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BENDING FATIGUE TESTS ON SiC-Al TAPES UNDER ALTERNATING STRESS AT ROOM TEMPERATURE

Johann Albrecht Herzog

Translation of "Dauerbiegeversuch mit SiC-Al-Bändern unter Wechselspannung bei Raumtemperatur", Zeitschrift fuer Metallkunde, Vol. 72, March, 1981, pp. 191-197.

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16. Abstract

The development of a testing method for fatigue tests on SiC-Al tapes with only a small number of SiC filaments under alternating stress and at room temperature is reported, and the results obtained. The fatigue strength curves resulting for this composite with relatively little fracture strain are discussed. They permit an estimate of its behavior under continuous stress and in combination with various other - and especially metallic - matrices.

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BENDING FATIGUE TESTS ON SiC-Al TAPES UNDER ALTERNATING STRESS AT ROOM TEMPERATURE

by Johann Albrecht Herzog

SUMMARY. The development of a testing method for fatigue tests on SiC-Al tapes with only a small number of SiC filaments under alternating stress and at room temperature is reported, and the results obtained. Special emphasis was placed on simple test arrangements and evaluation possibilities. The fatigue strength curves resulting for this composite with relatively little fracture strain are discussed. They permit an estimate of its behavior under continuous stress and in combination with various other - and especially metallic - matrices. /2*

The development of filaments dates back many years. During this period the chemical and physical bases for their formation and properties had to be investigated. The materials glass, boron and silicon carbides appeared particularly attractive, since all of them belong into the category of materials with relatively low densities compared to conventional, purely metallic filaments and wires; in addition, they showed advantageous corrosion and diffusion properties and, with the limitation of glass, also good temperature properties. More recently, graphite was added, a material with entirely different behavior.

Once a certain level of knowledge was achieved for glass, but especially for boron, the investigation of the physical and

* Numbers in margin indicate pagination in original foreign text

technological quantities - and especially, the strength factors - became important, since their knowledge is of decisive importance to the application of these fibers. As is customary, tensile stregth was the first to be determined. Next to it, the bending strength was essential to any judgement.

From the beginning, the filaments were envisioned as reinforcing fibers within a matrix. The experiences gathered with glass fibers in a plastic matrix provided the stimulation for tests with filaments made of other materials. An important additional criterion was the elasticity modulus for these materials. It was relatively small for glass, but for two other materials - boron and SiC - it was approximately twice as high as that of steel. This applies to room temperature. At higher temperatures, the elasticity modulus for glass decreases considerably at 200 to 250°C, while those for boron and SiC suffer only minor reductions at even higher temperatures, and graphite remains practically constant up to nearly 1000°C. As a rule, the behavior of tensile strength is analogous.

With the appropriate selection of the filament in a matrix used for a given application, the use of the resulting compounds was successful especially when the position and distribution of the filaments was appropriate to the expected stress /1/, as proven by many tests with such samples, for the most varied kinds of stress. It should be obvious that their application at other than room temperature has not progressed as far. A series of material data are still lacking, data the designer needs to gain confidence in new materials. In addition - as we shall mention only in passing - there is a need for appropriate, financially bearable manufacturing methods that will not always follow conventional paths.

While today we already have learned much about matrix materials, the development of composites requires still much farther reaching work with filaments that are difficult to carry out experimentally for reasons of dimension /2/. They begin with the determination of the tensile strength with the required central clamping.

If this already presents problems, then dealing with the fatigue behavior of these materials may be interesting, but so time consuming in its test development stage, that to date little has been done in this area, and then only at room temperature.

Even though most of the filament materials mentioned have been successfully evaluated in plastic matrices for specific application areas /3/, there is still a gap in the intermediate temperature range, where plastic is no longer adequate as a matrix. It is for this reason that metal matrix composites are being studied. The manufacture of narrow tapes of aluminum with SiC filament inclusions has become interesting for financial and other reasons. These tapes can then be pressed together in design-compatible arrangements and at suitable temperatures, to form composites of larger dimensions. Other metals and their alloys belong in these investigations, as long as they are compatible with the filament materials /4, 5/.

