Creep Deformation and Fracture of an Aluminum Composite Reinforced with Continuous Alumina Fibers*

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Creep tests were carried out on an aluminum composite reinforced with continuous alumina fibers at temperatures of 573 to 773 K to examine the mechanism of high temperature deformation and fracture of the composite.

The creep behaviour was different in the low and high stress ranges. The creep curves in the low stress range showed only mostly the primary or slight secondary stage without reaching the tertiary stage. The creep strain consisted of an irreversible component, possibly due to the plastic deformation of matrix around the misaligned fibers and the fracture of fibers at weak points, beside a reversible component due to the elastic and anelastic deformation of the matrix and fibers, although the former component was very small at lower stresses.

In the high stress range, the creep deformation proceeded by the local fracture of fibers and the plastic deformation of the matrix resulting in fracture of the specimen. The creep curves showed the primary, secondary and tertiary stages.

The critical stress which distinguished between the low and high stress ranges was about 500 MPa at 573 K and 450 MPa at 773 K. The critical stress was consistent with the threshold stress which was recognized in the stress dependence of the minimum creep rate. The critical stress, or the threshold stress is considered to be the minimum stress necessary for the individual cracks of fibers to propagate extensively and to cause the fracture of the whole specimen.

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I. Introduction

A continuous fiber reinforced aluminum matrix composite has been expected as one of the candidates for aerospace material in future, since it is excellent only in the specific strength and rigidity but in the high temperature strength compared with the other conventional aluminum alloys. The creep properties which are important in high temperature service, however, seem not to be well known for the aluminum matrix composite reinforced with strong continuous fibers like ceramics.

The creep curve and creep rate of a continuous fiber reinforced metal matrix composite have been considered by McLean for the following two cases: (1) fibers deform only elastically (non-creeping fiber) and the matrix deforms plastically as well as elastically, and (2) both of fibers and matrix deform elastically and plastically⁽¹⁾. Assuming that the matrix creeps in accordance with a power law creep for the applied stress, the creep curve and creep rate have been calculated and compared with the creep rates of the “*in situ*” composite (γ - γ' - Cr_3C_2). More detailed experimental examination, however, seems to be necessary in order to establish the creep model of a strong continuous fiber reinforced composite. Although many researches have been done mainly on creep deformation of the unidirectionally solidified

eutectic alloys called “*in situ*” composite⁽²⁾ or short fiber reinforced composites⁽³⁾⁻⁽⁷⁾, few researches have been reported on creep of the metal matrix composites reinforced with continuous ceramic fibers and the stress and temperature dependences of their creep curve are not well known.

In the present work, the creep deformation and fracture behaviour was examined in an Al matrix composite reinforced with continuous alumina fibers, which is supposed not to react with the matrix Al at high temperatures, in order to clear experimentally the creep behaviour of a continuous strong (non-creeping) fiber reinforced composite and obtain the information on the actual creep model.

II. Experimental Method

The material used was 6 mm thick sheets of an Al matrix composite unidirectionally reinforced with continuous γ -alumina fibers of about 17 μm in dia., which was fabricated with a squeeze casting method in Sumitomo Chemical Co⁽⁸⁾. The volume fraction of fibers was 50% and the chemical composition of γ -alumina was 85% Al_2O_3 -15% SiO_2 . Creep specimens were cut from the sheets with the tensile axis parallel to fiber axis and shaped in the shape and dimensions as shown in Fig. 1. Their surface was then polished with emery paper and etched away finally by immersing in a dilute HF solution for 5 to 10 min.

Since the creep elongation of continuous fiber reinforced composite is expected to be very small, the elongation was measured on both sides of specimen with two extensometers through detectors attached to the protrusions on both ends of the gauge section (see Fig. 1) and

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Fig. 1 Dimensions of creep specimen.

averaged arithmetically to get the creep elongation. Creep tests were carried out with a lever type testing machine at temperatures of 573 to 773 K under tensile loads in air.

