A new look at the application of metal matrix composites in a future aviation engine

S T Mileiko

Institute of Solid State Physics, Chernogolovka Moscow distr., 142432 Russia

Abstract. Three types of composites, namely (1) carbon-fibre/metal-matrix, (2) oxide-fibre/molybdenum-matrix, and (3) oxide-fibre/high-entropy-matrix are considered as potential materials for future aviation engines. Technological schemes for producing the composites and their mechanical properties, as well as the potentials of future development to maturing them are presented.

1. Introduction

The history of the development of the aviation gas turbine engine has been filled with the intention to decrease the specific fuel consumption and to increase the specific trust. Improvements in the engine design has been followed with the development of new metal alloys and fibre reinforced plastics. In Russia, the most impressive results in these fields are belonged to All-Union Institute of Aviation Materials and its great researchers. In the present context, such names as A.T. Tumanov, S.T. Kishkin, A.V. Logunov, S. G. Glazunov, and B.V. Perov are worth to mention.

By the present time, characteristics of nickel and titanium alloys are close to their physical limits; hence, a future engine cannot be entirely based on them. Fibre reinforced plastics (FRP) occupy and will occupy their niche, but this niche is limited by temperature limits of polymers and relatively low fracture toughness of FRP. Ceramic matrix composites (SiC/SiC and oxide/oxide) will find their place in stator structures of the hot parts of the engine. However, structural elements of low and high pressure compressor, blades of high pressure turbine, the engine parts that determine thermal efficiency and specific trust of the engine, require new materials. Metal matrix composites will be such materials, they will principally change the engine and its characteristics.

Three types of composites, namely (1) carbon-fibre/metal-matrix, (2) oxide-fibre/molybdenum-matrix, and (3) oxide-fibre/high-entropy-matrix are considered as potential materials for future aviation engines. Technological schemes for producing the composites and their mechanical properties, as well as the potentials of future development to maturing them are presented.

2. Carbon-fibre/titanium-matrix composites

Attempts to reinforce metal matrix, and particularly, titanium matrix have been known since 90s of the last century [1,2,3]. A number of the reasons prevented developing technological schemes used by the authors into industrial fabrication technologies. Still, the obvious need for further improving the performance of metal-based materials stimulated the present author's research group to develop a new technological scheme to reinforce titanium and nickel matrix with carbon fibres [4].

Schematically, the fabrication process of the composites is presented in **Figure 1**. An assemblage of the layers containing a titanium alloy (the main matrix), a mixture of titanium and nickel in a ratio close to the eutectic of the melting point of about 950ºC and carbon fibre is heated to a temperature just above of the eutectic and kept at this temperature no longer than 1 – 2 minutes under a pressure of about 1

kgf/cm^2. The melt of the Ti-Ni mixture infiltrates the carbon layer, titanium forms a layer of titanium carbide on the carbon filaments surface, the thickness of which depends on the time-temperature regime of the process. The rest of the mixture crystallizes and forms the intermediate matrix. The carbon-fibre/intermediate-matrix layer is actually a reinforcing component for titanium matrix.

Figure 1. Schematic of the process of producing carbon-fibre/titanium matrix composites. 1: Titanium layer, 2: Ti-Ni mixture layer, 3: Carbon fibre.
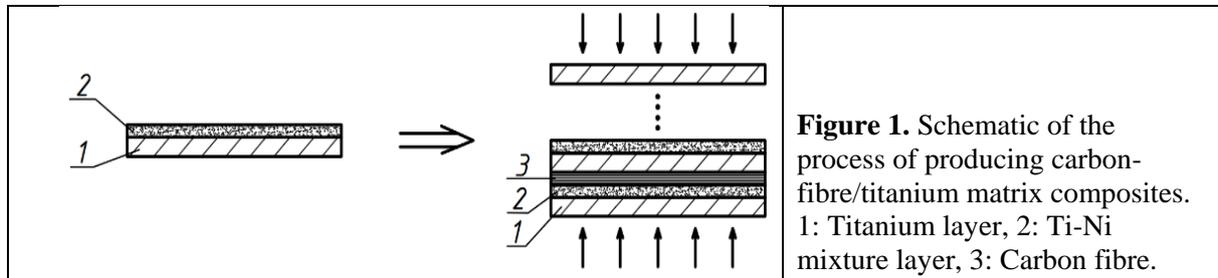
An example of the composite microstructure obtained in such a process is shown in **Figure 2**. It can be seen that the thickness of the titanium carbide layer on the fibre surface is about 300 nm, which is sufficiently small not to yield a catastrophic decrease in the fibre strength.

(a)

(b)

(c)

(d)
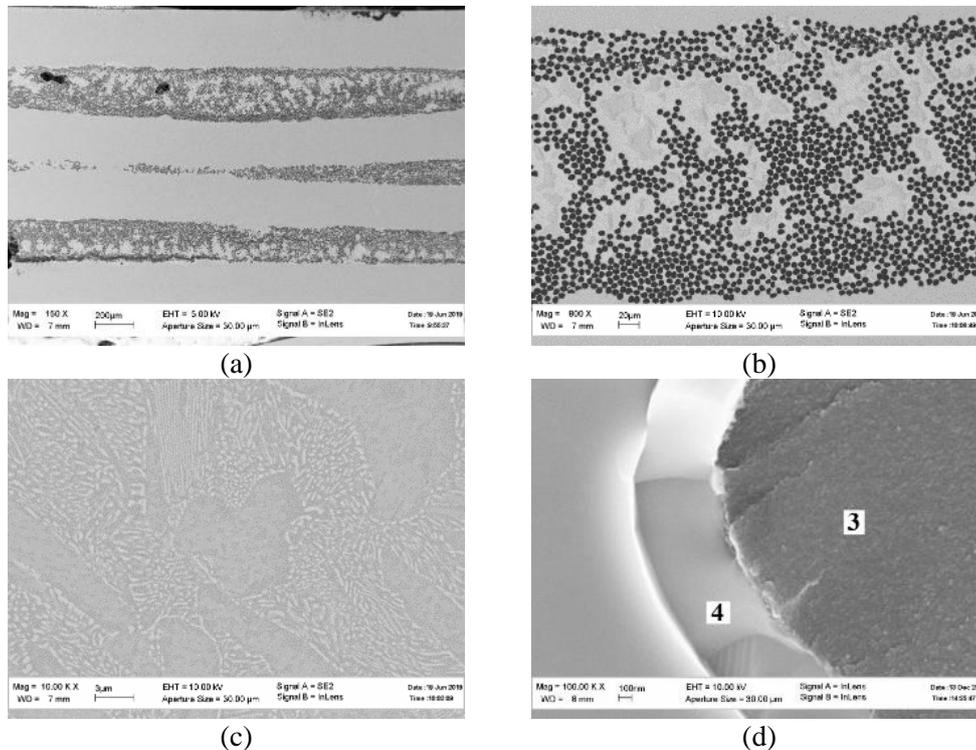
Figure 2. SEM micrographs of the carbon-fibre/titanium-matrix composite with the Ti-Ti$_2$Ni intermediate matrix. (a) A general view of the reinforcing and titanium layers; (b) The reinforcing layer; (c) The microstructure of the intermediate matrix; (d) A carbon fibre (3) covered by the titanium carbide layer (3).

