is for both curves about o.46.

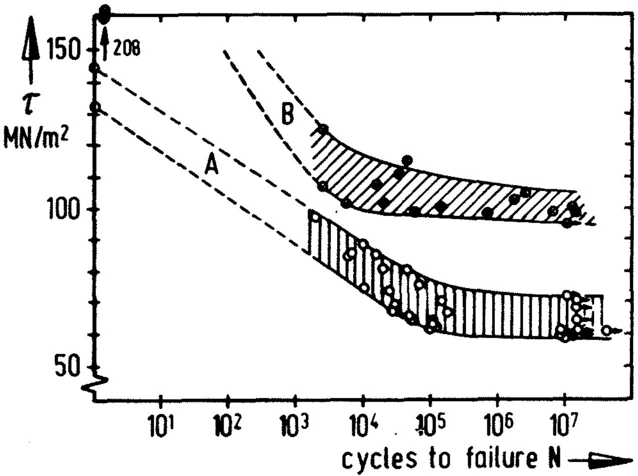

Fig.13: Torsional fatigue behaviour of BB$_4$C/6061

The tension-tension fatigue behaviour can render a first survey about the dynamic behaviour of the blade under high centrifugal stresses and low bending stresses due to gas flow loading. Therefore low A-ratios are most interesting. The results for unidirectional BB$_4$C/6061 are summarized in fig.14.

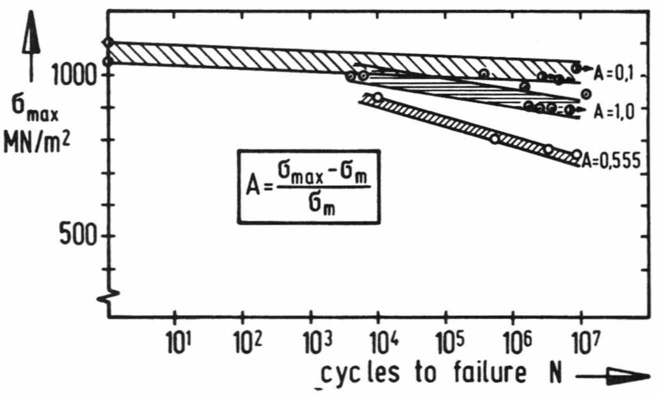

Fig.14: Tension-tension fatigue behaviour of $BB_4C/6061$

The specimens had a free length of 85 mm and a cross section of 2 mm x 9 mm. In the gripping area aluminum tabs, which enclose the specimen entirely, were adhesively bonded to the composite. The test frequency was 25 Hz, a complete fracture was defined as a failure. For A-ratios A = o.55 and A = 1.o pronounced delamination effects were visible before this complete fracture. These curves fit reasonable to values reported in the literature(7)(1o)(11), except curve A = 1.o. The reason is not yet clarified. All specimens for one A-ratio curve were cut from one plate. Because the acceptance tests did not show a change in tape quality, it may be influenced by the fabrication parameters that curve A = 1.o signalizes a higher dynamic stress level compared to the other two curves.