III. Experimental Results

1. Stress dependence of shape of creep curve

Typical examples of the creep curves at low, intermediate and high stresses are shown in Fig. 2. The general feature is that a large part of the creep curve is dominated by the primary creep stage. At a low stress, the entire creep curve consisted mostly of the primary stage so that the creep strain tends to saturate to a constant value, or the creep rate is estimated to be very small (below 10^{-9} – 10^{-10} s $^{-1}$) even if the stage of secondary creep appears. At a high stress, the stages of secondary and tertiary creeps are clearly recognized subsequent to the primary stage, resulting in fracture finally.

Irregular and discontinuous changes of elongation are recognized in the elongation-time curves showing the elongation of both sides of the specimen (Fig. 3) which has been recorded with two extensometers, especially when it reaches creep fracture in a short time at a high stress, although the creep curve shows apparently a smooth creep curve of the primary, secondary and tertiary stages as shown in Fig. 2(c).

Such irregular changes of elongation have evidently been observed in the case that the fracture occurs in a

Fig. 2 Typical creep curves at 673 K.

Fig. 3 Elongation-time curves recorded with two extensometers attached to the protrusions of both sides of specimen (see Fig. 1), corresponding to creep curve (c) in Fig. 2.

short time of a few seconds. It shows that the creep deformation of composite proceeds in an irregular way by the local fractures of fibers and the plastic deformation of the matrix around them.

2. Stress dependence of initial instantaneous strain

Instantaneous strain occurs at first on loading in the creep tests. The relations between the initial instantaneous strain and applied stress are shown in Figs. 4, 5 and 6 for the creep tests at 573, 673 and 773 K, respectively. The instantaneous strain is larger than elastic strain ϵ_e given by σ_c/E_c , shown by a broke line, which is expected when both the fibers and matrix deform elastically. Here, σ_c and E_c are the applied stress and Young's modulus of composite respectively. The measured value of E_c at 723 K, 140 GPa † , was used to calculate the ϵ_e shown in these figures. The value of E_c can also be estimated by the rule of mixture,

$$E_c = E_f V_f + E_m V_m, \quad (1)$$

where E_f and E_m are the elastic moduli of the fiber and matrix, respectively, and V_f and V_m are the volume fractions of the fiber and matrix, respectively. When the elastic modulus of the alumina fiber at 293 K, 210 GPa † , is used as E_f and that of Al at 673 K as E_m in eq. (1), the value of E_c is obtained as 132 GPa. Although the ϵ_e , estimated using this value of E_c , is a little larger than those shown in the figures, the measured instantaneous strains are still larger than the ϵ_e estimated in this way. It is concluded that the instantaneous strain measured contains a plastic component of strain.

The maximum creep strain, $\epsilon_{\max}$, which is expected when the fiber deforms elastically and the matrix deforms plastically so that stress in the matrix is fully relaxed, is shown by a dash-dotted line in the figures. The maximum creep strain is given by the following equation, as shown later,

$$\epsilon_{\max} = \frac{\sigma_c}{E_f V_f} \quad (2)$$

The values of instantaneous strain are near the $\epsilon_{\max}$ in small stress range and larger than it in high stress range as

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seen in these figures. The stress-strain curves are shown by the full lines in the figures, which have been obtained by tensile tests with a strain rate of 4.6×10^{-4} /s at each

Fig. 4 Stress vs. instantaneous and creep strain in the creep test at 573 K. Stress-strain curve obtained by the tensile test is also shown by a full line.

Fig. 5 Stress vs. instantaneous and creep strain in the creep test at 673 K. Stress-strain curve obtained by the tensile test is also shown by a full line.

Fig. 6 Stress vs. instantaneous and creep strain in the creep test at 773 K. Stress-strain curve obtained by the tensile test is also shown by a full line.

temperature. The instantaneous strain is nearly consistent with the strain in the stress-strain curve or somewhat smaller than this when compared at the same stress level.

