

# METAL-MATRIX HEAT-RESISTANT FIBROUS COMPOSITES

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## 1 Introduction

A far-reaching way to enhance temperature in various gas turbines and other machines is to replace superalloys and homogeneous ceramics with fibrous composites. This idea is now rather obvious; however, ways of the realisation are complicated and despite the composite community has been going along these ways for about 40 years we are now observing a success just in few directions, the development of SiC/SiC composites is perhaps a most successive one [1]. Heat-resistant metal-matrix composites (MMCs) are now in shadow but recent results obtained by the author's research group are formed a base for the hopes. These results have become possible due to (i) the invention of the internal crystallisation method for producing single crystalline and eutectic oxide fibres suitable for the use in structural applications [2] and (ii) an intensive use of micromechanical models of creep [3] in planning the experiments and interpreting their results.

In the present paper, these results are briefly reviewed. We are to start with a creep model for MMCs and its applications to analysing creep behaviour of various composite macrostructures, which is necessary to evaluate creep properties of a rather large variety of possible composites, then will proceed with fabrication technology of appropriate fibres and composites reinforced with them, and finally present creep behaviour of the composites. We are to conclude with a discussion of the prospects of such type of the composites.

## 2 Creep model

### 2.1 The basic

The basic model of creep behaviour of MMCs was published some years ago [2]. The model yields a dependence between composite stress  $\sigma$  and creep rate  $\dot{\epsilon}$  on the steady state as

$$\sigma = \lambda \sigma_m \left[ \left( \frac{\sigma_o^{(f)}}{\lambda \sigma_m} \right)^\beta \left( \frac{l_o}{d} \right)^{-\frac{m+1}{n}} \left( \frac{\dot{\epsilon}}{\eta_m} \right)^{\frac{1}{n}} V_f + \sigma_m \left( \frac{\dot{\epsilon}}{\eta_m} \right)^{\frac{1}{m}} V_m \right] \quad (1)$$

where matrix characteristics are connected to the

power law of matrix creep,  $\sigma = \sigma_m \left( \frac{\dot{\epsilon}}{\eta_m} \right)^{\frac{1}{m}}$ ; fibre

characteristics are determined by the Weibull based strength/fibre length dependence,

$$\sigma_*^{(f)}(l) = \sigma_o^{(f)}(l_o) \left( \frac{l}{l_o} \right)^{-\frac{1}{\beta}}; \lambda \text{ is a function of the}$$

fibre/matrix interface strength given by  $\alpha$   $0 < \alpha \leq 1$ ;  $n = m + \beta + m\beta$ ,  $d$  is a characteristic fibre diameter.

### 2.2 Usage of the model to analyzing experimental data

Two features of the usage of Eq. (1) are important. First, the effective fibre strength in the matrix,  $\sigma_o^{(f)}$ , depends strongly on the interface strength as a result of healing fibre surface defects by the matrix. The matrix acts similar to a coating, which is illustrated in Fig. 1.

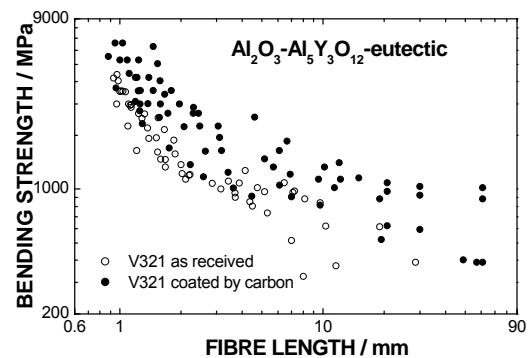


Fig. 1. The fibre strength versus its length for as received state and after coating the fibre with a carbon layer of a thickness of  $\sim 1$  micron.

This yields a necessity to connect a value of the effective fibre strength in a composite to the value of the interface strength given by  $\alpha$ .