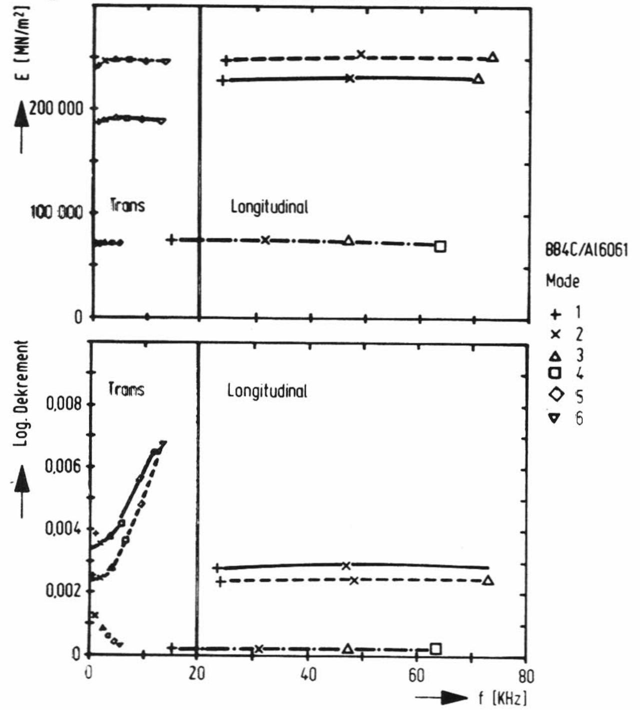

Fig.15: Damping behaviour and dynamic modulus measured at resonance frequencies

—·—·—·— Al 1100

------- $BB_4C/6061$, 0°

———— $BB_4C/6061$, 0°, ±45°

Damping behaviour One of the factors influencing the damping characteristic of a dynamic system is the material damping behaviour. Blades have to pass various resonance frequency regions and should offer high material damping capacity to limit the blade amplitude. Test results for the log. decrement of damping and for the dynamic modulus are summarized in fig.15. These values are measured in the free-free condition, i.e., the specimens (200 mm long, 9 mm wide and 3 mm thick) were supported at the nodal lines. The lay-up sequence is the same as for the torsional fatigue specimens. It is obvious that the damping capacity is higher for B/Al than for non reinforced aluminum.

Erosion resistance First inhouse tests concerning erosion resistance were made with a modified sand blast equipment to gain comparable values for different materials under the same testing conditions. This simple method leads to very reproducible values(12). Some of them are represented in fig.16, showing the weight loss versus the mass of sand hitting the target area normal to the surface with a velocity of 50 m/sec. The average diameter of the corundum grains was o.25 mm.

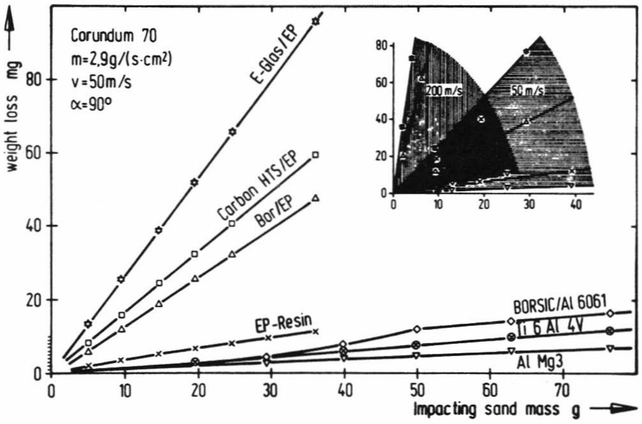

Fig.16: Erosion behaviour of different materials under the same test conditions

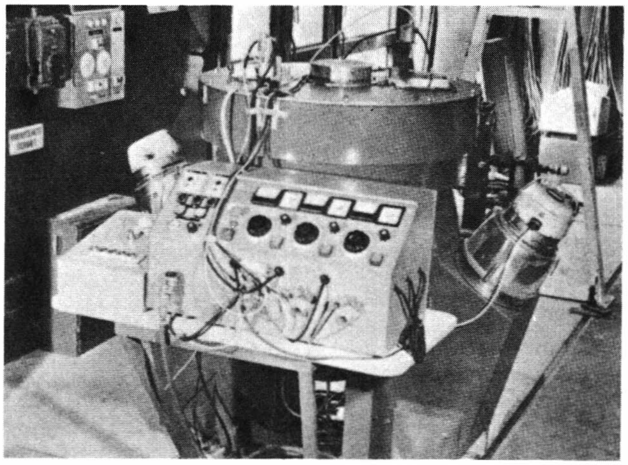

Fig.17: Centrifugal stand and erosion test equipment

The concentration of 2.9 $g/s \cdot cm^2$ is 4000 times as high as in a sandblast. In the upper right corner the velocity influence is demonstrated. It is clearly visible that the erosion resistance of B/Al is almost as good as in the case of Ti6Al4V under these conditions. To gain more realistic values a centrifugal stand was constructed to evaluate the erosion behaviour of real blade sections with and without protection, fig.17.