In the first series of the experiments titanium alloy of Trade Mark VT1-0, which is actually pure titanium with the flexure strength in the annealed state of about 500 MPa, was used as the matrix and carbon fibre of Russian producer UMATEX was used as a reinforcement. An example of the stress/displacement curve in 3-point bending of a composite specimen is presented in **Figure 3** and **Table 1**. The mean values of longitudinal σ_1^* and transverse σ_2^* strength, and critical stress intensity factor. It can be seen that (i) the value of composite stress is more than twice as large as that of the matrix; (ii) the specimen fails in the non-brittle manner; (iii) the composite strength in the direction transversal to the reinforcement direction is about 0.7 of that in the reinforcement direction.

The first item is the evidence of the effectiveness of the reinforcement of titanium with the carbon fibre wrapped in the intermediate matrix. The third one can be, perhaps, explained by a sufficiently high strength of the intermediate matrix. It is important to point out that the low anisotropy of the composites under consideration makes them principally different from carbon fibre reinforced plastics. The second important advantage of the fibre reinforced titanium as compared with fibre reinforced plastics is a stability of their microstructure at high temperatures [5].
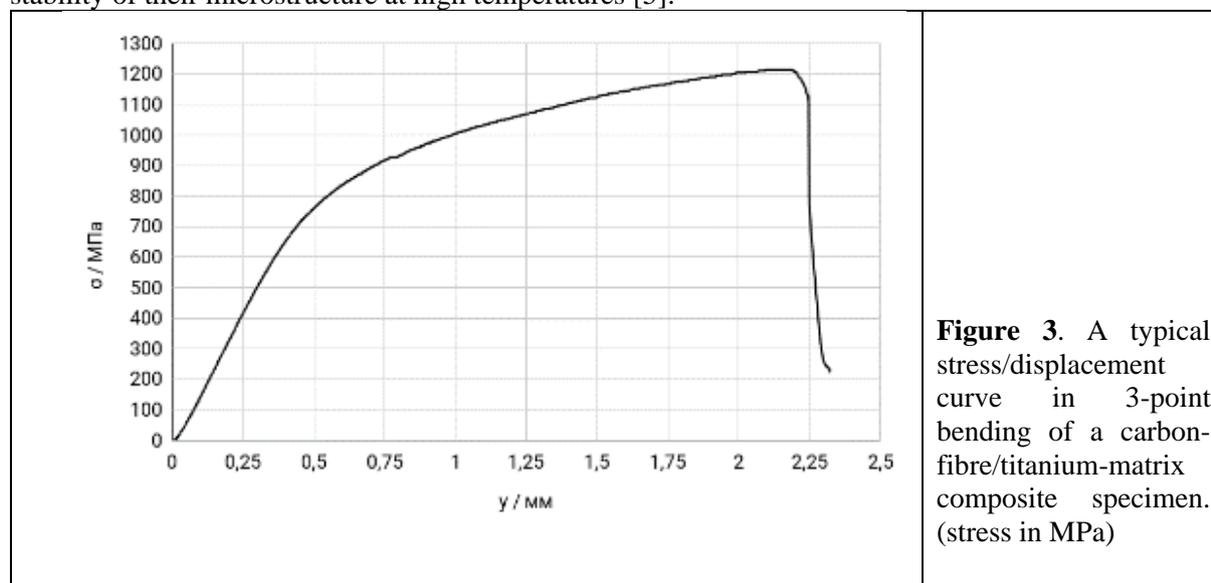
Figure 3. A typical stress/displacement curve in 3-point bending of a carbon-fibre/titanium-matrix composite specimen. (stress in MPa)

Table 1.The mean values of longitudinal and transverse strength and critical stress intensity factor of carbon-fibre/titanium-matrix composites of the first series of experiments.

Property	Value
$\sigma_1^*/\text{M}\Pi\text{a}$	1095
$\sigma_2^*/\text{M}\Pi\text{a}$	770
$K^*/\text{M}\Pi\text{a}\cdot\text{m}^{1/2}$	23.6

Comparing the mechanical properties of the composites just presented with those obtained in testing carbon-fibre/titanium-matrix composite produced by another technological scheme also with an intermediate eutectic matrix [1] shows that the microstructure of such type of the composites can be very flexible. It can be adjusted to a particular application. For example, composites with a density of 3.22 g/cm^3 described in Ref. [1] had the Young's modulus in the fibre direction equal to 210 GPa.

Obviously, the mechanical properties of the composites will be further improved by using appropriate titanium alloys as the main matrix instead of pure titanium in the first experiments.

The same fabrication root can be used to produce composites with nickel alloys as the matrix [4].

An optimization of the composite microstructure and development of industrial technologies of making structural elements will allow designing low-pressure compressor with the carbon/titanium blades and high-pressure compressor with the carbon/nickel blades. Both types of the blades will be of much lower weight than the present ones.

3. Oxide-fibre/molybdenum-matrix composites

The present mainstream in looking for heat resistant materials beyond nickel alloys is developing Mo-Mo$_5$SiB$_2$-Mo$_3$Si alloys aimed at the use temperatures up to 1300°C [6,7]. The alloys developed up to now are characterized by sufficiently high oxidation resistance, but the creep resistance of the alloys with relatively high fracture toughness ($K^* \approx 14$ MPa·m$^{1/2}$) at temperatures higher than 1200°C is rather low [8]. A change in the alloy microstructure by increasing the volume fraction of hard particles yields an increase in strength and creep resistance, but at the same time makes the alloys rather brittle ($K^* = 5$ - 8 MPa·m$^{1/2}$) [7,9]. **Figure 4** built up by using the experimental data published in Ref. [7] demonstrate