Secondly, the model described allows replacing relationship (1) by a simple power law normally accepted while interpreting experimental data on creep of any materials [4]. An important point is a possibility **to calculate** the value of exponent  $q$  in the approximation

$$\sigma = C\dot{\epsilon}^{1/q} \quad (2)$$

Rewriting Eq. (1) as

$$\sigma = AV_f\dot{\epsilon}^{1/n} + B(1-V_m)\dot{\epsilon}^{1/m} \quad (3)$$

where  $A$ ,  $B$  and  $C$  are combinations of the constants in the relationships written in the original form and looking for values of  $q$  and  $C$ , which provide the best approximation of Eq. (3) with Eq. (2), which means to provide a minimum to the integral

$$\Sigma = \int_{\dot{\epsilon}_1}^{\dot{\epsilon}_2} (AV_f x^{1/n} + B(1-V_m)x^{1/m} - Cx^{1/q})^2 dx, \quad (4)$$

in which the limits of integration are the limits of creep rates of interest. In the present context they are  $10^{-4}$  and  $10^{-1} \text{ h}^{-1}$ . An example of the calculated values of  $q$  is presented in Fig. 2.

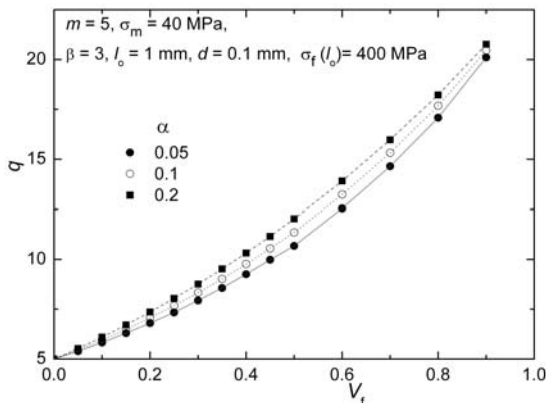


Fig. 2. Calculated value of exponent  $q$  in a power function approximating creep-rate/stress dependence of a composite.

It is important to note that the values of the exponent at fibre volume fractions sufficiently high are much larger than the value of  $m$ . This has a clear physical meaning since creep behavior of a composite with a large fibre volume fraction is determined by the fibre strength.

A comparison of exponent  $q$  calculated and the exponent values obtained in the experiments with 2-steps loading of specimens is presented in Fig. 3. Obviously, the calculation yields an acceptable result.

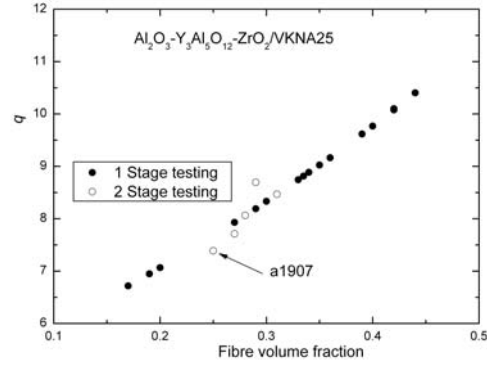


Fig. 3. Calculated values of the exponent,  $q$ , and the values obtained in the experiments. The values of structural parameters are as follows:  $m = 5$ ,  $\beta = 3$ ,  $l_0 = 1 \text{ mm}$ ,  $d = 0.1 \text{ mm}$ ,  $\alpha = 0.4$ , which corresponds to the effective fibre strength equal to 600 MPa.

The creep model just described allows analysing an effect of a non-homogeneous fibre packing in the cross-section of a composite specimen. Fibre clustering can affect essentially creep properties of oxide-fibre/Ni-based-matrix composites with a non-ideal interface. It is mainly due to a fact that in some systems in that family of the composites the interface strength goes down at fibre volume fractions  $V_f$  larger than some value of  $V_f$  [5]. This means that the interface strength within the clusters can be lower than that outside of the clusters. At the same time, the value of exponent  $q$  depends strongly on fibre volume fraction (Fig. 2). Therefore, a problem of creep of a composite rod with non-homogeneous fibre packing occurs to be non-linear and hardly can be solved analytically. Hence, we present simple solution for a model specimen just to illustrate potential effects semi-qualitatively.