/3

Silicon carbide filaments with particularly good properties and a very small scattering in their strength values, were developed by Gruber for the Berghof Research Institute, in Tübingen /6/. Because of their ready utilization in many applications, these tapes are now being manufactured /7/. This report deals with their fatigue strength at room temperature.

GENERAL REMARKS

Fundamentally, the tests were performed at a 50 Hz line frequency. This frequency source is very constant and readily available. The sample was a SiC-Al tape, firmly clamped at one end (cantilever). These basic concepts made a series of conditions necessary:

1. The sample's eigenfrequency must be adjusted exactly to the line frequency.
2. Clamping must always be very even and precisely guaranteed.

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Figure 1. View and section of SiC tape with 5 filaments

Figure 2. View and section of SiC tape with 16 filaments

3. The amplitude of the oscillations must be large enough and controlable, to obtain fracture at customary stress cycle frequencies.
4. A method must be available to measure the amplitude without interfering with the oscillation, and with sufficient accuracy.
5. The determination of the bending stress must be performed near the clamping site, accessible to a realistic judgement of the results.
6. The stress cycle frequency must be determined within relatively narrow limits.

Only when all of these conditions can be met by relatively simple means can work be successful and the fatigue strength curves be determined. Unfortunately, however, considerable development work is associated with each of these conditions until they can be satisfactorily applied.

Further basic conditions are an exact knowledge of the elasticity modulus of the sample and its moment of inertia with respect to an axis perpendicular to the plane of oscillation. A view of the samples used and their cross-sections is provided in Figures 1 and 2, above, for tapes with 5 and 16 SiC filaments, respectively. The material between the filaments is pure aluminum. As can be seen, the aluminum on the filaments in the tape plane is very thin.

For this reason, it probably will contribute only very little to the moment of inertia. Hence the moments of inertia were taken in such manner that only the filaments were considered. Thus the moment of inertia for 5 SiC filaments in tape $J^5 = 5d^4\pi/64 = 0.255 \cdot 10^{-4} mm^4$ and for 16 SiC filaments in the tape $J^{16} = 16\ d^4\pi/64 = 0.785 \cdot 10^{-4}\ mm^4$, when the filament diameter is d = 0.1 mm. If instead of considering a circular section for the filaments, the rectangular section of the SiC tape is used, then we obtain

$$J^5 = d^3b/12 = 0.86 \cdot 10^{-4} mm^4 \quad \text{and} \quad J^{16}\ d^3b_1/12 = 3.31 \cdot 10^{-4} mm^4$$

These values differ considerably from each other. For this reason the moment of inertia was determined independently in a static bending test with a SiC tape cantilever with a dead load at 8 mm distance from the point of clamping, and measurement of the bending deflection with a 1/100 dial gauge. The following values were obtained, with $J = Pl^3/3E\delta$, where the value of the modulus of elasticity was taken as $E = 420\ kN/mm^2$.

The results were: $J^5 = 0.237 \cdot 10^{-4} mm^4$ and $J^{16} = 1.35 \cdot 10^{-4} mm^4$ as averages of two series of tests. The ratio $1/\delta \geq 16$ was within permissible limits for the use of the bending equation.

The modulus of elasticity for SiC filament materials is sufficiently well known from tensile tests and was used, together with the value mentioned above, in the calculations of the bending stress.

The sample is made to oscillate in the cyclic field of an electromagnet. It is made, however, of non-magnetic material. And even if it were made from magnetic material, without special precautions it is difficult to achieve amplitudes large enough to achieve a sufficiently high stress at the clamping point, to obtain fractures in the fatigue strength range between approximately $N = 10^5$ and 10^8. Such amplitudes are achieved only when a weight - i.e., an additional mass - is placed on the cantilever that stores sufficient energy to force large amplitudes and to obtain large resonance oscillations. A cork-weight was used for this purpose; to avoid friction losses as much as possible, securing at the clamping point was prepared with particlar care. The influence of the cantilever dead weight on stress at the clamping point to that caused by the additional mass is relatively small, as can be shown by static calculations.

For the tests, an oscillatory system was used consisting of a /4
basic system - also mounted as a cantilever - to generate the oscillations, and a test cantilever attached to it as a system containing the SiC tape with cork weight, i.e., the real sample.