so called conflicts between strength and toughness in metal alloys [10,11] clearly: increasing the hard particles content in molybdenum yields an increase in the compression strength and a drastic decease in the fracture toughness.
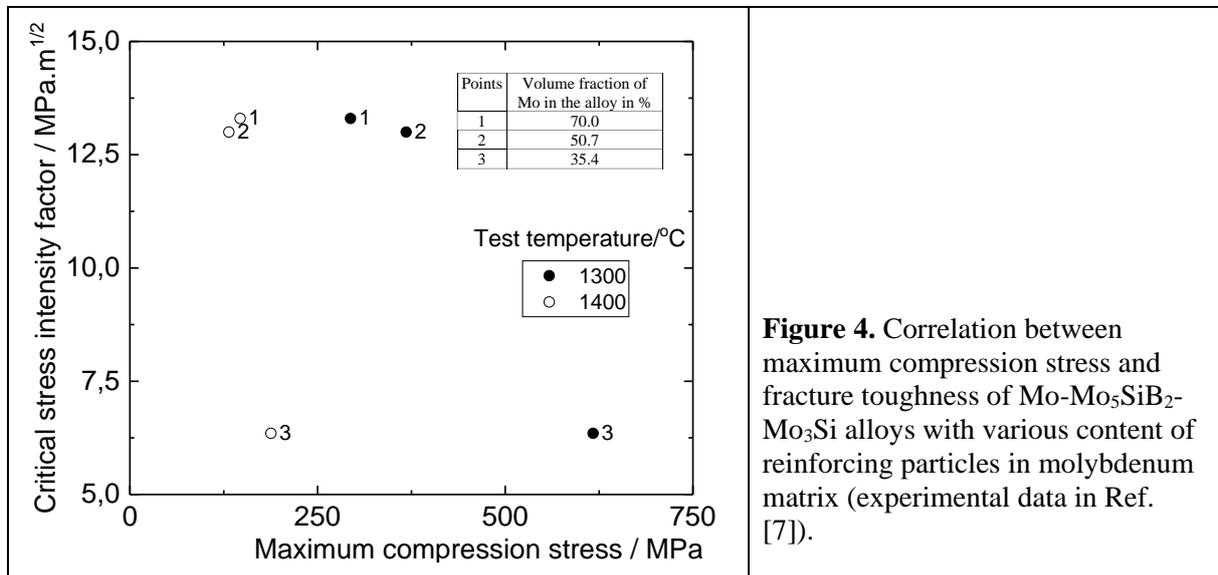
Figure 4. Correlation between maximum compression stress and fracture toughness of Mo-Mo_5SiB_2-Mo_3Si alloys with various content of reinforcing particles in molybdenum matrix (experimental data in Ref. [7]).

Metal matrix composites containing brittle fibres can be even tougher than the unreinforced matrix: a large fracture zone ahead of the crack tip created by multiply fracturing of the fibres at weak points outside of the continuation of the crack plane can be full of the plastic microzones. The total elastic energy dissipation can be larger than that within the singlr plastic zone in the pure matrix [10,12].

Hence, oxide-fibre/molybdenum-matrix composites produced by the internal crystallization method (ICM) for making oxide/molybdenum composites developed long time ago [13] turned out to be an attractive heat resistant material after a possibility to decease essentially the oxidation rate of molybdenum matrix by reinforcing it with an appropriate oxide fibre became clear [14,15]. The ICM has been described in a number of publications, see i.e., [10,13]; still, a schematic of the method is presented in **Figure 5** for the convenience of a potential reader. The Figure makes the procedure clear and does not need any explanations.
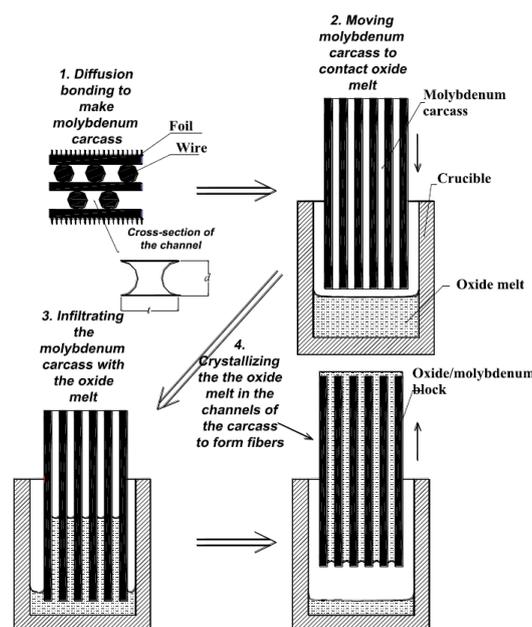
Figure 5. Schematic of the internal crystallization method.

The microstructure, mechanical properties and oxidation resistance of a family of such composites including those reinforced with oxides in the Al_2O_3-Y_2O_3 (Al_2O_3-$Al_5Y_3O_{12}$, $AlYO_3$, $AlYO_3$- $Al_2Y_4O_9$), Y_2O_3-SiO_2 (Y_2O_3-Y_2SiO_5, Y_2SiO_5 and Y_2SiO_5-$Y_2Si_2O_7$), Yb_2O_3-SiO_2 (Yb_2O_3-Yb_2SiO_5, Yb_2SiO_5 and $Yb_2Si_2O_7$) systems and mullite-ZrO_2 eutectic have been studied. Some of the results have been published [16,17,18], some new results are to be published. Typical microstructures of three composites of the family are illustrated in **Figure 6**. The composites contain fibres composed of yttrium-aluminium perovskite YAP ($AlYO_3$) with $Al_2Y_4O_9$ (YAM) inclusions, a rather well known mullite-zirconia eutectic and ytterbium monosilicate (Yb_2SiO_5).

All composites studied are characterized by fracture toughness much higher than that of the matrix (**Figure 7**), which is pure molybdenum recrystallized in the process of the composite fabrication (see **Figure 5**). The corresponding value of the critical stress intensity factor of the matrix is about 9 $MPa \cdot m^{1/2}$. It should be noted that the most tough composites are those containing yttrium monosilicate fibres (Y_2SiO_5), which can be a result of possible plasticity of this silicate [19]. High temperature strength of some oxide-fibre/molybdenum-matrix composites is presented in **Figure 8.**

YAP-based-fibre/ molybdenum-matrix composite; "black" phase: YAP ($YAlO_3$), "grey": $Al_2Y_4O_9$ [18].	Mullite-zirconia-fibre/molybdenum-matrix composite [16].