Let a specimen has two kinds of the fields of equal areas, one containing fibre clusters with volume fraction  $2V_f$ , and another field being a pure matrix; so that the average fibre volume fraction in both specimens is  $V_f$ . Consider, first, the case of the interface strength independent of fibre volume fraction. A simple calculation of creep resistance of specimen yields results shown in Fig. 4.

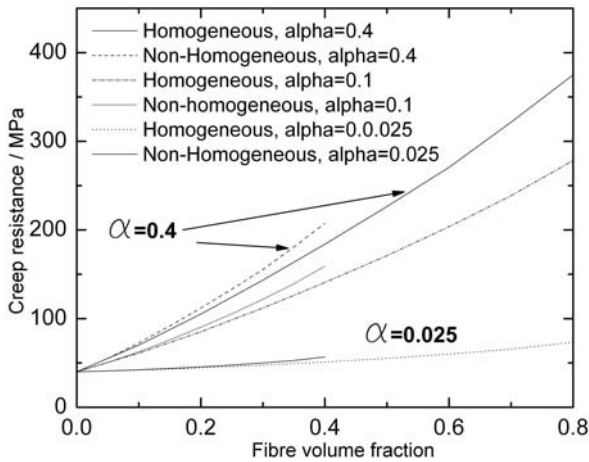


Fig. 4. Calculated dependencies of creep resistance of model composites with homogeneous and non-homogeneous fibre distribution in the cross-section.

The values of interface strength and effective fibre strength are taken as  $\alpha = 0.4$ ,  $\sigma_o^{(f)} = 600$  MPa;  $\alpha = 0.1$ ,  $\sigma_o^{(f)} = 300$  MPa;  $\alpha = 0.025$ ,  $\sigma_o^{(f)} = 150$  MPa.

(Note that as mentioned above, the fibre effective strength depends on the interface strength.) It can be seen that creep resistance of the composites with strongly non-homogeneous fibre packing is not lower than that for a composite with homogeneous fibre packing. A reason for such behaviour of composites with non-homogeneous fibre distribution is clear, it is a result of a strong non-linear dependence of exponent  $q$  on fibre volume fraction, Fig. 2, which yields a non-linear dependence of the creep resistance on fibre volume fraction.

In the case when the interface strength depends on fibre volume fraction the creep-resistance/fibre-volume-fraction dependence goes along a curve corresponding to a large value of  $\alpha$  and then moves to curves corresponding to smaller and smaller  $\alpha$ .

Two consequences follow. First, a general dependence of the creep resistance on fibre volume fraction has a maximum at some values of  $V_f$ . This has been observed earlier [3]. Secondly, deviation of the fibre distribution from a homogeneous one shifts the maximum to smaller values of  $V_f$ .

### 3 Fabrication technology

Single crystalline and eutectic fibres are produced by the internal crystallisation method that allows crystallizing a bundle containing hundredths and thousands of the fibres [2]. The fibres obtained and used in the composites up to the present time are single crystalline sapphire and YAG as well as eutectics  $\text{Al}_2\text{O}_3\text{-Al}_5\text{Y}_3\text{O}_{12}$  (AY),  $\text{Al}_2\text{O}_3\text{-Er}_5\text{Y}_3\text{O}_{12}$  (AEr),  $\text{Al}_2\text{O}_3\text{-Al}_5\text{Y}_3\text{O}_{12}\text{-ZrO}_2$  (AYZ),  $\text{LaAl}_{11}\text{O}_{18}\text{-AlLaO}_3$  (ALa)

Two commercially available superalloys [6,7] have been used as matrix materials. The alloy marked as VKNA-4U contains Al, Cr, W, Ti, Co, Mo and C. That marked as VKNA-25 differs from VKNA-4U by the presence of 3.5% Rhenium.

Composite specimens were obtained by pressure infiltration of a fibre bundle placed in quartz ampoule [8]. Temperature and pressure of argon gas in the infiltration process were  $1550^\circ\text{C}$  and 0.5 MPa, respectively. Crystallisation of the matrix was performed in the axial temperature gradient to make a single crystalline microstructure of the matrix. The diameter and length of the specimens were  $\sim 5$  and  $\sim 50$  mm, respectively.