Impact resistance The largest obstacle on the way to flight test and serial production of composite blades is the FAA requirement about foreign object damage. Most of the recent investigations in the field of B/Al as a blading material are dealing with the increase of impact resistance(5)(6). A real large progress is reported in improving the notched Charpy impact values four times higher than those reached with Ti6Al4V. This advance could be realized by optimizing the material only with respect to high impact values. This material is characterized by a 8 mil diameter boron fiber arranged in an aluminum matrix A 1100 with a fiber orientation ±15° to the main loading axis. The joint efficiency for this material was already dicussed in connection with fig.11. Based on these results I wonder, whether it will be possible to combine high impact resistance values with high dynamic and high long term shear values for this type of material.

Our own activity concerning the impact resistance just started by instrumentation of an impact pendulum equipment to record load elongation curves. The unidirectional reinforced unnotched $BB_4C/6061$ specimens were 45 mm long with a cross section of 6 mm x 6 mm. The impact vector was normal to the fiber direction and normal to the pressing direction, thus simulating a blade impact. An improvement of the hitherto obtained impact strength in the order of 65 KJ/m^2 is a task for the near future.

The results of Part II, materials evaluation, can be summarized as follows: Apart from a necessary increase of impact resistance which seems to be obtainable, all other results are encouraging to use B/Al and these fabrication methods to continue the program.

Realization of a twin blade

The twin blade concept should be verified using the first stage compressor blade of the J79 engine, fig.18. Several circumstances made it reasonable to select this blade as a demonstrator. A large experience exists with the original blade in service. The company MTU took part of this experience and inhouse test equipments for this blades are available there. The geometry of the blades, as constant profile cord, distance and pitch of the blades in the blade root area, are favourable to gain first experience in realization of a loop attachment. Moreover a US-Air Force sponsored program for a substitution of this blade type in B/Al can give additional informations about the influence of different root designs.

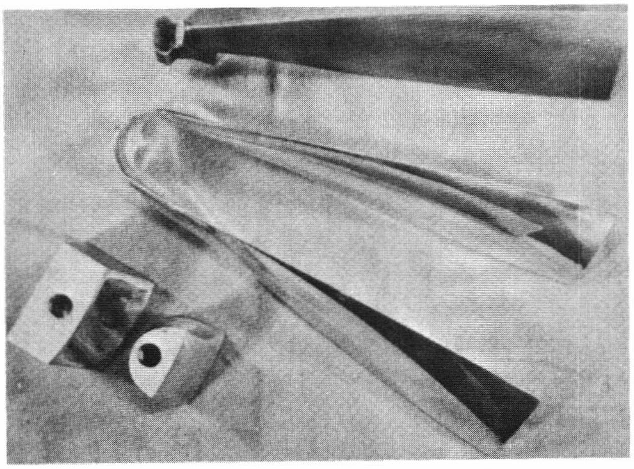

Fig.18: Real size twin blade($BB_4C/6061$) with Al-fitting pieces, and original J79 blade(steel 4o3)

Design aspects

Blade spacing, blade angle or blade setting and rotor diameter, as well as the complete airfoil geometry are the same for the metal as for the composite design, which is characterized by the following items:

(a) Within the airfoil section a spar-skin concept is realized. At present the outer skin is a pure aluminum foil, o.2 mm thick, due to fabrication requirements. Two torsional layers ±45° are increasing the torsional stiffness and prevent transverse fiber fracture in the leading and trailing edge area. As the outer Al-skin these torsional layers are disposed parallel to the profile surface covering the entire airfoil section, whereas the rest of the profile volume is filled in the first approach with 0°-layers. These 0°-layers are arranged symmetrically to the profile axis forming steps toward the blade tip due to the decreasing profile volume, fig.19. Because no matrix flow can compensate surplus material, a proper filling of the blade volume is absolutely necessary for a constant pressure distribution and thus for a good consolidation of B/Al material. However, the number of 0°-layers and the shape of each individual layer depends on the tape thickness of the purchased material. Therefore a computer program was developed to plot the shape of the needed number of 0°-layers, taking into account even a combination of different layer thicknesses in one blade.