G0059, wanted fibre material is Yb_2SiO_5-fibre/molybdenum-matrix composite

Spectrum	O	Si	Yb
Spectrum 1	76.76	11.02	12.22

$\Leftarrow$
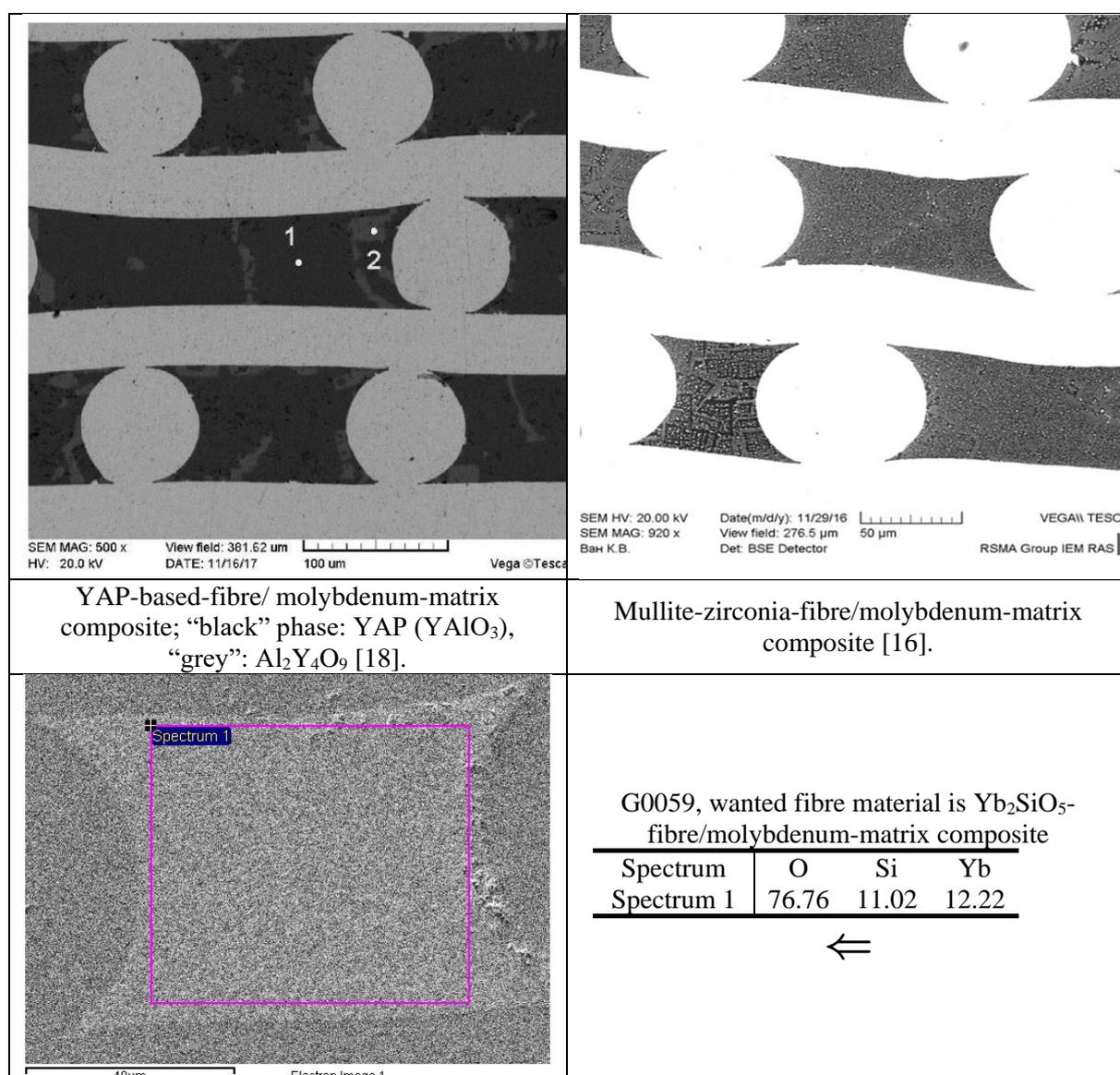
Figure 6. SEM micrographs of composites with molybdenum matrix.

YAP-based-fibre/ molybdenum-matrix composite [18].	Mullite-zirconia-fibre/molybdenum-matrix composite [16] . E-1 and E-2 are of eutectic and zirconia-rich off-eutectic compositions, respectively
Silicate-fibres/molybdenum-matrix composites	
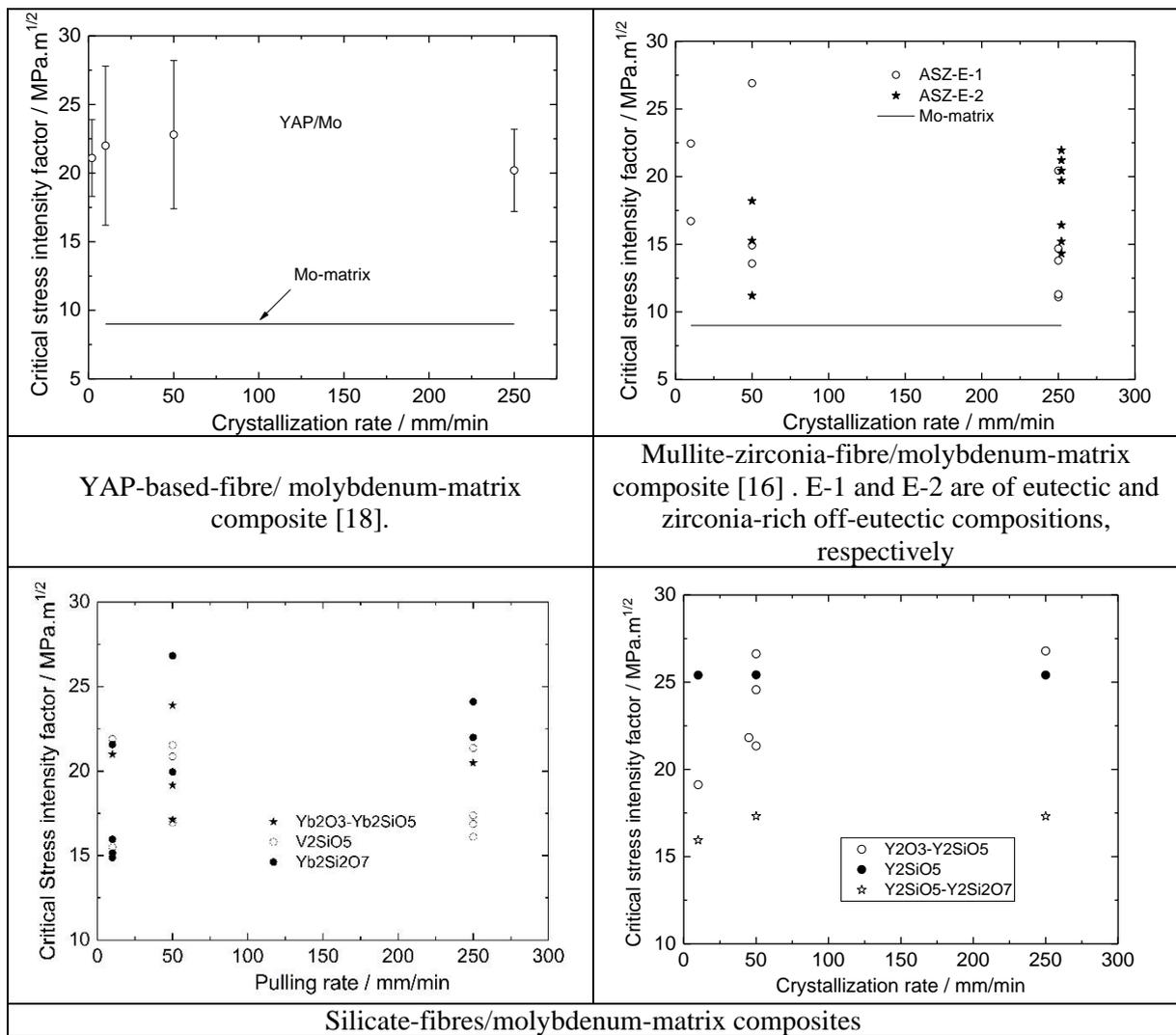
Figure 7. Fracture toughness of oxide-fibre/molybdenum-matrix composites versus the fibre crystallization rate.