The creep strain, at which creep tests have been interrupted on the way (near the saturation strain) without reaching fracture, or the fracture strain are shown in the figures. Although there is a scattering in the values by each specimen, the fracture strain is about 1%. Some of these data were obtained by repeating successively the creep tests 2 or more times on one specimen as follows: initial creep test was done at a low load (or low temperature) for about 100 h (sometimes about 50 h), unloaded, recovered for 10–20 h or more at the test temperature, and then subsequent creep test was carried out at higher load (or at higher temperature). These data are marked by the alphabet and the numeral such as a1, a2..., where the alphabet means each specimen and the numeral shows the number of tests done on the specimen. The other data points with no marks were obtained by creep test of only one time at a given load. When the creep deformations are compared between the specimen with history of prior tests and one without prior test at the same stress level, the instantaneous strain is about same in both type of specimens, although the time-dependent creep strain after the instantaneous deformation seems to be somewhat smaller in the former specimen than in the latter one at temperatures of 573 and 673 K. This tendency of the time-dependent creep strain is not clear at 773 K, possibly due to a large scattering of the instantaneous strain and creep strain by each specimen.

3. Recovery behavior after creep deformation

Some specimens were crept till near the saturation strain in the low stress range, where only the primary stage was mainly observed, unloaded and then held at the temperature of creep test for some time to examine the recovery behavior. One example of the recovery experiments is shown in Fig. 7. Creep strain decreased instantaneously on unloading and then exponentially with time, and finally appeared to settle down to a constant value, that is a permanent strain. The permanent strain

Fig. 7 Typical recovery curve at 573 K after creep (442 MPa) and unloading.

Fig. 8 Permanent strain vs. instantaneous strain (ϵ_0) and total creep strain relations.

Fig. 9 Relation between instantaneous strain ϵ_0 on loading and instantaneous recovery strain ϵ_{r0} on unloading.

was very small and increased gradually with the creep strain or initial instantaneous strain when they were small, as shown in Fig. 8, and it increased rapidly as the creep strain exceeded about 0.6% or the instantaneous strain was above 0.5%. The creep deformation seemed to reach the fracture stage in many cases, as seen in Figs. 4–6, when the creep strain or instantaneous strain exceeded these values respectively.

Instantaneous recovery strain on unloading, ϵ_{r0} , increased with the creep stress or strain and it was about equal to the instantaneous strain on loading, ϵ_0 , as shown in Fig. 9. The difference of both instantaneous strains, $\epsilon_0 - \epsilon_{r0}$, is also shown in the figure. It shows that the ϵ_0 is larger than the ϵ_{r0} when the ϵ_0 increases above 0.5%. The value of ϵ_0 equal to 0.5% corresponds to the point at which the permanent strain begins to increase rapidly as seen in Fig. 8.

4. Stress dependence of minimum creep rate

The secondary and tertiary stages were recognized in the creep curve obtained at a high stress and, therefore, the minimum creep rate, $\dot{\epsilon}_m$, was estimated. The relation between the minimum creep rate and applied stress, obtained in the high stress range, are shown in a logarithmic

Fig. 10 Minimum creep rate $\dot{\epsilon}_m$ vs. applied stress σ relation.

plot in Fig. 10. Here, the points with the arrow mark show the creep rates obtained at the stage of interruption of test after the creep time of 100 h or more, where the tertiary stage is not recognized so that it is uncertain whether the stage is primary or secondary, and the true minimum creep rate is supposed to be smaller than these points.

As seen in Fig. 10, the minimum creep rate depends strongly on the stress and approaches to zero as the stress decreases below some critical values, that is, this shows the presence of threshold stress for creep deformation. The threshold stress appears to depend on creep temperature, it is about 500 MPa ($\log \sigma = 2.70$) at 573 and 673 K and 450 MPa ($\log \sigma = 2.65$) at 773 K. The threshold stress in this case means the critical stress, below which creep deformation shows only the primary stage or secondary stage with very small strain rate and above which shows the primary, secondary and tertiary stages resulting in fracture. Therefore, it is practically an important parameter representing the creep strength of the composite.