The basic oscillatory system c,d consists of two 0.3 mm thick iron sheets of 22 x 22 mm, glued together securing between them two spring wires of 0.7 mm diameter, c as shown in Figure 3, below. Leaving out approximately 7 mm, the springs were firmly secured e, and the sheets brought to oscillate in the cyclic magnetic field. To one of the sheets sample a was secured by means of a commercial adhesive; then a iron sheet strip was glued over the assembly, edge matching the sheet edge, b (thickness 0.3 mm), to obtain a clamping as firm and secure as possible.

As we have already mentioned, in order to obtain larger amplitudes, more energy must be applied to the sample. This was accomplished by means of cork-weight f, fastened to the sample at such a distance to the point of clamping that full resonance is achieved. The distance between the point of clamping and the center of mass is very sensitive, if a sharp resonance point and hence larger amplitude - i.e., greater stress - is to be achieved at the point of clamping. The weight was glued on. Depending on sample dimensions the dimensions of the weight must be adjusted; the most rapid way of accomplishing this is by means of a few tests. It was a little smaller for the SiC tape with 5 filaments than for the larger sample with 16 filaments.

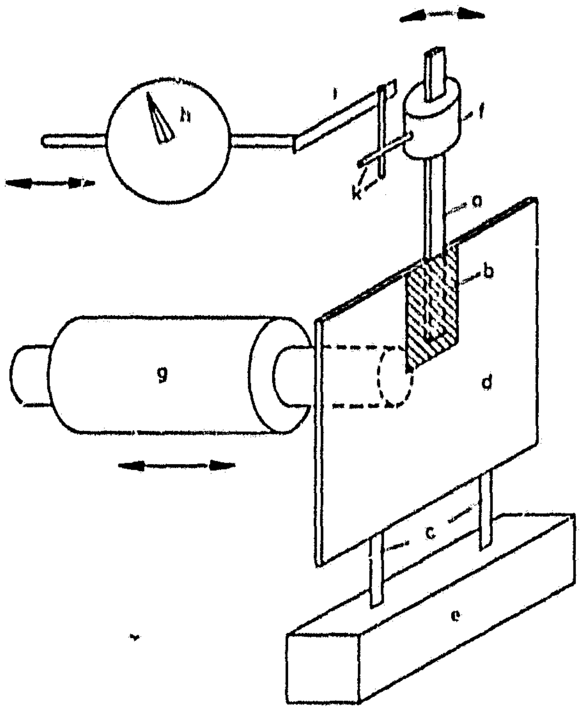

Figure 3. Schematic of test arrangement for the testing of SiC tapes in bending fatigue tests with alternating stress, around a unstressed rest position.

a Sample; b sample clamping; c basic system springs; d iron sheet (magnetic mass); e rigid clamping of base system; f cork weight; g Electromagnet (displaceable); h measuring device (displaceable); i paper strip; k SiC fibers.

The cork-weights f were cork cylinder sections of 4 mm diameter and 4 mm in length in the first case, and 4 mm diameter but approximately 6 mm length in the second case. The distance to the clamping point was approximately 13 mm for the 5-filament tape and nearly 10 mm for the 16 filament tape. The iron sheet-spring wire system may not be adjusted to its own resonance point by varying the spring wire lengths, but must remain below it.

While it is possible to precalculate these two values - and this was attempted - the magnitude of the system values needed as a starting point for the calculations is extraordinarily sensitive and since then determination of the distance between point of clamping and the center of the additional mass has been accomplished more rapidly and better by experimentation. Once the correct position is known for the cork weight, it is easy to then measure that distance, necessary in the calculation of σ_{max}.

For the tests performed, an iron-filled alternating current coil was used, of only 2 watt (g, in Fig. 3), energized from the line. Test execution may have become easier using a higher output - the values originally contemplated were 20 to 25 watt. The coil could be displaced in its axial direction for some distance by means of a screw. Thus, the distance to the fixed oscillating system in front of it could be increased or reduced continuously, to adjust the amplitude of the oscillating sample.