### 4 Creep behavior of oxide-fibre/nickel-matrix composites

Creep experiments are carried out on cylindrical specimens loaded in bending by either step-wise loading and in such case the value of  $q$  is determined directly or by a single load, in which case  $q$  is calculated. Then tensile creep characteristics of the composites are calculated by using a solution of the creep problem for a beam under bending. A corresponding procedure is described in details in [3].

Some examples of dependencies of the creep resistance (accepted as a stress to cause 1% creep strain for 100 h) on fibre volume fraction are presented in Fig. 5.

It can be seen that for a particular composition creep resistance can reach a value of 150 MPa at a temperature of  $1150^\circ\text{C}$ . It is important to point out that the density of the composites under consideration is between 6.5 and  $6.8 \text{ g/cm}^3$  at sufficiently high fibre volume fraction, At the same

time the density of modern superalloys are approaching  $9 \text{ g/cm}^3$ .

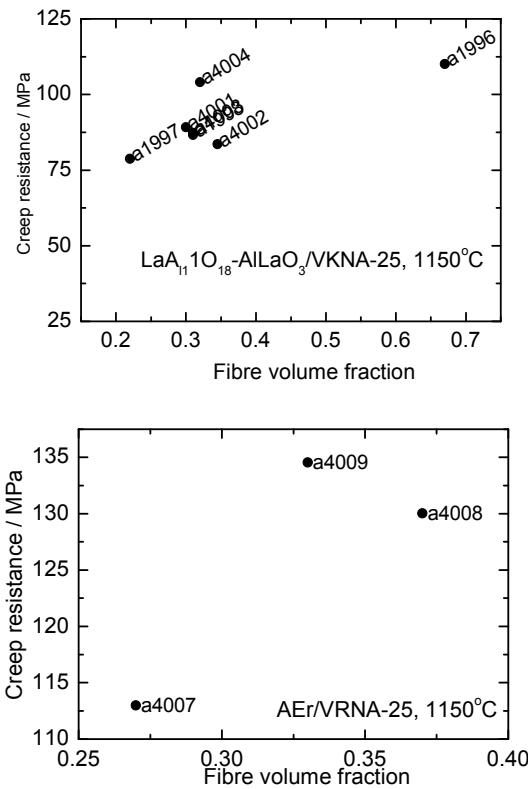
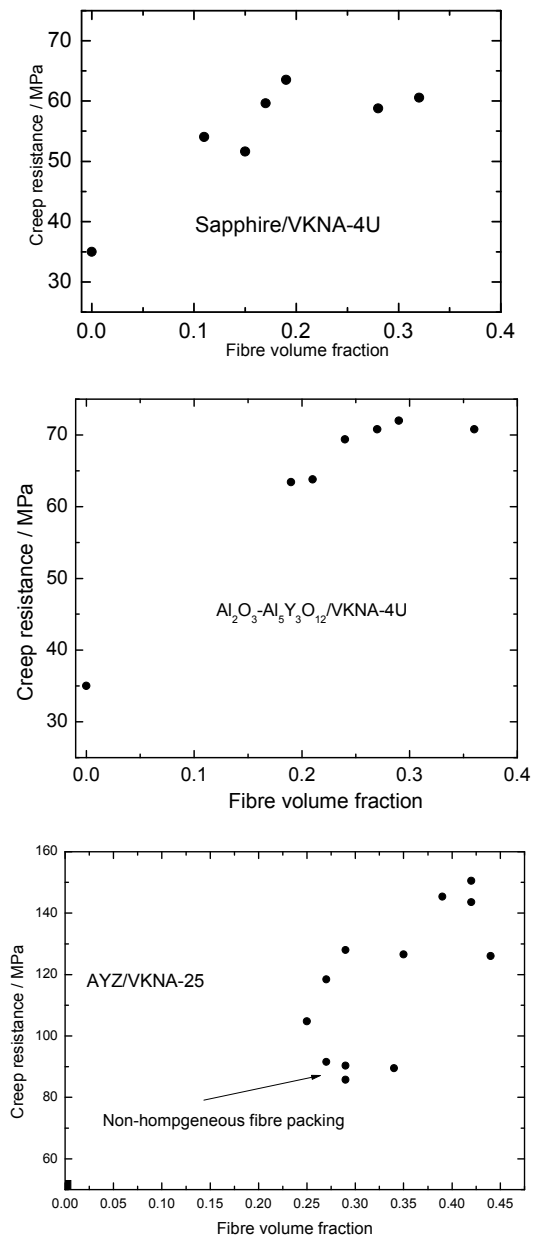