YAP-based-fibre/ molybdenum-matrix composite [18].	Mullite-zirconia-fibre/molybdenum-matrix composite [16]. E-1 and E-2 are of eutectic and zirconia-rich off-eutectic compositions, respectively

Yb$_2$SiO$_5$+(Yb$_2$O$_3$ inclusions)
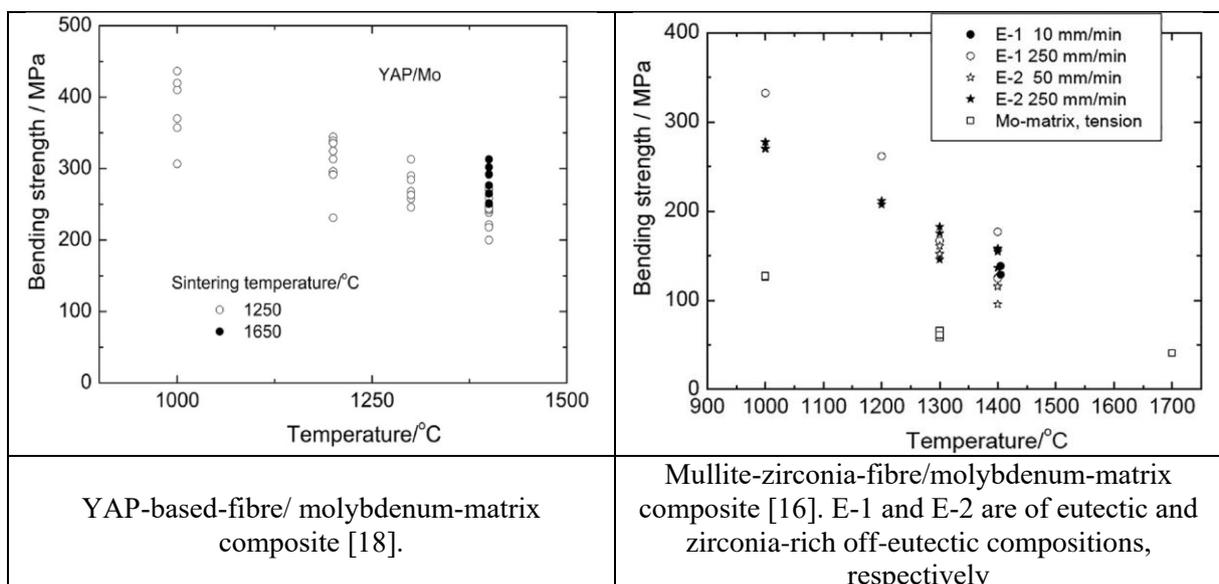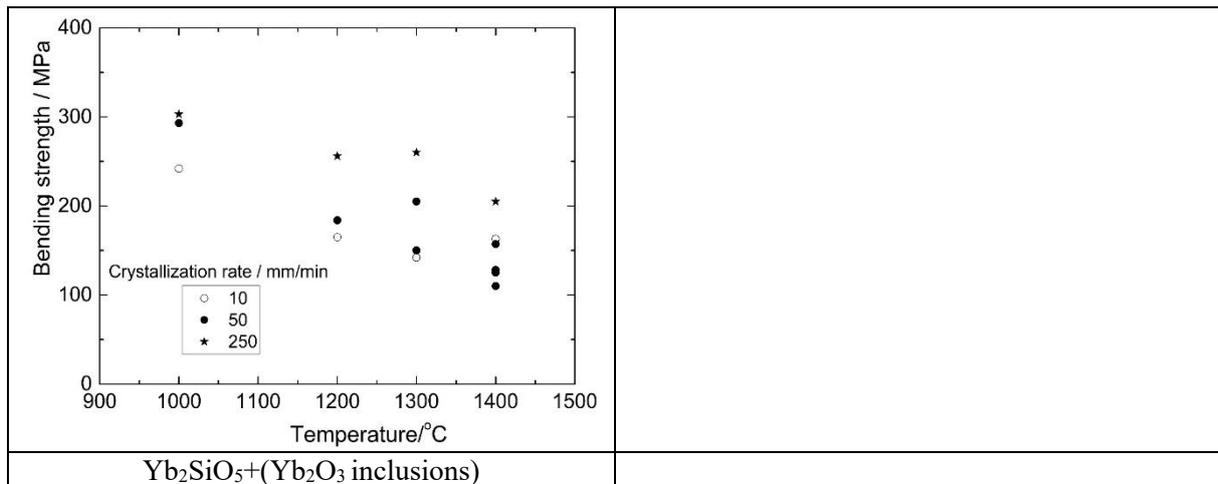
Figure 8. High temperature strength of some oxide-fibre/molybdenum-matrix composites.

Oxidation resistance of molybdenum as the matrix in the composites under consideration is much higher than that of pure molybdenum; two examples of the oxidation kinetics is presented in **Figure 9**. Obviously, the composites need to be coated to decrease the oxidation rate down to an acceptable value. Preliminary experiments in coating and testing the specimens with YAP-based fibres and yttrium molybdates coatings were performed together with research teams of Ufa State Aviation Technical University and Central Institute of Aviation Motors (Vardanyan and Myktybekov). The qualitative results are presented in **Table 2**.

| Yb$_2$O$_3$-Yb$_2$SiO$_5$-fibre/Mo-matrix | YAlO$_3$-fibre/Mo-matrix |
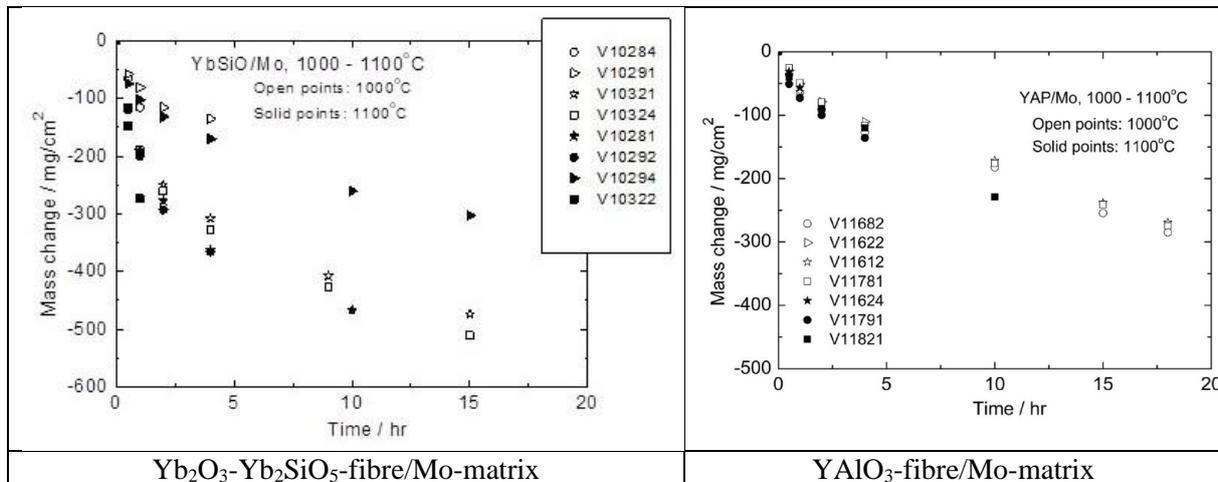
Figure 9. Oxidation kinetics of two types of the composite specimens at temperatures 1000 and 1100°C. Various points stand for the various specimens; their numbers are shown in the graph field.