Another important development was the measurement of the amplitude at the weight of the oscillating cantilever sample without interfering with the oscillatory process. After experimenting various approaches the problem was solved by using a 1/100 dial gauge h. At the primary sensing element, with an adjustment screw, on one side the screw could be very precisely adjusted to the desired contact point. On the other side of the sensor, where there normally is a spherelet a paper-strip i was affixed and onto it, at a right angle to its axis, a section of SiC filament k was glued to the paper surface. At the midpoint of the length of the cork cylinder weight, in the plane of the test tape and perpendicularly to its axis, another segment of SiC filament k was pressed into the cork and glued in place. During their contact, these two filaments cross at right angles and it is possible to observe the contact adjustment with great precision, because the filament at the gauge leaves its rest position. This deflection is easy to see especially when the sample is oscillating. At rest, the gauge is adjusted to filament contact, then the initial reading is taken and the gauge reading taken to the desired amplitude. Next the oscillatory process is initiated and the amplitude so increased by bringing the iron core closer to the iron sheet in the basic

Figure 4. Photographic bending curve. 1.3 x

system, that the two filaments barely touch, i.e., such that the longer filament at the gauge just begins to oscillate. Figure 3 (see p.7) shows this construction in schematic form. In this fashion, the value of the bending deflection at the point the weight is applied can be measured with fair precision and without interfering influence, directly and ready for use in the calculation of σ_{max}. The amplitudes necessary to achieve fatigue fractures must lie near 6 mm for the 5-SiC filament tape. This means a ratio of length to deflection of $l/\delta = 8/6 = 1.5$. This ratio is much too small to apply the bending equation and hence one must be prepared for eventual errors in its application, due to the neglect of the shearing stress in the filaments.

For a SiC-Al tape with 16 filaments, for which a photographic bending curve (see Figure 4, above) was available, the calculated static bending curve was composed of 3 portions. In the first place was calculated the contribution to the bending deflection caused by the dead weight stress for a length of 8 mm (position 8 in Figure 5, below), the distance between the clamping point of the cantilever and the cork weight; in second place, the contribution due to the dead weight of the sample per mm distance between the weight and the free end was calculated, and third and last, the contribution resulting from the cantilever sample with additional weight at position 8 (i.e., at 8 mm from the clamped end). The three components together result in y_{calc}, the static bending deflection at the site of the weight. In order to compare this value to the dynamic, photographically determined bending /5

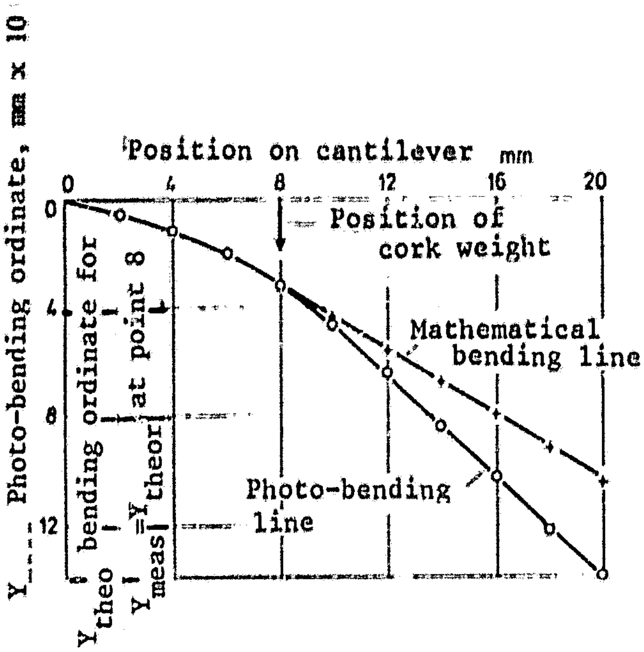

Figure 5. Comparison of the photographic bending curve with the mathematically computed bending line, with point load and dead weight

curve, y_{calc} is equated to y_{meas} - with the help of a multiplication factor - such that $y_{meas} = n \cdot y_{calc}$, where n can be readily computed; here y_{meas} is the ordinate measured at position 8 of the photographic bending curve.

