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Oxidation behaviour of particle reinforced MoSi\textsubscript{2} composites at temperatures up to 1700 °C
Part III: Oxidation behaviour of optimised MoSi\textsubscript{2} composites

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Abstract
The topic “Oxidation behaviour of particle reinforced MoSi\textsubscript{2} composites at temperatures up to 1700 °C” is discussed in a three part publication. In the first part of this paper a literature survey on the oxidation behaviour of MoSi\textsubscript{2} and MoSi\textsubscript{2} composites has been given. In the second part an initial screening at 1600 °C revealed those composites which may be suitable for high temperature applications. The low temperature oxidation behaviour of selected composites in the “pest” region was examined as well. Additionally, the effect of iron impurities on the high temperature behaviour of the composites was explained. The present part deals with a detailed investigation of an optimised MoSi\textsubscript{2}/HfO\textsubscript{2} composite. These investigations include high temperature oxidation at 1500 to 1700 °C and low temperature oxidation at 400 and 500 °C.
1 Introduction
In the previous parts of this publication a literature review [1] and an initial screening test [2] were used to check the suitability of selected MoSi2 composites for high temperature applications. While in some cases limited oxidation resistance at 1600 °C of the material was expected due to formation of eutectics of the phases, the high temperature oxidation was seriously deteriorated by iron contamination. The series of composites were successively optimised and three composites containing SiC, ZrO2 or HfO2, respectively, were discovered to be most suitable for temperatures of 1600 °C and above. SiC composites have been investigated in detail in a separate work and are taken into consideration in the discussion section of the present paper. MoSi2-HfO2 composites showed a somewhat superior behaviour compared to MoSi2-ZrO2 composites so that optimisation was focused on the former. Further experiments were therefore carried out at temperatures up to 1700 °C to investigate the oxidation behaviour of the optimised MoSi2-HfO2 material in more detail and to obtain potential limitations of it.

2 Materials and methods
2.1 Materials
The optimized MoSi2-HfO2 composite investigated here was a composite containing 15% HfO2 from production at a laboratory scale with a low iron contamination. Following the labelling introduced in part II of the present publication, the name of the series is I2, which stands for the second series from the manufacturer Fraunhofer IFAM. Characteristics of this series are given in Table 1.

<table>
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<th>Series</th>
<th>Reinforcement particles</th>
<th>Characteristics</th>
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<tr>
<td>I2</td>
<td>HfO2</td>
<td>homogeneous, low Fe content, two series with hot pressing temperature of 1450 °C or 1550 °C, respectively</td>
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The two samples of this series were manufactured at different hot pressing temperatures, i.e. 1450 and 1550 °C, respectively. The corresponding specimens have been labelled I2a (1450 °C) or I2b (1550 °C).

The structures of the samples showed some distinctions: I2a was widely homogeneous, however, some large oxide precipitations have been found, Fig. 1, whereas I2b showed large areas depleted in HfO2, see Fig. 2.
2.2 Methods
All experiments and post experimental investigations were conducted following the description given in part II of this paper.

3 Results
Extended investigations were applied especially to the I2a specimens. Based on its homogeneous structure and low iron content this material is close to the expected final development stage. New labels are necessary for these specimens, since several tests were performed with identical samples. The specimens were distinguished by a letter following a number which indicates the oxidation temperature divided by 100, e.g., specimen 15.A is one of the samples oxidised at 1500 °C.
3.1 Oxidation at 1500 °C

Table 2 gives the mass changes of MoSi₂/HfO₂ after 30, 100 and 300 h exposure, respectively. Specimens 15.A and 15.B as well as 15.C to 15.E were each cut from the same bending sample. Note the discrepancy in mass changes between A and B compared to C to E. It was found that the latter had a higher density (6.3 versus 6.05 g/cm³). Primarily the mass gain within the first 30 h was very dissimilar, whereas following this period oxidation rates were nearly the same, Fig. 3.