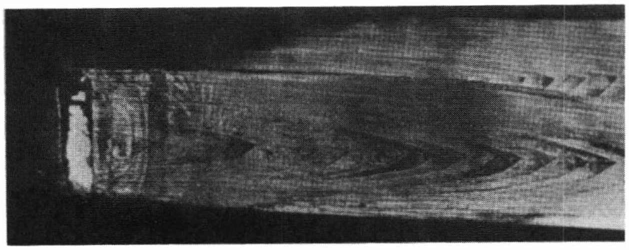

Fig.19: Shape and arrangement of 0°-layers after the first pressing step

(b) The blade loop is built up only by these 0°-layers which should bear centrifugal and bending loads. The realization of the loop implies that each single 0°-layer must be unrollable. Therefore the blade profile has to change into a symmetrical profile. This transition is smoothly done outside the airflow channel. The loop itself can be shaped as a symmetrical profile. The height of the loop arc is a compromise between the largest possible bending radius and the space needed for the blade disk connection.

Fabrication

Technological problems but even more quality assurance aspects were the reasons to shift to a two step fabrication method. In the first step the U-shaped unidirectional reinforced spar is pressed and consolidated. This load carrying member can be controlled visually and by nondestructive testing as well as in vibration before the torsional layers and the outer skin are brazed to this spar in a second fabrication step.

The purchased B/Al tapes were smoothly brushed after qualification tests with an iron brush to remove surplus plasmaspray material. The computer plotted contours of the 0°-layers (about 52 pieces) and of the four torsional layers were transfered to the tapes. Cutting the layers to size was done with a cutting tool mechanically or by hand. After ultrasonic cleaning in freon the individual layers were positioned in a negative mould and sucked to the mould surface by vacuum, fig.20.

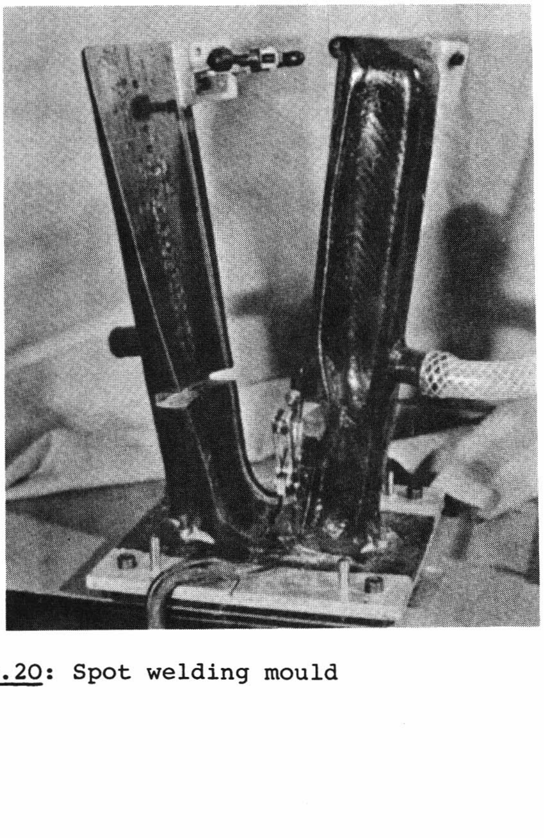

Fig.20: Spot welding mould

Their fixation to a package was possible by resistant spot welding. As filler additional pure Al-foils must be placed around these 0°-layers because the first pressing step was also done in the final pressing tool and the spar has naturally a smaller volume than the final blade. To transfer the whole package from the fixing tool to the pressing tool the blade sections were clamped at the blade tips as shown in fig.21. The tool, fig.22, was heated up in an argon atmosphere with a rate of 80°C/h to pressing temperatures of 620°-630°C. The pressing sequence was the same as in fabricating the simplified loop attachment.