All ordinates of the static bending curve were multiplied with the value of the multiplier, for the various positions along the cantilever and the resulting curve was compared to that determined photographically. As Figure 5, above, shows, in the main area of interest between positions 0 and 8 the two curves differ little from each other. The investigation was performed with a fairly large number of samples. Because of the satisfactory agreement between the two curves for the stress calculation near the clamping point - the site of greatest stress - for further evaluation it was possible to use $\sigma_{max} = 3Edy_{meas}/2l^2$, where σ_{max} is the stress at the clamping point, E the elasticity modulus for the SiC filament, y_{meas} the measured amplitude for the weight and l the distance from the weight to the clamping point. It should be noted that the moment of inertia does not appear in the equation, but that the correlation between σ_{max} and y_{meas} depends on J.

Finally, the time elapsed until sample fracture must be measured. For values up to $N = 10^5$ a stop watch was used for this purpose, and either visual or acustical observation. For longer running samples, optical-photographic registration was used, with clockwork action.

EXPERIMENTS AND OBSERVATIONS

Samples must be carefully glued and anchored; the weight must be just as carefully placed in exactly the right position by brief oscillation and anchored with a drop of diluted adhesive. Following a control oscillation, it is glued to its position permanently. The adhesive must be sufficiently dry to avoid changes in the geometrical arrangement. Once these conditions have been met, the system can be set to oscillating by means of the magnetic coil, and the distance between the iron sheets and the magnetic core be so adjusted that the desired amplitude is just achieved; as we have seen above, this can be controlled by observing the light oscillation of the SiC filament connected to the dial gauge. The magnitude of the amplitude is very sensitive at resonance, by its nature, and in theory can go to ∞. Because of losses such as imprecise system values, frequency deviations, friction losses, etc., usually there is oscillation around some maximum value determined by such influences. The smallest modifications in the system or the sample result in very large amplitude reduction, to be adjusted in the beginning until constant value is reached. However, this could no longer be accomplished after extended sample runs and the cause for such a behavior was investigated. During the most painstaking observations in search of possible cracks or delamination of the sample, no modifications could be found. But quite casually, during observation of a sample under very favorable conditions at moderate microscope magnification and appropriate illumination - a dark field, in this case - an extrusion of small particles was observed at the surface of each

Figure 6. View of a SiC tape with extrusions at the fatigue fracture site near the cantilever clamping point. Appeared long before fatigue fracturing. 40 x

Figure 7. Double extrusion by one of the fibers. 120 x

filament in the tape, along a line close to the clamping point, as shown in Figures 6 and 7, above, for a SiC tape with 5 filaments. Under careful observation, the SiC tapes with 16 filaments showed evidence of similar extrusions.

If, now, during dynamic operation the cross-section of the sample changes, then the resonance must be affected, with the consequent drastic reduction in amplitude. Naturally, questions will arise as to the cause of these extrusions.

It is probably safe to assume that the SiC filament is not free of initial stress /7, 8, 9/. The filament is formed on a W wire by deposition of SiC and hence consists of two materials at high temperatures. If we assume that during cooling of the SiC filament after its production, both components shrink according to their expansion coefficients, then initial stress must exist in the filament. While the expansion coefficients for W and SiC are not significantly different, that for the metal is surely larger than that for SiC; this will lead to pressure stress, especially at filament surface, while in the interior of the filament tensile stress must occur, to maintain the equilibrium.

If, during filament bending, and depending on the level of initial stress, a sufficiently large bending pressure stress is added on the pressure side, then these extrusions may occur, while some balancing relief could occur on the tension side. In the subsequent study of individual filaments, tested in the same manner under bending fatigue stress techniques, it was established that these sites were also visible, and that there, too, sudden resonance decreases occurred, i.e., that amplitude decreases were observed.

The SiC filament surface is not smooth, but may be rather char- /6
acterized as grained. These small notches contribute to fatigue loading sensitivity and favor this type of behavior.

Let us include some brief considerations, at this point. The expansion coefficient for tungsten, at 1200^0c, is approximately $5.65 \cdot 10^6$, while no precise values are available for SiC. By comparison with other, similar materials, it should be in the neighborhood of $3.5 \cdot 10^6$. If we accept this value, then the difference between the two coefficients is $\alpha = 2.15 \cdot 10^6/^0C$; or, for a length of 1 m, a change in length of $\Delta l = \alpha t l = 2.15 \cdot 10^6 \cdot 1500 \cdot 1000 =$ 3.21 mm. The tension is, then, $\sigma = \Delta l E/l = 3.21 \cdot 420 \cdot 10^3/1000 \approx$ 1.35 kN/mm^2. This most probably is an extreme value. Even if the actual value α for SiC lies between 4.0 and $4.5 \cdot 10^6$, we would still have a stress of an average value of 0.8 kN/cm^2. This is quite sufficient to cause the extrusions on the pressure side, during bending. What is remarkable is that these extrusions always appear at all 5 or, respectively, 16 filaments, near the clamping site, and for many of the samples.