Table 2: Mass changes of MoSi₂/HfO₂ (series I2a) after 30, 100 und 300 h oxidation at 1500 °C in air (in mg/cm²)

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<tr>
<td>30 h</td>
<td>1.112</td>
<td>1.002</td>
<td>0.392</td>
<td>0.345</td>
<td>0.394</td>
</tr>
<tr>
<td>100 h</td>
<td>1.186</td>
<td>1.296</td>
<td>0.607</td>
<td>--</td>
<td>0.568</td>
</tr>
<tr>
<td>300 h</td>
<td>--</td>
<td>1.508</td>
<td>--</td>
<td>--</td>
<td>0.832</td>
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Figure 3: Mass change of MoSi₂/HfO₂ (series I2a) at 1500 °C

The lower density observed for specimens A and B can cause higher open porosity. Surface defects can have a significant influence in the first hours of oxidation, because the actual surface area is larger than measured. This would result in a higher calculated oxidation rate. This effect seems to be observed in case of specimens A and B.
Independent of the density the oxide layer thickness was 4 µm after 30 h, 5-10 µm after 100 h and 10 µm after 300 h.

3.2 Oxidation at 1600 °C

Despite of similar densities of specimens 16.A to 16.C and 16.D to 16.F, which again were each cut from one bending sample, as well as similar oxide layer thicknesses, mass changes varied partially strongly, see Table 3. The reason for this could not be determined exactly. Both restricted oxygen transport to the specimen support surface and an inhomogeneous second phase particle distribution could cause different mass gains. The summarised mass gain after 300 h was lower for oxidation at 1600 °C than it was at 1500 °C, due to the smaller increase within the first 30 h. Mass changes between 30 and 100 and between 100 and 300 h showed higher oxidation rates at 1600 °C compared to 1500 °C, see Fig. 4.

The oxide layer thickness was 4 µm after 30 h, 8 µm and 10 µm after 100 and 300 h, respectively, which was similar to the values obtained at 1500 °C.

There was no evidence of contact reactions with the HfO$_2$ supports, however, the oxide layer was less developed or not present in the contact area, see Fig. 5.

Table 3: mass change of MoSi$_2$/HfO$_2$ (series I2a) after 30, 100 and 300 h oxidation at 1600 °C in air (in mg/cm²)

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<tr>
<td>30 h</td>
<td>0.536</td>
<td>0.537</td>
<td>0.599</td>
<td>0.388</td>
<td>0.274</td>
<td>0.218</td>
</tr>
<tr>
<td>100 h</td>
<td>0.758</td>
<td>--</td>
<td>0.882</td>
<td>0.585</td>
<td>--</td>
<td>0.575</td>
</tr>
<tr>
<td>300 h</td>
<td>--</td>
<td>--</td>
<td>1.154</td>
<td>0.96</td>
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Figure 4: mass change of MoSi₂/HfO₂ (series I2a) at 1600 °C

Figure 5: Support area of specimen 16.A (MoSi₂/HfO₂, series I2a) after 30 h at 1600 °C in air: reduced oxidation

Intensive agglomeration of hafnon particles occurred with increased oxidation duration. Whereas a homogeneous distribution was observed from a SEM image after 100 h, see Fig. 6, there were large dense packed areas of these particles after 500 h, see Fig. 7.
3.3 Oxidation at 1700 °C

To avoid the observed reduced oxidation at the contact surface, the supports were given a shape that provides line contact with the specimens.

A very irregular oxidation behaviour of the specimens occurred in this test, although all specimens were cut from the same bulk material. Three out of six specimens were damaged after 30 h by formation of big bubbles in the oxide scale, Fig. 8. After cooling a powdered substance was discovered in the affected areas, see Fig. 9. The remaining three specimens (17.B, 17.C and 17.F) had largely
undamaged oxide scales and increased masses. Only tiny bubbles causing the loss of the oxide scale were found on the small areas, though the integrity of the material was unaffected. Two of these specimens were oxidised additional 70 h, where to they were defective as well, see Fig. 10. The SEM image on the right side of Fig. 11 shows MoO$_3$ crystals in the powder on the specimens.