5. Relation between creep rupture life and minimum creep rate

The creep rupture life t_f is plotted against the applied stress in Fig. 11. The rupture life decreases with increasing stress, corresponding to the variation of the minimum creep rate with the stress in Fig. 10. Fracture occurs instantaneously on loading of about 700 MPa ($\log \sigma = 2.85$). The rupture life increases rapidly near the threshold stress in accordance with the stress dependence of the minimum creep rate in Fig. 10.

Fig. 11 Relation between rupture time t_f and applied stress σ . Fig. 12 Relation between minimum creep rate $\dot{\epsilon}_m$ and rupture time t_f .

Correspondence between the stress dependence of the minimum creep rate and that of the rupture life shows that there is a close relation between them. It is well

known that Monkman-Grant relation holds between minimum creep rate $\dot{\epsilon}_m$ and rupture time t_f in many metals and alloys. This relation is expressed as follows:

$$\dot{\epsilon}_m^m \times t_f = C, \quad (3)$$

where m is a constant about equal to 1 and C a constant which is equivalent to the rupture strain and called the effective creep ductility. Both of them do not depend on temperature and stress. Figure 12 shows the logarithmic plot of the $\dot{\epsilon}_m$ and t_f for the present material. The relation of eq. (3) holds well for the present composite material too, with the m value equal to 1.0 and the C value equal to 1.0×10^{-3} .

6. Observation of fracture surface

Figure 13(a) and (b) show the macroscopic feature of fracture surfaces in the specimens fractured by creep under different stresses at 673 K. The fracture surface shows an intense unevenness generally, which tends to increase with lowering stress. Enlargements of these fracture surfaces are shown in Fig. 14(a) and (b) respectively. The flat region, where many fibers have broken locally on the same plane as seen in Fig. 14(b), increases as the stress is higher, resulting in the more flat fracture surface. At low stress, each fiber tends to break on different planes (Fig. 14(a)) and the macroscopic unevenness of the fracture surface becomes more intense.

As seen in these fracture surfaces, the fibers are fractured in a brittle manner. Pulling-out of fibers from the matrix by detachment in the fiber/matrix interface seems not to occur. The Al matrix adheres on the surface of fibers pulled out, showing that the matrix is ruptured by shear deformation between the fibers.

Fig. 13 SEM photographs of fracture surfaces of specimens ruptured by creep at 673 K under stresses of (a) 541 MPa and (b) 664 MPa.

Fig. 14 Enlargements of fracture surfaces shown in Figs. 13(a) and (b).

IV. Discussion

1. General creep behavior

Creep curves of the present composite were mainly dominated by the primary creep in the stress range of the present experiments. However, the creep behavior was different between a low stress range below a stress of about 400–500 MPa and a high stress range above it. That is, the creep curve shows only the primary stage even after 100 h or more in the low stress range, so that the creep strain appears to approach a saturation value without reaching the secondary or tertiary stage. In the high stress range, the creep curve shows the primary, secondary and tertiary stages and reaches the fracture. The critical stress which distinguishes between the low and high stress ranges is estimated to be about 500 MPa at 573 K and 450 MPa at 773 K from Figs. 4–6, and therefore seems to be somewhat dependent on the temperature.

Since the minimum creep rate is near zero at stresses below the critical stress, the critical stress should be equal to the threshold stress, which is recognized in the stress dependence of the minimum creep rate as shown in Fig. 10. The creep deformation at low stresses below the critical stress is supposed to occur by elastic deformation of the fiber and elastic/plastic ones of the matrix. Ideal creep behavior in this case is described by the three element model, as mentioned in the next section, and the creep curve shows only the primary stage.