Figure 8, below (page 14) shows the initial stress condition in the filament on top; at the bottom of the figure is shown the condition of initial stress plus bending stress. That representation can convey an idea of the stress condition during testing. We can see that when pressure stress is superimposed, the stress

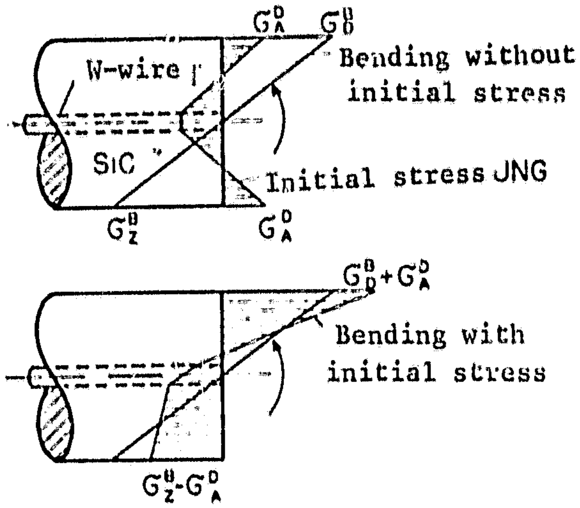

Figure 8. Stress distribution and modification during bending stress of a SiC fiber without (top) and with (bottom) initial stress. σ_A^D = initial compressive stress, σ_A^Z = Initial tensile stress, σ_D^B = bending pressure stress, and σ_Z^B = flexural tensile stress

limit of the material is reached first at the pressure side, while on the tension side the overlaid tensions acts as a relief. In the fatigue bending test, each side is alternatingly subjected to this high a stress; the possible influence of the notches will determine on which side extrusions will appear first. A direct measurement of these conditions is quite complex and should be reserved for a special study. It is possible, however, that the tests of this kind planned for the future bring some insights; it could be that tests performed under temperature show different behavior and provide indications for further analysis of the processes taking place.

RESULTS

Starting from these bases and the methods described, a series of samples were submitted to fatigue bending tests under alternating stress conditions at room temperature, and inspected; the fatigue strength curves shown in Figure 9, below, for SiC tapes with five filaments and in Figure 10, below, for tapes with 16 filaments,

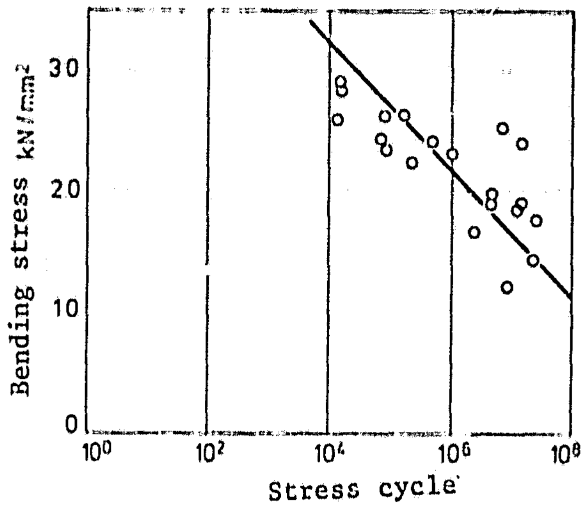

Figure 9. Bending stress durability for SiC tapes with 5 fibers, at room temperature

were obtained.