It is interesting to compare strength and fracture toughness of the composites under consideration with the same characteristics of molybdenum alloys, which have been developing and studied by many research groups all around the world for the last twenty or so years. First of all, it should be pointed out that formation of Mo$_5$SiB$_2$ particles in molybdenum invented many years ago [20] provides a protection from the rapid oxidation of the alloys. Further investigations have confirmed the effect [21,22,23]. The composites with pure molybdenum matrix are characterized by lower oxidation resistance (**Figure 9**) but much higher fracture toughness (compare **Figure 4** and **Figure 7**).

Table 2. Results of testing YAP/Mo composite specimens coated by three types of yttrium molybdates in the flame of a propane-butane torch.

Coatings→			$Y_2Mo_3O_{12}$		Y_2MoO_6		Y_6MoO_{12}	
View of the coated composite specimens →		Original	Front surface	Rear surface	Front surface	Rear surface	Front surface	Rear surface
Temprature/°C→			1350	1100	1240	1000	1430	1180
Time/sec→		0	305		100		170	

Comparing mechanical and oxidation properties of modern molybdenum alloys for the high temperature usage and bearing in mind special features of the mechanical behavior of metal matrix composites [10,12] stimulated the author's research group to combine the internal crystallization method for making oxide/molybdenum composites developed long time ago [13], in which pure molybdenum is used as the matrix, with the present knowledge of the behaviour of molybdenum alloys [6,7]. It is not reasonable to wait for the time when appropriate molybdenum alloy in the form of foil and wire necessary to make the matrix according to stage 1 in **Figure 5** will be available. A way to get the matrix composed of Mo-Mo_5SiB_2-Mo_3Si is to modify the first stage of making the molybdenum carcass. This stage now consists of three steps: (1) Making a foil/wire/slurry assemblage by winding a molybdenum wire over a flat surface of molybdenum foil, filling the gaps between neighbouring wires with a slurry containing silicon and boron, repeating the procedure with the next layer of the wire/foil couple. (2) Diffusion bonding of the assemblage in vacuum at a temperature of 1250 °C. The organic binder of the slurry is burned out during a slow heating of the assemblage. (3) Heat treatment of the carcass at a temperature of about 2000 °C. All details of the process are described in [24,25]. The original matrix is filled with Mo_5SiB_2 and Mo_3Si phases during the heat treatment,

Such modification of the molybdenum matrix yields an essential increase in strength and fracture toughness of the composites. **Figure 11** presents the temperature dependence of strength and strength at 1400°C of composites with Al_2O_3-$Al_5Y_3O_{12}$ and $YAlO_3$ (YAP) fibres reinforcing pure molybdenum and molybdenum alloy matrices. It can be seen that the values of high temperature strength of composites with pure molybdenum matrix are 236±34 and 251±31 MPa with Al_2O_3-$Al_5Y_3O_{12}$ and $YAlO_3$, respectively. Modifying the matrix leads to the strength values of 301±47 and 393±41 MPa for the composites with Al_2O_3-$Al_5Y_3O_{12}$ and $YAlO_3$, respectively.

Even more interesting data were obtained in evaluating fracture toughness of the composites. Measuring the value of critical stress intensity factor K^* was performed by testing in 3-point bending composite specimen with a notch and an apparent value of K^* was calculated according to ASTM-399:

$$K^* = \frac{3QLc^{1/2}}{2h^2w}Y\left(\frac{c}{h}\right)$$

where

$$Y = \left[1.96 - 2.75\frac{c}{h} + 13.66\left(\frac{c}{h}\right)^2 - 23.98\left(\frac{c}{h}\right)^3 + 25.22\left(\frac{c}{h}\right)^4\right].$$

Here L is distance between the supports, c is notch length, h and w are height and width of the specimen, respectively. These sizes in the present experiments are $L \approx 60$ mm, $h \approx 15$ mm, $w \approx 5$ mm, $c \approx (0.45 - 0.55)h$. The value of Q corresponds to a maximum load.
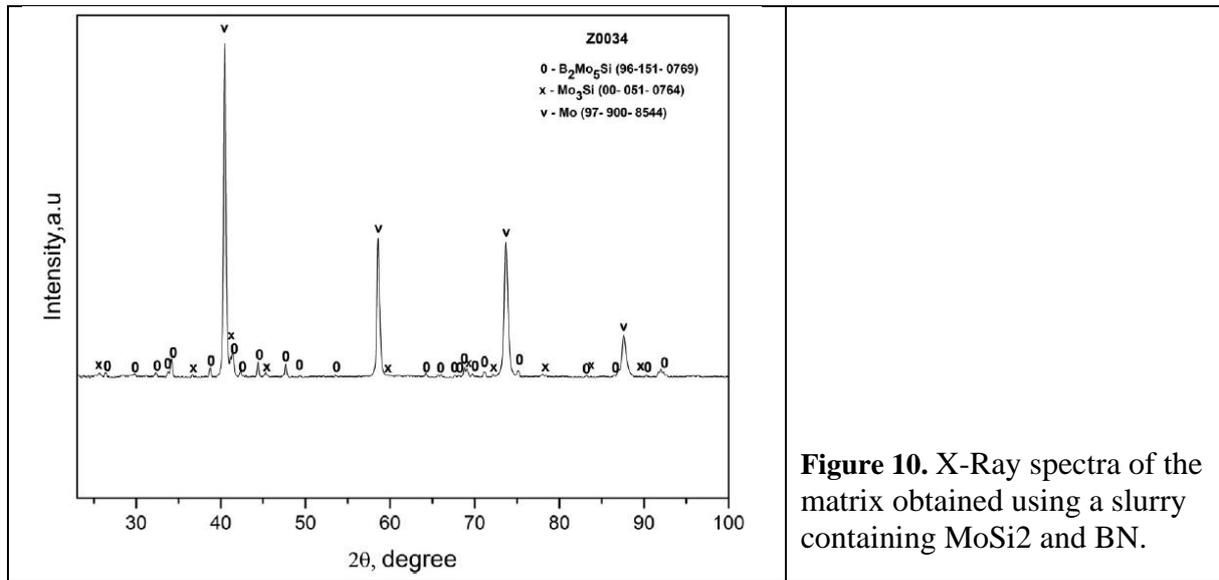
Figure 10. X-Ray spectra of the matrix obtained using a slurry containing MoSi2 and BN.
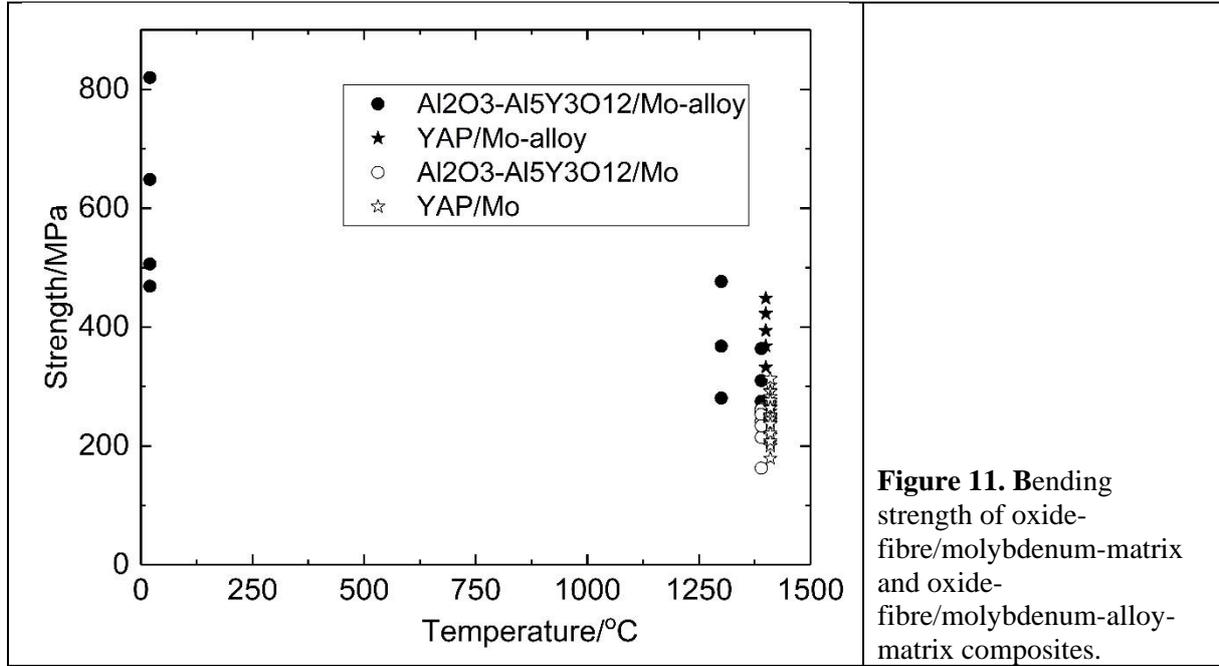
Figure 11. Bending strength of oxide-fibre/molybdenum-matrix and oxide-fibre/molybdenum-alloy-matrix composites.