In the high stress range above the critical stress, the creep deformation leads to the fracture of composite through the tertiary stage. Therefore, breaking of the fibers is expected to occur at their weak points during the creep. These cracks increase in their size and number, ac-

companied by the plastic shear deformation of the matrix, with the creep time and finally result in the macroscopic fracture of the composite.

2. Creep deformation in the low stress range

(1) Three-element model for creep of composite

An ideal creep deformation of a composite reinforced unidirectionally with continuous fibers, in which the fiber deforms only elastically and the matrix does plastically as well as elastically, can be described by the three element model as shown in Fig. 15(a). Here, spring means the elastic deformation and dashpot the viscous deformation (plastic deformation in the present case). The creep curve and the subsequent recovery behavior after unloading, predicted from the three-element model, are schematically shown in Fig. 15(b).

According to this model, initial instantaneous strain ϵ_0 is caused from the elastic deformation of both the fiber and the matrix and given by σ_c/E_c . The stress in the matrix is released to zero as creep proceeds, so that the fibers bear all the applied stress by the elastic deformation. Then, the creep strain approaches a saturation

Fig. 15 (a) Three element model for creep deformation of composite, (b) creep curve for the three element model.

value, $\varepsilon_{\max}$, finally, which is given by eq. (2). When the applied stress is removed on the way of creep deformation, the strain decreases instantaneously by elastic strain ε_e , and then it decreases exponentially to zero. This model predicts that the permanent strain, which should remain on being recovered for a enough time after unloading, is zero.

(2) Initial instantaneous strain ε_0

Creep behavior of the present composite is somewhat different from the above prediction of the three-element model. Instantaneous strain ε_0 is generally larger than elastic strain ε_e of the composite, as seen in Figs. 4–6. It is rather near maximum strain $\varepsilon_{\max}$, which should be obtained when the stress in the matrix is fully released, and tends to be larger than this at high stresses. The following reasons are considered for such large values of instantaneous strain.

(a) Since the applied stress on the composite is in the very high stress range for the Al matrix, plastic deformation of the Al matrix occurs so rapidly that it is observed as the instantaneous strain.

(b) All fibers in the composite are not necessarily parallel to the tensile axis and some off-axis fibers, inclined to the tensile axis, are locally observed as shown in Fig. 16. Such misalignments of fibers causes to make larger the instantaneous elastic strain by lowering the elastic modulus of the composite.

(c) Furthermore, there are components of tensile stress normal to the fiber axis and shear stress parallel to it in the matrix around the off-axis fibers. These stress components cause an irreversible plastic deformation of the matrix.

(d) With increasing the stress, local breaks of the fibers at the weak points in the distribution of fiber strength or detachment of the fiber/matrix interface are considered to be a more important factor for the irreversible plastic deformation in the instantaneous strain.

(3) Relation between initial instantaneous strain ε_0 and instantaneous recovery strain ε_{r0}

When the creep test was done in the low stress range

Fig. 16 Optical micrograph of alumina fibers in the Al matrix, showing local misalignments of some fibers.

where the creep curve showed only the primary stage, instantaneous recovery strain ε_{r0} on unloading was almost equal to instantaneous strain ε_0 on loading. It is expected that both instantaneous strains, ε_{r0} and ε_0 , are equal, when both strains contain only elastic component as in the case of the three element model. In the present case, however, the ε_0 contained the instantaneous plastic strain of the matrix besides the elastic one. Therefore, it is supposed that the anelastic component due to the plastic strain of the matrix are equal in the instantaneous strains at loading and unloading. When the value of ε_0 is larger than 0.5% with a higher stress, the ε_0 was larger than the ε_{r0} . This shows that an irreversible strain component, $(\varepsilon_0 - \varepsilon_{r0})$, appears in the initial instantaneous strain, possibly due to the breaks of fibers or the permanent plastic strain of the matrix around the off-axis fibers. In facts, the permanent strain, which remained on recovery after unloading, increased rapidly as the ε_0 was larger than the ε_{r0} (Fig. 8).