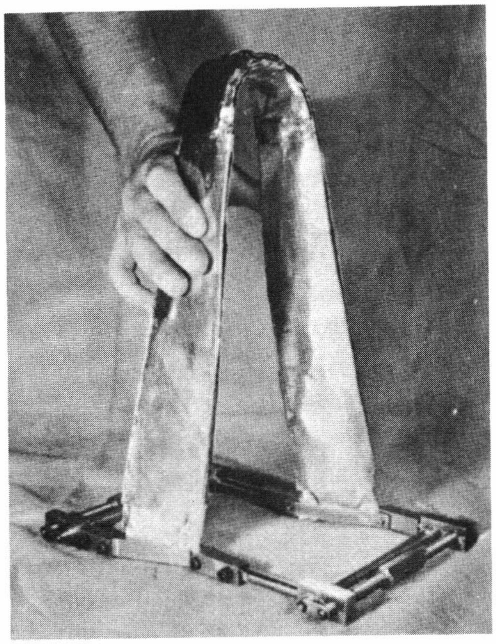

Fig.21: Assembled twin blade before the first pressing step

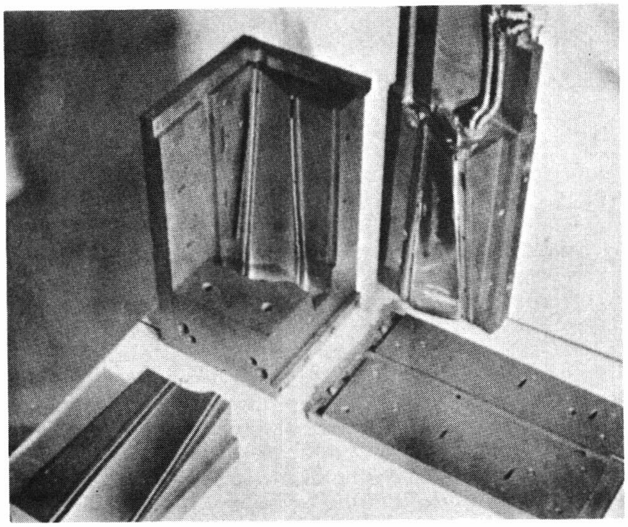

Fig.22: Main parts of the pressing tool for the twin blade fabrication

The pressure, related to the projection area, was 65 MN/m^2 for the loop consolidation as well as for densifying the airfoil-sections. The total time at pressing temperature was o.5 h, followed by a cooling down phase of about 5 h. Using a nickel foil as a separator it was possible to peal off the additional Al-filler foils from the pressed spar, fig. 19. The maximum tip displacement of the single layers was up to now ±2 mm. This is a very encouraging result. However, contrary to our experience in fabricating single airfoil sections without a root it was almost impossible to realize a proper filling of the twin blade volume. The main reason is that the contour of a slip cast molded twin blade, which gives the basic values for the computer program, is not exactly identical with the contour of the pressed B/Al twin blade. Obviously the contact areas of the mold are displaced by heat and pressure. This has to be prevented by a time-consuming modification of the pressing tool. A short term solution was to correct the obviously inadequate pressure distribution after the first pressing step by non reinforced proper shaped correction layers at the second pressing step. The results gained with this temporary, inadequate method were anyhow astonishing. The lay-up sequence for the second pressing step is demonstrated in fig.23.