Figure 12 demonstrates typical load/displacement curves obtained that indicate clearly at non-brittle behaviour of the composites. The set of values of K^* in Table 3 reveals a rather large scatter, which is a result of the present unstable technology. However, the largest values in this set, $32 - 44$ MPa·m$^{1/2}$, cannot be reached for molybdenum alloys. Stabilizing the fabrication technology, no doubt, will lead to the composites with fracture toughness corresponding to the largest values already obtained. The materials with such fracture toughness can be the first candidate to replace nickel superalloys in turbine blades.
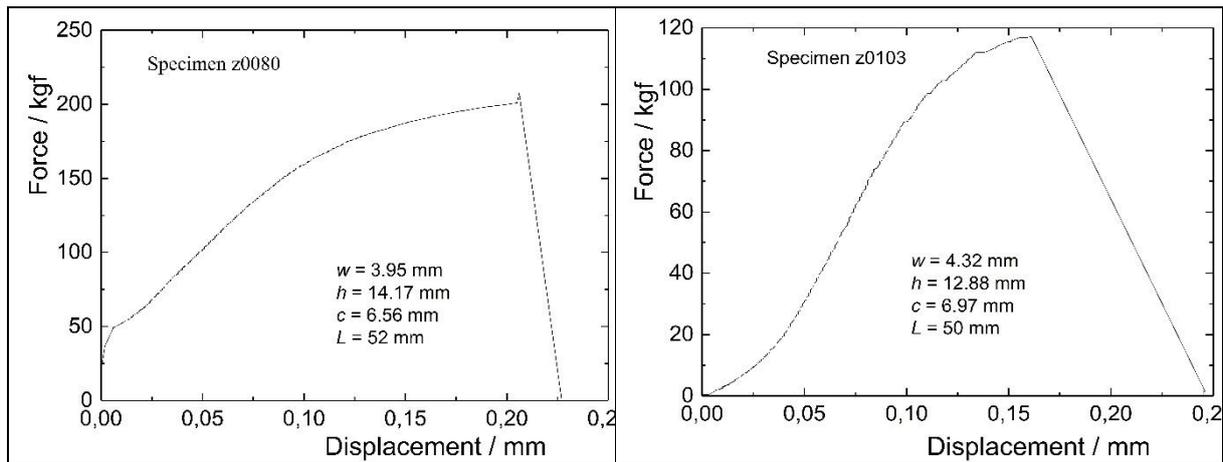
Figure 12. Typical load/displacement curves in 3-point bending tests of composite specimens with the notch.

Table 3. Fracture toughness and creep resistance at 1300°C of some oxide/molybdenum-alloy specimens.

Specimen Number	$K*$/MPa·m$^{1/2}$	Creep resistance/MPa	Fibre material
Z0070	44.0	85	Al_2O_3-$Al_5Y_3O_{12}$-eutectic
Z0080	37.8	90	YAM-YAP
Z0072	32.3		Al_2O_3-$Al_5Y_3O_{12}$-eutectic
Z0103	27.7		Yb_2SiO_5
Z0077	27.5	51	YAM-YAP
Z0097	26.9		Y_2SiO_5
Z0081	24.6		YAM-YAP
Z0104	20.1		Y_2SiO_5
Z0094	20.0		Yb_2SiO_5
Z0096	17.5		Yb_2SiO_5
Z0075	16.9		Al_2O_3-$Al_5Y_3O_{12}$-eutectic
Z0071	16.2		Al_2O_3-$Al_5Y_3O_{12}$-eutectic

Large specimens to measure critical stress intensity factors were cut into six sub-specimens to measure strength and creep resistance. Creep tests were performed in 3-poit bending (**Figure 13**). The experimental data obtained allows calculating creep resistance (1% of creep deformation for 100 hrs) by using of a model developed earlier [26]. Creep properties of some specimens are presented in **Table 3.**

Comparing the creep data obtained with corresponding data for Mo-Mo$_5$SiB$_2$-Mo$_3$Si alloys reveals an advantage of the composites. Early creep tests of the most tough alloys shown their low creep resistance. Hence, attempts to improve creep properties were noticed rather long time ago. Let's mention two recent attempts.

First, the results of testing the alloys characterized by the value of K* no higher than 13 MPa·m$^{1/2}$ with addition of titanium were published in Ref. [27]. Creep resistance of the specimens tested at 1200°C is about 185 MPa. There is no direct data on creep at 1300°C, extrapolating the data obtained at higher creep strains yields the value of creep resistance about 60 MPa.