(4) Effect of temperature on initial instantaneous strain

Scattering in values of the initial instantaneous strain and their average values are larger at the high temperature of 773 K than those at 573 and 673 K, when compared at the same stress level. Furthermore, it is clearly seen at 773 K creep tests in Fig. 6 that the larger the initial instantaneous strain, the larger the time dependent creep strain, $\varepsilon_c - \varepsilon_0$, is. On the other hand, this tendency is not clear at 573 K.

Deformation of fibers and the matrix are constrained by each other, unless their interface is detached. However, the constraint to the deformation of fiber by the matrix should be lowered at high temperatures due to the decrease in strength of the matrix. It is expected, therefore, that at the higher temperature, the more largely the deformation of the composite, such as the instantaneous strain and time-dependent creep strain, will be affected by the misalignments of fibers and their strength distribution, which are different by each specimen. On the other hand, at low temperatures, the constraint by the matrix is high and suppresses the direct effect of fibers, such as that of the misalignments or their strength distribution, on the instantaneous strain and time-dependent creep strain. This makes small the value of these strains and their scattering by each specimen at low temperatures.

(5) Permanent strain after recovery

The permanent strain, which remains on recovery for a enough time after unloading, that is an irreversible component of creep strain, is not generally zero and increases with the creep strain or instantaneous strain as shown in Fig. 8. However, the permanent strain is very small ($< 0.1\%$) when the creep strain is below about 0.6% (or the instantaneous strain $< 0.5\%$), showing approximately such creep behaviour as that predicted from the three element model. When the creep strain is larger than 0.6%, the irreversible strain which cannot be restored by

recovery begins to increase rapidly. This strain is supposed to be caused from the irreversible plastic deformation of the matrix near the off-axis fibers and the breaks of fibers at their weak points.

The relation between the permanent strain and instantaneous strain, also shown in Fig. 8, shows that the permanent strain begins to increase rapidly as the instantaneous strain is larger than about 0.5%. This value of instantaneous strain corresponds to the applied stress of about 450–500 MPa. This is nearly equal to the critical stress which discriminates the creep behavior in the low stress range from that in the high stress range.

3. Creep deformation in the high stress range

In the high stress range, the total creep strain is definitely larger than the maximum saturation strain $\varepsilon_{\max}$ predicted from the three-element model and the initial instantaneous strain is also larger than this. The secondary and tertiary creep stages appear subsequent to the primary stage in the creep curve and eventually fracture occurs at the elongation of 1% or so.

The creep curve is not necessarily smooth and shows some irregularities. The irregularities are especially evident in the creep curve when it reaches the fracture stage at a short time (a few seconds or minutes) as shown in Fig. 3. It shows that the creep deformation proceeds sometimes rapidly or slowly by the sequence of local breaks of the fibers and their extension, being accompanied by the plastic relaxation of the matrix around them. The creep deformation, in this case, is expected to proceed in the following two ways.

(a) Local breaks of the fibers occur at their weak points, accompanying the plastic relaxation of the matrix around them, but do not propagate directly to the neighboring fibers. Creep deformation proceeds through the sequence of such fiber breaks and the plastic relaxation of the matrix around them.

(b) The local fiber breaks extend directly to the neighboring fibers due to the stress concentration, being accompanied by the plastic deformation of the matrix around them, thus results in the advance of creep deformation.

According to the observation on the fracture surfaces, they show generally the intense unevenness. The unevenness is the more intense as the creep test is done at the lower stress so that the creep fracture takes a longer time. The flat regions tend to increase as the creep fracture occurs in the shorter time at creep under the higher stress. When the applied stress is low, the breaks of fibers at the weak points may occur in many places in the specimen but they do not propagate to their neighboring fibers. In this case, the cracks due to the fiber breaks extend by the process (a) mentioned above, resulting in the fracture surface with the intense unevenness. At creep under the higher stress, the cracks due to the fiber breaks tend to propagate by the process (b), so that a flat region appears in the fracture surface.