The test was repeated with two more specimens (17.G and 17.H), which again showed diverse behaviour. It is believed that the material used for these specimens originated from varied lots. 17.G was cut from the bulk material already used for 17.A to 17.F, whereas 17.H was part of a specimen prepared for a bending test. This sample had a higher density (6.3 instead of 6.1 g/cm$^3$).

At 1700 °C mass gains were significantly higher than at 1600 °C: between four and twenty times as high after 30 h, see Table 4.

Figure 8: MoSi$_2$/HfO$_2$ (series I2a) after 30 h at 1700 °C in air: formation of big “glass” bubbles on three out of six specimens and spallation of edges
Figure 9: MoSi$_2$/HfO$_2$ (series I2a) after 30 h at 1700 °C in air: left side: powder beneath bursted bubble, right side: undamaged oxide scale

Figure 10: MoSi$_2$/HfO$_2$ (series I2a) after 100 h at 1700 °C in air: collapsed bubble connecting the specimens
Figure 11: MoSi$_2$/HfO$_2$ (series I2a) after 100 h at 1700 °C in air: crystals of MoO$_3$ were identified in the powder on the specimens.

Table 4: Mass change of MoSi$_2$/HfO$_2$ (series I2a) after 30 and 100 h oxidation at 1700 °C in air (in mg/cm$^2$)

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<tbody>
<tr>
<td>30 h</td>
<td>-0.112</td>
<td>4.184</td>
<td>2.144</td>
<td>-12.325</td>
<td>-6.517</td>
<td>4.328</td>
<td>-19.415</td>
<td>0.968</td>
</tr>
<tr>
<td>100 h</td>
<td>--</td>
<td>-12.399</td>
<td>-22.78</td>
<td>--</td>
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In Fig. 12 the remnants of a bubble above a cavity are visible. It is assumed that the cavity leads to an accumulation of Mo$_5$Si$_3$, which was detected in several composites investigated. From sites like this one larger amounts of molybdenum oxide can form.
No contact reactions with the HfO₂ supports occurred, however, the supports contacting edge stuck to the oxide scale in some cases. During cooling some edges of the specimens spalled off. Due to spallation and evaporation of gaseous products mass changes do not solely result from oxide scale growth.

3.4 Continuous thermogravimetric investigations at 1500 °C
Three measurements for the MoSi₂/HfO₂ composite revealed rapid mass gain at the beginning of oxidation and lower growth rates after formation of a dense SiO₂ scale after 5-10 h, see Fig. 13. Mass loss as it is usually observed for pure MoSi₂ at the beginning of oxidation occurred in one test only and was rather small.
3.5 Oxidation at “pesting” temperatures

Two specimens each of type I2a, I2b and pure MoSi$_2$ were oxidised at 400 °C. One of each type was preoxidised for 70 h at 1400 °C in air to detect the influence of preoxidation. Fig. 14 shows the specimens after 575 h oxidation. The I2b specimen without preoxidation disintegrated completely, the powder covered some other specimens.
Specimens without preoxidation

Green-yellowish crystals formed after 90 h on the composites. Pure MoSi$_2$ had a dull black surface with white oxidation products like observed on MoSi$_2$/SiC (series G4) in ref. [2] after 500 h at 500 °C. After 250 h specimen I2b cracked into three parts and MoO$_3$ formed on this and on the I2a specimen. Pure MoSi$_2$ showed MoO$_2$ crystals at the edges. Disintegration of I2b was nearly complete after 300 h. I2a was covered with a dense layer of crystals, however, no cracking occurred. Pesting seemed to be limited to the surface region. No further changes were observed for pure MoSi$_2$.