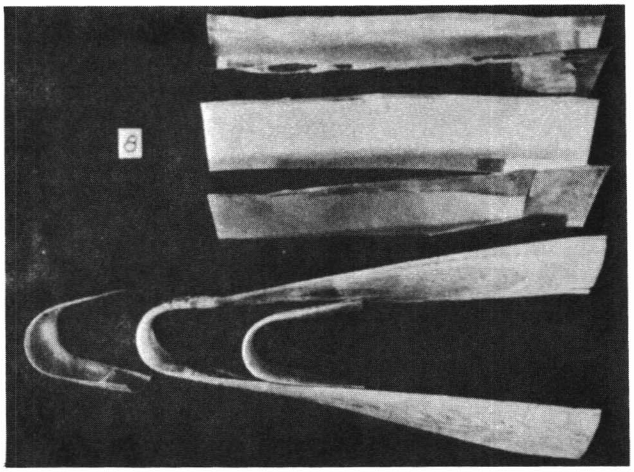

Fig.23: Spar, preformed end caps, torsional layers plus correction layers and outer skin before the second pressing step

Testing

Normally, first tests are static tests. However, composite minded people know testing of unidirectional material in fiber direction sometimes is a problem.This is also valid in simulating centrifugal loads to the twin blade loop. Before conducting low cycling fatigue (LCF) tests in a centrifugal stand, vibration tests were made on an electrodynamic vibrator to prove the twin blade under cyclic bending stresses in the first resonance frequency, fig. 24.

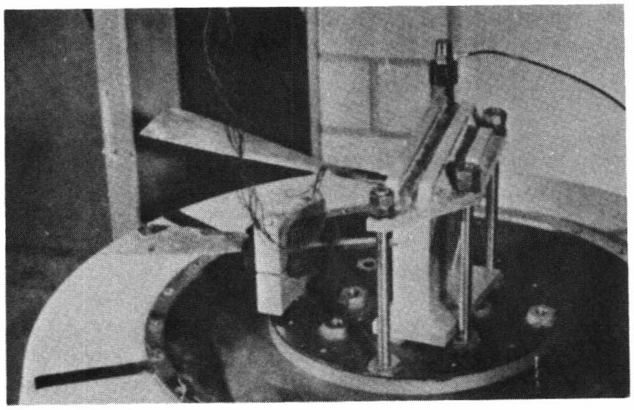

Fig.24: Shaker test of B/Al twin blade Nr.2

The results of five twin blade tests are summarized in fig.25, where the tip to tip deflection is plotted versus the cycles to failure. A drop in resonance frequency of 3% is defined as a failure. The numbers at the different amplitudes are indicating that most of the blades were tested at more than one stress level, due to the limited blade number.

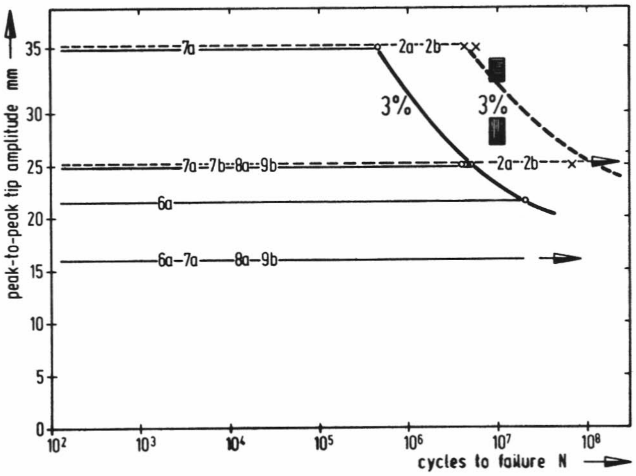

Fig.25: Shaker test results, valid for BB_4C/6061 twin blades tested at resonance frequency in first bending mode (140 ±20 Hz)

▥	measured value amplitude a * frequency f according to the a·f-method[13] for the original J79 blade
▤	estimated value according to the experience of MTU with the a·f-method for a fictive J79-Ti-blade

We found several effects which were responsible for a frequency drop during testing:

(1) The design of the blade fittings had an essential influence. Out of three configurations the version which envelops the entire loop with a tight fit showed the best results. For these first tests an Al-alloy was selected as a fitting material shaped

by simple sand casting to the geometry of the loop.