Fig. 5. Creep resistance of oxide-fibre/Ni-based-alloy matrix composites versus fibre volume fraction at  $1150^\circ\text{C}$ .

A compilation of the data presented in Fig. 5 is plotted in Fig. 6 as a dependence of the maxima of creep resistance of the composites reinforced with various oxide fibres on fibre volume fraction. Such presentation that shows by arrows possible developments being not completely rigorous demonstrate clearly an effect of particular fibre/matrix combinations on the creep properties in this family of composites.

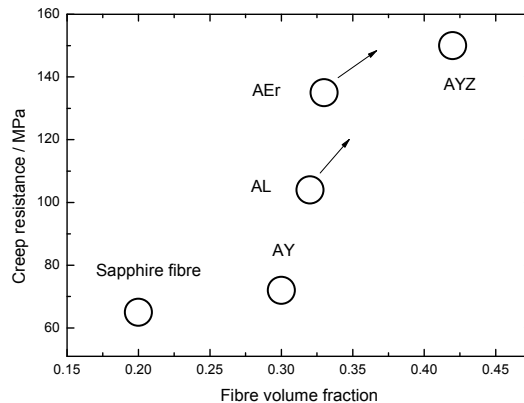


Fig. 6. Maxima of the creep resistance of various composites.

## 5 Prospects of heat-resistant MMCs

The history of development of the Ni-based heat-resistant Ni-based alloys is presented in Fig. 7. It is clear that at the present time the maximum use temperature of MMCs can be between 1150 and 1200°C as compared with 1100°C for prospective superalloys. A further increase in the use temperature will be possible if matrices with higher melting point are available.

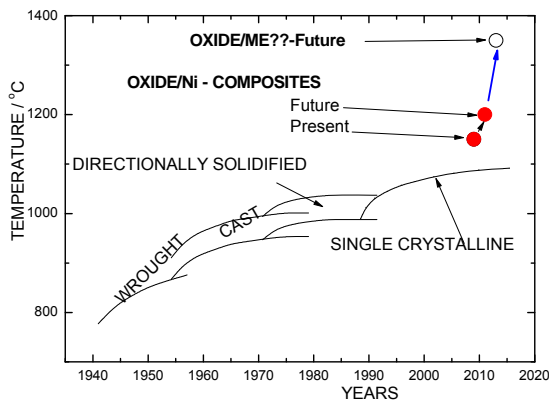


Fig. 7. Retrospective and prospects of Ni-based heat-resistant alloys as dependence of the maximum use temperature on the year of the development. Also state of the art of the composite with the prospects is shown. The use temperature of superalloys is defined as that to provide stress rupture equal to 150 MPa on the 1000 h time base.

## 6. Main conclusions

1. An intensive use of the micromechanical model in planning the experiments and interpreting their results and developing express methods of creep testing allows speeding up a process of development of creep resistant composites essentially. This has given a possibility to perform creep testing of a large number of the composites
2. The present stage of the development is characterized by oxide-fibre/nickel-based composites of a density as low as 6.5 – 6.8 g/cm<sup>3</sup> with creep resistance at a temperature

of 1150°C reaching 150 MPa on a 100 h base.

3. The methodology of developing creep resistant composites can be definitely used to obtain composites with better creep characteristics than those presented in the paper.

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