A second test was performed at 500 °C. After 100 h the surfaces appeared black, subsequently a thin yellowish layer formed, Fig. 15. No disintegration or cracking happened within 500 h testing time.
Preoxidised specimens

Minor damage in small areas of the oxide scale was observed for the preoxidised specimens. Fig. 16 shows spots of white powder found after 250 h. A brown oxide scale occurred on pure MoSi$_2$ after 90 h and has turned dark green when the test was finished. The white spots on the composites grew slightly until the end of the test.

No disintegration was observed when these specimens were subsequently oxidised for another 500 h at 500 °C. The white spots increased insignificantly in size and some MoO$_3$ was found on pure MoSi$_2$. 
4 General discussion and conclusions of the paper (including findings of parts I and II)

4.1 High temperature oxidation

4.1.1 Oxidation of pure MoSi$_2$

At high temperatures a dense SiO$_2$ scale forms quickly and hinders the formation of MoO$_3$ by lowering the oxygen partial pressure. Fig. 17 shows that at low oxygen partial pressures MoO$_3$ will not form.

![Thermodynamic stability of the condensed phases in the system Mo-Si-O](image)

Figure 17: Thermodynamic stability of the condensed phases in the system Mo-Si-O [3]

Therefore, above 1000 °C MoSi$_2$ will transform into Mo$_5$Si$_3$ while SiO$_2$ originates in the selective oxidation of silicon following equation (1). MoO$_3$ cannot evaporate if the specimen is sealed with SiO$_2$, and a layer of Mo$_5$Si$_3$ will form beneath the oxide scale. Otherwise Mo$_5$Si$_3$ would oxidise to MoO$_3$ and SiO$_2$ according to equation (2).

\[
5 \text{MoSi}_2(s) + 7 \text{O}_2(g) \rightarrow \text{Mo}_5\text{Si}_3(s) + 7 \text{SiO}_2(s) \quad (1)
\]

\[
2 \text{Mo}_5\text{Si}_3(s) + 21 \text{O}_2(g) \rightarrow 10 \text{MoO}_3(g) + 6 \text{SiO}_2(s) \quad (2)
\]

However, Melsheimer [4] and Bundschuh [5] observed that no layer of Mo$_5$Si$_3$ is formed at high temperatures (1500 °C), because molybdenum diffuses through the SiO$_2$ scale and oxidises to MoO$_3$ at the surface. In the present work the specimens oxidised at 1600 °C not only showed no Mo$_5$Si$_3$ in the metal boundary layer, but all Mo$_5$Si$_3$ in this region which was observed prior to oxidation disappeared as well. An accelerated diffusion of molybdenum, occurring because phase boundary diffusion is enhanced by the second phase particles, prevented the formation of a Mo$_5$Si$_3$ layer.
4.1.2 General considerations on the influence of second phases

The oxide scale on MoSi₂ grows inward since diffusion of oxygen in SiO₂ is faster than that of silicon [4]. Within the oxide scale the oxidic second phase particles react with SiO₂ to form silicates gathering at the surface. For example traces of zirconium found in the oxide scale of MoSi₂/ZrO₂ indicated some solubility in SiO₂ as well as diffusion causing the gathering of particles at the surface. Small particles also coagulated in the core-area of the material to form large ones, combined with growing matrix grains. Hence, modified mechanical properties are most likely. Neither matrix grain growth nor a coarser particle distribution was observed for the MoSi₂/SiC composite, making this one more suitable for high temperature applications.

As perceived in series I₁, oxidation rates of the composites increased moderately compared to pure MoSi₂. Second phases permit faster oxygen transport to the MoSi₂/SiO₂ interface because they widen the SiO₂ network.