At first it seems remarkable that typical fatigue strength behavior should be observed also for ceramic filaments such as SiC. Both types of tape show relatively large scattering around a line obtained as an average by the least squares method. By its nature, sensitivity is higher at higher stress. Also remarkable is the fact that in the 16 filament tapes no more fractures occur below ≈2.0 kN/mm^2, up to N = 10^8, in contrast to the 5-filament tapes, in which a fracture is still observed at ≈1.5 kN/mm^2. The number of filaments seems to play a role, here, since where there are more filaments, the weak spots will be more evenly distributed. The tests were performed to a bending fatigue strength limit of N = 10^8. For N = 10^6 - a limit that already is quite high in relation to bending fatigue strengths of light metals, for instance - even small increases in stress can already cause fatigue cracks, because of the scattering. Stresses below this area should not lead to fatigue cracks up to a limit of N = 10^7 - 10^8. If we assume the tensile strengths of 4.0 to 4.5 kN/mm^2 established by Gruber, then fatigue crack-safe stresses of 2.0/4.1 ≈ 0.5 are established for the 5-filament tape, and of 2.5/4.1 ≈ 0.6 for the 16-filament tape.

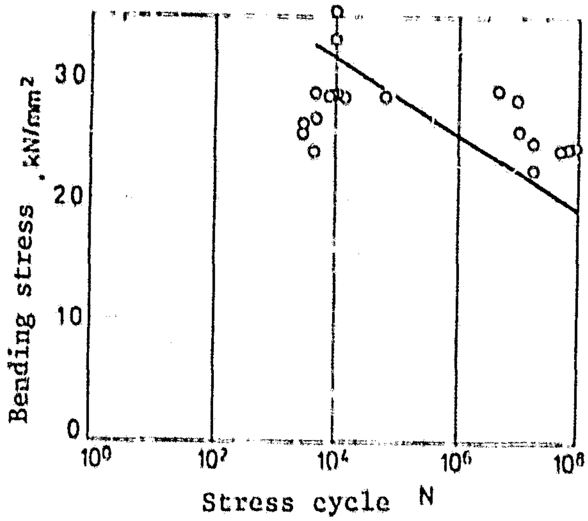

Figure 10. Bending stress durability for SiC-Al tapes with 16 fibers, at room temperature.

When compared to metals, composites with ceramic filaments show relatively small expansion values and differences in expansion are balanced essentially by the matrix material. Composites are already being used in some construction applications /1, 3, 10, 12/, but their safety values or, respectively, stress limits, used in calculations, are not very well known. It can nevertheless be assumed, however, that even at equally high permissible stresses in comparison to metals, significant advantages can be derived in terms of weight savings. This should be the subject of special analyses, which undoubtedly could shed much light on discussions regarding the applicability of SiC filaments and tapes.

SUMMARY AND CONCLUSIONS

SiC-filaments tapes, with 5 and 16 filaments embedded in pure aluminum, were investigated. Filament wetting and the thin matrix stems connecting the filaments - in the cases of the 5-filament tapes - are unobjectionable.

The tapes were tested for bending fatigue under alternating stress conditions, with a vertical rest position. Typical fatigue strength curves were obtained also for the SiC filaments, showing fatigue fractures in the stress cycle range $N = 10^6$ to 10^8; these are stress cycle values, however, that are of little practical interest. Between $N = 10^6$ and $N = 10^8$ the curve falls fairly rapidly. The tests were performed at room temperature. No delamination was observed, either prior to or following the tests.

Special methods had to be developed for clamping, obtaining the necessary amplitude magnitudes, measuring these amplitudes without interfering with the resonance oscillation, and for measuring stress cycle values; mathematical calculations were necessary to establish reliable methods for the determination of maximum stress at the fracture point. Considerations regarding initial stresss in the filaments and its effect on stress fracturing were taken into consideration. Simultaneously with the fatigue tests, microscopic analyses of the fractures and of fracture initiation were performed.

We consider very desirable further fatigue tests on filaments of other materials, tests at higher temperatures and, when they become available, tests with tapes of different matrices. Comparison of the results would provide a fairly complete picture of the behavior of such filaments. These tests should be continued.

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The work on the fatigue strength of the SiC filaments was made possibly by the loan of a research microscope by Prof. Dr. W. Bunk, Director of the Institute for Materials Research DFVLR, Cologne-Wahn, whom we wish to especially thank, here. In addition, SiC filaments and tape material was graciously placed at our disposal by Dr. P. Gruber of the Berghof Research Institute, Tübingen; the author is particularly grateful for it.

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