(2) The tolerances between the cast fitting pieces and the loop were equalized by a low temperature melting metal. This fast and simple solution had the disadvantage that the contact pressure of this material was very low. Thus the material was squeezed out of the gaps during vibration, changing the resonance frequency by a change of the clamping condition.

(3) A requirement to fabricate the blades in a closed die under pressure, imposes that the surface material must have a higher melting temperature than the rest of the blade material. Using the corrosion resistant 6061-alloy, the realization of this demand was only possible with a pure Al-1100 outer skin material. However, pure aluminum has a very low fatigue resistance. Thus the utilization of the excellent fatigue behaviour of B/Al is limited in blade bending tests by early cracks in the Al-1100 skins followed by a frequency drop, signalizing a failure.

Accepting point (2) and (3) as failure criterias, the solid 3%-line in fig.25 represents the obtained results, whereas the dashed 3%-line signalizes an outlook to futural possible blade behaviour. The dashed line was obtained by testing a blade without an Al-11oo skin. This blade did not fulfil the requirements of surface smoothness but demonstrated excellentfatigue behaviour, if point (2) is not accepted as a failure criterion. It could be clearly demonstrated by reembedding the blade, whether a measured frequency drop was caused by a change of the clamping condition or by blade failure. It stands only for a blade failure if the resonance frequency was the same before and after reembedding. Transmitting the results of this first approach to a second generation blade, the cycles to failure could be increased by a factor 10. The failure mode changed from skin cracks to edge-parallel cracks within the torsional layers.

Reviewing the dynamic results four aspects are very encouraging:

- The sustained stress levels are quite high. A tip to tip deflection of 25 mm is corresponding with 3^{o}/oo strain, measured in the highest stressed blade root area. For B/Al this is adequate to 50% static failure strain.

- It seems that cracks in the torsional layers are not initiating cracks in the 0^{o}-layers. As soon as the stiffness in the high stressed blade area is dominated by the stiffness of the 0^{o}-layers, the cracks in the torsional layers stopped and no further frequency drop was noticeable.

- Even severe damage of the trailing and leading edges have no strong influence to the fatigue behaviour of the blade. That was demonstrated by one blade which was slinged off the shaker during vibration test caused by a fastener failure.

- It seems to be possible to reach the high dynamic values realized with Ti-blades also with second generation B/Al blades, which offer additional advantages due to their low crack propagation velocity.

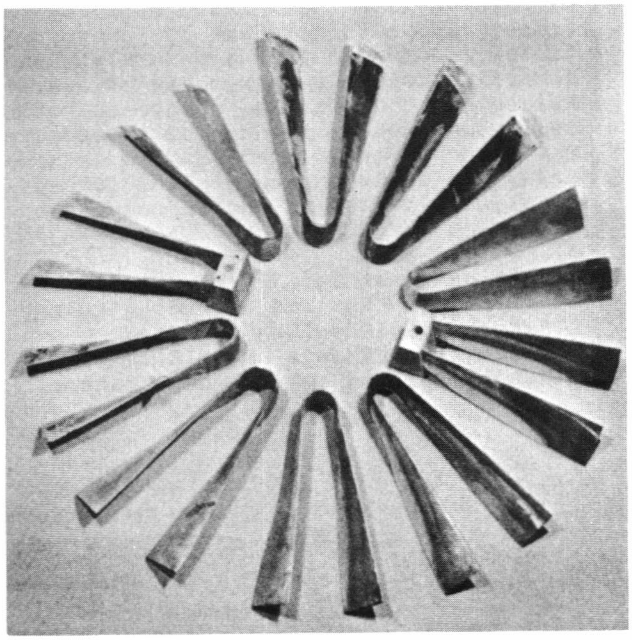

Fig.26: B/Al twin blades as-fabricated, ready for tests and already tested

Summary

(1) A loop type attachment for B/Al compressor blades has been realized using a J79 first stage blade as a demonstrator.