Lower mass gains for the oxidic and carbidic reinforced composites of series G₂ compared to series I₁, though the scale thicknesses were slightly higher, were due to evaporation of MoO₃. The surplus of molybdenum coming from the mill caused a higher amount of Mo₅Si₃ in the materials, which is preferably oxidised to MoO₃. The series of boridic reinforced composites cannot be compared since their structures and phases originating from different manufacturing routes were totally different. The high amount of SiO₂ in the boridic reinforced composites of series G₂ and G₃ results from the usage of MoO₂ and ZrB₂ or HfB₂, respectively, when producing the sinterpowders. Thermodynamic calculation showed that these phases react according to equation (3), while in absence of MoO₂ only Mo and Si react to form MoSi₂, see equation (4). Considering atmospheric oxygen, the formation of SiO₂ is thermodynamically possible, however, the other reaction products in equation (5) were not found in the material, indicating that no reaction with atmospheric oxygen had happened.

\[
\begin{align*}
\text{Mo} + 12 \text{Si} + 5 \text{MoO}_2 + 2 \text{ZrB}_2 & \rightarrow 4 \text{MoSi}_2 + 2 \text{MoB} + 3 \text{SiO}_2 + \text{ZrB}_2 + \text{ZrSiO}_4 \quad (3) \\
\text{Mo} + 2 \text{Si} + \text{ZrB}_2 & \rightarrow \text{MoSi}_2 + \text{ZrB}_2 \\n\text{Mo} + 2 \text{Si} + \text{ZrB}_2 + 6 \text{O}_2 & \rightarrow \text{MoO}_3 + \text{SiO}_2 + \text{B}_2\text{O}_3 + \text{ZrSiO}_4 \quad (5)
\end{align*}
\]

4.1.3 Thermogravimetric measurements

Unlike pure MoSi₂ the MoSi₂/HfO₂ composite revealed a significant mass gain right from the start of oxidation, turning into parabolic growth over the course of the test. Compared to pure MoSi₂ and ZrB₂ and ZrB₂/SiC reinforced MoSi₂ mass gain was accelerated in the first hours of oxidation and kept the pace of mass gain of the MoSi₂/ZrB₂/SiC composite thereafter, see Fig. 18. The surface was quickly sealed by the growing SiO₂ scale, decelerating oxygen transport and slowing down mass gain. Mass loss due to evaporating MoO₃ did not occur. This can be explained by a smaller affected surface area (15% less when particles are distributed ideally) and a faster growing oxide scale. Bundschuh et al. measured no initial mass loss for MoSi₂/SiC composites when the amount of SiC was sufficiently high and explained this with the formation of a dense SiO₂ scale from SiC particles [6]. In case of the HfO₂ reinforced MoSi₂ composite the mentioned accelerated diffusion of oxygen caused rapid sealing of the surface and a high oxidation rate throughout the testing time, see Fig. 19. A higher mass gain for ZrO₂ and HfO₂ reinforced MoSi₂ composites compared to MoSi₂/SiC was also confirmed in discontinuous tests at 1600 °C in air.
Figure 18: Mass change as a function of time for several MoSi$_2$ composites at 1500 °C in air

Figure 19: Mass change as a function of time for MoSi$_2$/HfO$_2$ compared to MoSi$_2$/SiC at 1500 °C in air
The characteristics of oxidation kinetics did not change at higher temperatures. Several factors must be taken into account for explaining the same scale thickness but lower mass gain at 1600 °C versus 1500 °C during the first 30 hours of oxidation:

1) The diffusion rate of Mo in SiO₂ increased with the higher temperature and with a lower viscosity of the oxide scale. That means that more MoO₃ will evaporate, leading to higher mass loss. The rather short path of diffusion within the first hours facilitates rapid evaporation.

2) Bottleneck pores and pits will be closed quickly when the oxide scale growth rate is high and the viscosity is low. The actual surface area will rapidly match the geometric one, giving a “true” oxidation rate, whereas in the other case the area used to calculate the rate is actually larger than assumed, leading to lower rates. Fig. 20 facilitates understanding of this process.