Secondly, an alloy of same fracture toughness with additions of aluminium and germanium was tested at 1250°C in Ref. [28]. Creep rate on the steady state part of creep curve $\dot\varepsilon$ = 2.78·10^{-8} c^{-1} corresponding to 1% of creep deformation for 100 hrs was reached at the stress less than 50 MPa.
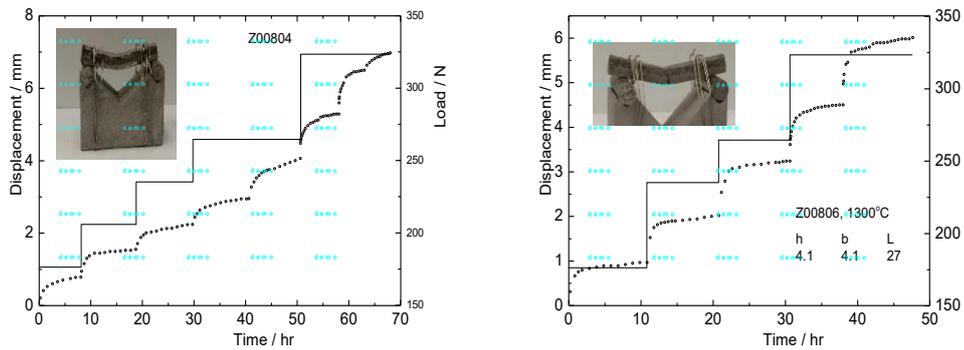
Figure 13. Creep curves at 3-poit bending of two sub-specimens from original specimen Z0080 tested to measure fracture toughness (see **Table 3**). Test temperature 1300oC. Non-steady parts of the curves have been obtained after cooling and unloading the specimens; hence, they include compensation of the gaps in the loading system of testing machines.

4. Oxide-fibre/high-entropy-matrix composites

Such type of the composites can also be considered as a material for the future turbine blade. A high entropy alloy (HEA) obtained for the first time by Yeh [29] and Cantor [30] is actually equi-atomic mixtures of 5 or more elements in a form of the solid solution that cannot contain intermetallics. Note that the whole family of HEAs is really huge and the alloys of the family are characterized by a large variety of the properties. Some of them have sufficiently high short-time strength at high temperatures, high ductility and sufficiently good oxidation resistance. However, there is no publications, which would show high creep resistance of HEAs at really high temperatures. That is why there is no really high temperature HEAs to be now considered as materials "beyond nickel superalloys".

A many-components composition of HEAs makes them an ideal matrix for the oxide fibre reinforcements as it can be found such alloys that contain element to provide wetting oxides. A principal possibility to obtain such composites were shown by a Russian-Ukrainian group in 2013 [31]. The microstructure of a Al_2O_3-$Al_5Y_3O_{12}$-ZrO_2/FeCoNiCrW composite produced by the pressure casting (1.5 atm) at a temperature of 1530°C and its strength/temperature dependence are presented in **Figure 14**. It is important to note that that the values of composite strength at room temperature and at 1200°C are nearly the same. Two factors can determine this effect. First, this can be a result of high fibre/matrix interface strength, which results in loading the fibre to high stresses. The second factor is a shift of the critical value of fibre volume fraction to higher values as a result of increasing the matrix fracture toughness with temperature. Both factors are important from the point of view of creep behavior of the composites since creep resistance is determined mainly by strength of fibre and fibre/matrix interface [32].
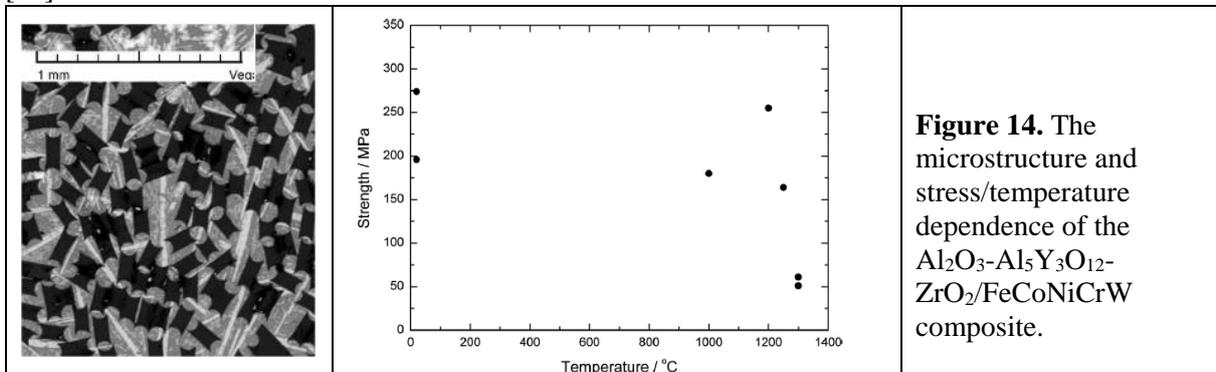
Figure 14. The microstructure and stress/temperature dependence of the Al_2O_3-$Al_5Y_3O_{12}$-ZrO_2/FeCoNiCrW composite.

The author's research group is now planning to develop such type of the composites by using HEAs with higher melting points aiming at the use temperature of 1400 - 1500°C.

5. A new look at the application of metal matrix composites in a future aviation engine

Designing aviation gas turbine engine with the thorough usage of the new metal matrix composites will change the whole image of the engine. A rigorous estimation of the effect to be obtained requires a corresponding quantitative analysis. Here we are just to evaluate the effect qualitatively.

Let's compare two correlations: the first correlation gives the specific fuel consumption (SFC) of the engines versus their development year (after Logunov and Schmotin [33]) and the second one presents well known dependence of the use temperature of nickel superalloys on the year of the development, **Figure 15**. The extrapolation of the second correlation to ~ 1400°C, which is the target temperature of the development of high temperature metal matrix composites, yields an expected decrease in SFC of about 25% as compared to a present value of ~ 0.5 kg/kgf·hr.
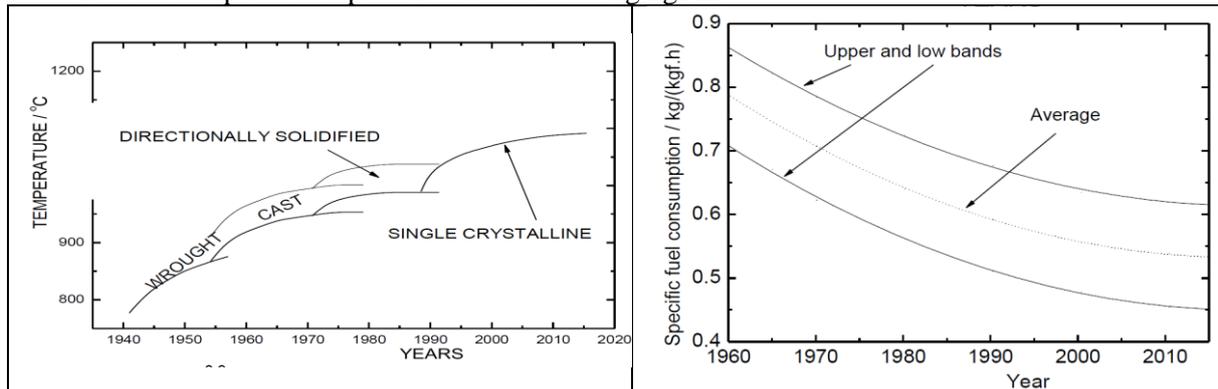
Figure 15. The use temperature of nickel superalloys and the specific fuel consumption of the engines versus the development year.

The replacement of titanium and nickel alloys in low and high pressure compressors by carbon-fibre/titanium matrix and carbon-fibre/nickel-matrix composites leads to an essential increase in the specific thrust.

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