(2) Tests and fabrication of 10 simplified loops and 14 original size twin blades (fig.26) were performed under laboratory conditions.

(3) It could be demonstrated that a B/Al loop attachment with a radius of R = 16 mm can sustain external tensile forces up to a stress level of $\sigma_z = 1000$ MN/m^2 at RT.

(4) At 250^{o}C test temperature the short time values obtained with this loop attachment reached 80% of the RT values.

(5) Based on these results and on stress rupture properties found in the literature the sustainable stress level of this loop attachment is estimated to be 500 MN/m^2 for a long term application (1000 h at 350^{o}C).

(6) The reached high stress levels combined with a low density of B/Al material allow the realization of a hollow blade-

loop concept.

(7) Vibration tests with the original size twin blades in the first resonance bending frequency showed that a peak to peak tip amplitude of 20 mm has been endured by these first generation blades up to 10^7 cycles without any frequency drop.

(8) A possible weight saving of 23% was calculated in a feasibility study by redesigning a three stage low pressure titanium compressor of a modern engine according to the requirements of a B/Al twin blade concept. The change in rotor design was not as pronounced as expected. The even number of blades which is necessary to apply the twin blade concept is already a fact in modern compressor concepts.

(9) Investigations of B/Al twin blades in a whirling-arm test rig according to the LCF-method, blade-loss and blade containment experiments as well as FOD tests are planed for the near future.

References

(1) Mangiapane J.A., Satter S.A., Gray D.F., Timoshenko J.A.
Development of Metal-Matrix Composite Blading for Gas-Turbine Engines, AIAA Paper No.68-1o37

(2) Johns R.H., Impact Testing of Composite Fan Blades, SAMPE Quarterly, July 1974

(3) Toth I.J., Metal Matrix Composite Blade Fabrication Methods, 19th SAMPE, Vol. 19/1974

(4) Siegel M., Presentation to NMAB Committee on Metal Composites, Bel Harbour, Fla. December 1973

(5) Melnyk P., Toth I.J., Development of Impact Resistant Boron/Aluminum Composites for Turbojet Engine Fan Blades, NASA CR 134770, May 1975

(6) McDanels D.L., Signorelli R.A., Improved Impact-Resistant Boron-Aluminum Composites for Use as Turbine Engine Fan Blades, NASA TMX-71875, Febr.1976

(7) Grüninger G., Kochendörfer R., Fiber Reinforced Materials for Application in the Cold Part of Turbine Engines, AGARD-CP-112, Toulouse 1972

(8) Kochendörfer R., Der Einsatz faserverstärkter Werkstoffe bei Verdichterschaufeln, Zeitschrift für Flugwissenschaften 23, Heft 12, 1975

(9) Kochendörfer R., Grüninger G., Stellbrink K., Mechanical Properties of Composite Materials and Design Concepts for Composite Structures, ESRO SP 99, March 1974, Third Testing Symposium, Frascati, Italy 1973

(1o) Menke G.D., Toth I.J., The Time dependent Mechanical Behaviour of Metal Matrix Composites, AFML-TR-71-1o2, 1971

(11) Kreider K.G., Dardi L., Prewo K., Metal Matrix Composite Technology, AFML-TR-71-2o4, 1971

(12) Armbrust S., Das Erosionsverhalten faserverstärkter Werkstoffe, Kunststoffe 63, Heft 12, 1973

(13) Armstrong E.K., Stevenson R.E., Some Practical Aspects of Compressor Blade Vibration, J. of the Royal Aeronautical Society, Vol.64, March 196o, Nr. 591, p. 117/13o.