3) The specimens had a larger support surface with reduced oxygen supply and impeded oxide scale growth. The estimated oxidised surface is larger than the actual one, resulting in a lower calculated growth rate.

Long oxidation tests with more than 100 h duration revealed slightly higher oxidation rates at elevated temperatures due to accelerated diffusion. The slope of the mass gain curves is a little steeper for 1600 °C than for 1500 °C, see Fig. 21.
Raising the furnace temperature to 1700 °C, the threshold of 1680 °C for formation of the eutectic phase of the system SiO2-HfO2 is surpassed and with liquid phases the oxidation accelerates drastically. The HfO2/MoSi2 composite is therefore not suitable for applications with temperatures of 1700 °C and higher. Although time to failure was not always within 30 h, all specimens failed for the same reason. Bubbles were formed by evaporation of gaseous MoO3. During cooling, smaller parts of the specimens spalled off and a powder had formed.

The precondition for bubble formation is a higher pressure within the bubble than the ambient pressure. The boiling point of MoO3 is at 1155 °C. Fig. 22 shows that at 1700 °C the vapour pressure of MoO3 is more than 2.6 bar. However, for technical applications the vapour pressure should not exceed 10^{-4} bar, where evaporation leads to measurable mass losses and reduction of the cross section [7]. Added vapour pressures of silicon oxides and MoO2, being around 10^{-6} at 1700 °C, increase the value of 2.6 bar even further.
Figure 22: Calculated vapour pressures of gaseous oxides of molybdenum and silicon as a function of temperate at an oxygen partial pressure of 0.2 bar

To obtain pressures of more than the atmospheric pressure of 1 bar high amounts of MoO$_3$ are necessary. Since MoO$_3$ is primarily formed from Mo$_5$Si$_3$, these precipitations which occurred in the delivered material play an important role.

Fig. 23 facilitates understanding of the bubble formation. Prior to oxidation precipitations of Mo$_5$Si$_3$ exist in the subsurface area. During oxidation a layer of SiO$_2$ is formed. The SiO$_2$ scale grows at its inner interface, moving towards the Mo$_5$Si$_3$. Reached by the layer, Mo$_5$Si$_3$ is oxidised to a high concentration of MoO$_3$ below the SiO$_2$ scale. While at this very high temperature oxygen for this oxidation is delivered quickly through the scale, MoO$_3$ cannot diffuse fast enough outwards. The pressure causes the formation of a bubble in the scale with low viscosity. Fig. 24 shows such a bubble in the SiO$_2$ scale. The element distribution of Mo proves residues of the Mo-rich phase Mo$_5$Si$_3$ at the edge of the bubble. HfO$_2$ surface particles can even accelerate transport of oxygen to the Mo$_5$Si$_3$, causing its oxidation to SiO$_2$ and gaseous MoO$_3$. SiO$_2$ again reacted with HfO$_2$ to form HfSiO$_4$, which is now detected directly above and below the bubble. Aluminum in the oxide scale results from evaporation from the furnace chamber surface and enhances the diffusion rate of oxygen through the layer.
Figure 23: Bubble formation through oxidation of MoSi$_3$
Fig. 12 shows that the process described can produce holes in the material. Bubble formation was observed chiefly at very high temperatures, as oxygen transport to oxidise high amounts of Mo$_5$Si$_3$ is sufficient and scale viscosity is low enough, nevertheless it occurred in a smaller degree at 1600 °C as well.

In case the bubbles did not burst, the gaseous MoO$_3$ condensed during cooling and a layer of MoO$_3$ remained on the material, just like in the pesting tests. When the gas condensed in pores, the voluminous crystals led to stresses, cracking and spallation of the material.