The minimum creep rates, shown in Fig. 10, represent the rate of deformation of composite controlled by the

propagation of cracks mentioned above. Large stress dependence of the creep rate, seen in Fig. 10, is supposed to come from such deformation mechanism. However, the minimum creep rate appears to depend on the temperature; that is, the higher the temperature, the larger the creep rate is. This temperature dependence may be explained by either of the followings: creep deformation is controlled by the plastic relaxation of the matrix in the propagation of cracks through the process (a) or the strength of the fiber/matrix interface (or fiber itself) decreases with the temperature. It has been well established in the creep of metals and alloys that the relation between creep rate and stress is affected by the temperature dependence of Young's modulus E and reasonably well described by using the modulus-compensated stress, σ/E , instead of stress σ . Since the temperature dependence of elastic modulus of the alumina fiber is supposed to be so small, compared to that of the matrix Al, in the present temperature range from room temperature to 773 K, Young's modulus of the composite at each temperature is estimated by using the rule of mixture (eq. (1)) from Young's modulus of the alumina fiber at room temperature (210 GPa) and that of Al at each temperature. The relation between the minimum creep rate and the modulus-compensated stress, σ/E , corrected by Young's modulus of the composite at each temperature, is shown in Fig. 17. The temperature dependence of the creep rate in this plot is smaller compared with that shown in Fig. 10, although the creep rate at 773 K is still a little higher than that at lower temperatures.

The threshold stress, below which the minimum creep

Fig. 17 Minimum creep rate $\dot{\varepsilon}_m$ vs. applied stress corrected by Young's modulus of composite, σ/E .

rate approaches zero, has been recognized at the stress of about 450 to 500 MPa. This stress is considered to express the lowest stress necessary for the local breaks of fibers to develop and result in fracture of the whole specimen.

It is possible, however, under some stress conditions that the creep deformation proceeds by the local breaks of fibers being accompanied by the plastic relaxation of the matrix even under stresses lower than the threshold stress, but the extension of these cracks remains within a local range without leading to the macroscopic fracture so that the creep deformation stops finally. Creep under this situation seems to occur at higher stresses in the low stress range. The irreversible strain component (permanent strain) which is recognized at creep in the low stress range appears to be caused from such local breaks of fibers and partially from the irreversible plastic deformation of the matrix around the off-axis fibers.

V. Conclusions

The creep behavior of the present composite was different between the low and high stress ranges. The critical stress which distinguished these two ranges was about 500 MPa at 573–673 K and 450 MPa at 773 K.

In the low stress range, creep did not reach the fracture stage and the creep curve showed almost the primary stage or, in addition, the secondary stage with a very small strain rate (below 10^{-9} – 10^{-10} /s), if it is recognized as a secondary stage. The creep strain consisted mainly of a reversible component due to elastic and anelastic deformations of the fiber and the matrix at lower stresses, although a very small permanent strain ($<0.1\%$) was recognized during the recovery after creep deformation. The permanent strain increased rapidly near the critical stress with increasing applied stress. The permanent strain or irreversible strain was estimated to come from the plastic deformation of the matrix around the misaligned fibers and the local fiber breaks at their weak

points.

In the high stress range, the creep curve showed the primary, secondary and tertiary stages, resulting in fracture of the composite. The fracture surfaces showed that the creep deformation in this stress range proceeded by the local fiber breaks accompanied by the plastic relaxation of the matrix around them.

The critical stress was consistent with the threshold stress which was recognized in the stress dependence of the minimum creep rate. The critical stress, or the threshold stress is considered to represent the minimum stress necessary for the individual cracks of fibers to propagate extensively, through the plastic relaxation of the matrix, resulting in fracture of the composite.

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