Spallation of some edges during cooling might result from the slightly higher thermal expansion coefficient of cristobalite versus MoSi$_2$ ($\alpha_{\text{cristobalite}} = 10.3 \times 10^{-6} \text{ K}^{-1}$, $\alpha_{\text{MoSi}} = 8.5 \times 10^{-6} \text{ K}^{-1}$). In addition, the modification of cristobalite changes from a to the low temperature modification b between 270 and
200 °C, combined with a decrease in volume of 1.9 to 2.7% [9]. Both occurrences bring tension into
the scale. Since this kind of spallation did not occur at 1600 °C and since the affected area is rather
small, the stresses seem to be only slightly above the critical value.

4.2 Oxidation at “pesting” temperatures
The composite MoSi2/HfO2 of series I2 revealed the relation of pesting to the microstructure.
Disintegration occurred for the specimen pressed at 1550 °C but not for that pressed at 1450 °C. The
density for the latter was determined to be higher. The lower density indicates more pores and
microcracks, where pesting generally begins.

Second phase particles could enhance pesting of MoSi2 since oxygen diffuses more quickly at phase
boundaries than through the volume. Additionally, some oxides like ZrO2 and HfO2 are fast oxygen
conductors. However, formation of MoO3 was limited to the surface of the I2a specimen with higher
density, denying that the particles cause accelerated oxidation in the interior of the sample. Selective
oxidation at the surface might result from introducing defects when grinding the sample prior to the
test.

At low temperatures the particles could influence the oxidation behaviour in several ways. Since they
are oxides themselves (ZrO2 and HfO2) or easily develop an oxide scale (SiC), the oxidation rate of the
composites should be decreased compared to pure MoSi2. This can be explained as follows: For oxide
second phases the affected surface of the composite is decreased ideally by the amount of the second
phase, i.e. for the composites described in this paper only 85% of the surface can oxidise, resulting in
a lower oxidation rate based on the entire surface. For SiC, oxidation of this phase can result in
formation of an oxide scale which seals the surface and prevents further “pest” oxidation. On the
other hand, all second phase particles provide additional interfaces, acting as starting points for
pesting and increasing the oxidation rate.

Though composites and pure MoSi2 cannot necessarily be compared at a certain temperature because
of the dependence on the composition, the resistance to pesting of the pure MoSi2 specimen is most
likely due to its high density, since neither oxidation at 400 °C nor the successional one at 500 °C lead
to disintegration.

Preoxidation even of series I2 did not completely prevent pesting as planned, indicated by the white
spots on the oxide scale after 575 h at 400 °C, see Fig. 16. It is concluded that the incubation time is
prolonged by preoxidation, since the material will show accelerated oxidation later. The same was
observed for pure MoSi2.

Based on these results the second phase particles have a rather small influence on pesting of MoSi2
composites, but as for pure MoSi2 the microstructure is crucial. High density and preoxidation will
provide a higher resistance against pesting.

4.3 Conclusions for MoSi2 composites containing ZrO2 or SiC
The problems observed in the oxidation of MoSi2/HfO2 at very high temperatures, i.e. above 1600 °C,
like the formation of a liquid phase at 1700 °C can easily be transferred to the composite containing
ZrO2. The eutectic temperature of SiO2-ZrO2 is in the same range. Generally, Zr and Hf and their oxides
are quite similar.

Since there are no eutectics in the MoSi2/SiC-SiO2 system, it is assumed that the temperature limit of
MoSi2/SiC is somewhat higher. Silica melts at 1723 °C. However, high amounts of Mo5Si3 may lead to
bubble formation similar to what had occurred at 1600 °C when testing MoSi2/HfO2, which is below
the eutectic temperature of HfO2-SiO2. Evaporation of CO causes bubbles in the silica scale of SiC at
1700 °C [10] and has to be considered in addition to gaseous MoO₃ when testing the MoSi₂/SiC composite.

As a general conclusion it may be stated that optimised MoSi₂ composites can be suitable for use up to something like 1600 °C (but not for temperatures significantly higher).

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6 Literature