Evaluation of the effect of interphase zone on the properties of the Al-Al₂O₃ composites

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Abstract. A theoretical study of the mechanical characteristics of the composite system Al-Al₂O₃. A justification for the reduced strength values of composite samples associated with the possible occurrence of increased residual stresses has been proposed. The influence of interfacial zone (for which the composition and approximate thickness have been determined) on the mechanical properties of the material has been studied; it is shown that within the framework of the classical model of multilayered cylindrical fibres the interfacial zones do not significantly influence the material properties, but can affect the level of residual stresses.

1 Introduction

Modern composites have not only a wide spectrum of physical-mechanical properties but are also capable of their directed change, for example, to increase fracture toughness, to regulate stiffness, strength and other properties [1-15]. These possibilities are extended to the application in fibre composites of various nature and geometry, that is, to the creation of hybrid composites [16-28]. In addition, the synergetic effect (coordinated joint action of several factors in one direction) is typical for these materials.

The properties of the interface or interfacial zone, primarily the adhesive interaction of fibre and matrix, determine the level of the properties of composites and their preservation in operation [29-41]. Local stresses in a composite reach their maximum values just near or directly at the interface, where material destruction usually begins. The interface must have certain properties to ensure effective transfer of mechanical stress from the matrix to the fibre [42-45]. The adhesive bond at the interface must not be destroyed by thermal and shrinkage stresses arising from the difference in temperature coefficients of linear expansion of matrix and fiber or as a result of chemical shrinkage of the binder during its curing.

2 Calculation of interfacial layer parameters

To estimate the interfacial layer at the interface between the aluminium oxide fibres and the matrix containing Mg, the ratio obtained above is used:

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\[ h(t) = K_0 \exp \left[ -\frac{E + \kappa \sigma_{kk}}{2RT} \right] \sqrt{t}, h(t) \equiv \delta(t) \]

Here \( K_0 \) is a pre-exponential parameter determined experimentally, \( E \) is the activation energy of the reaction zone growth process, \( R = 8.314 \) is a universal gas constant, \( T \) defines process temperature on the Kelvin scale, \( \sigma_{kk} \) is a spherical tensor. The parameter \( \kappa \) is determined by experimental data.

The following activation energies are known for the studied spinel interfacial growth processes.

In the investigated aluminium-based composites the reaction takes place:

\[ (3/4(Al_2O_3)+Mg \rightarrow (3/4)MgAl_2O_4+(1/2)Al) \]

The process starts at a temperature of 900 K. The activation energy is known for as \( E = 103 \) kJ.

It is important to note that in aluminum-alumina composites for the considered temperature ranges there is no reaction directly between the aluminum matrix and fibers, i.e., aluminum oxide fibers should not undergo destruction, as this process can start only at temperatures above 900°C.

In this case, we know from literature sources the only experimental point, defined by the following parameters:

- Temperature \( T = 1020 \) K.
- Process time \( t = 5 \) min
- Pressure \( P = 130 \) MPa (here \( P \) is the spherical stress tensor)
- The thickness of the interfacial layer: \( h = 20 \) nm.

As a result of modeling, we need to determine the change of interface layer width and analyze its dependence on pressure and temperature, if the temperature changes in the range \( T=970-1020 \) K (700-750°C), process time changes in the range \( t=1-3 \) min, and the pressure of process realization is in the range \( P=3000-4000 \) kPa (30-40 atm.).

For a composite based on aluminium alloy containing magnesium alloying additives and fibre-reinforced aluminium oxide it is known that diffusion processes resulting in spinel formation \( (3/4(Al_2O_3)+Mg \rightarrow (3/4)MgAl_2O_4+(1/2)Al) \) begin at a temperature of 900 K. The following parameters are known for such a process:

\[ K_0 = 7.07 \text{ nm s}^{-0.5}, \]

- \( E = 103 \) kJ,

First, we define the parameter \( \kappa \) referring to the above experimental data. As a result, it is found that \( \kappa = 0.235714 \).

After determining the value \( \kappa \) the dependence of interfacial layer thickness on curing time can be established.

In Figure 1 this dependence is plotted for the parameters:

\[ K_0 = 7.07 \text{ nm s}^{-0.5}, E = 103 \text{ kJ}, T = 1020 \text{ K}, P = 3000\text{Pa}, \]
Further the influence of pressure and temperature on the interfacial layer formation rate is investigated.

It is found that in the specified range of these characteristics the growth of the interfacial layer is independent of them. This is demonstrated in Figure 2, which shows the dependences for the interfacial layer thicknesses when the parameters:

\[ K_0 = 7.07 \text{ nm s}^{-0.5}, \quad E = 103 \text{ kJ}, \quad P = 3000\text{Pa}. \]

The upper curve is plotted for temperature \( T = 1020 \text{ K} \) and the lower curve for \( T = 720 \text{ K} \).

Let us find out whether the accuracy of the activation energy determination affects the interfacial layer thickness estimates. To do this we first again determine the parameter \( \kappa \), by the experimental test and then plotted - the dependence of the layer thickness on the dwell time.

The following activation energies are compared: 1. \( E = 103 \text{ kJ} \), 2. \( E = 90 \text{ kJ} \). It was found that for these activation energies the parameter \( \kappa \) does not actually change. As a result, the accuracy of the activation energy setting in the specified ranges has no effect on the interfacial layer thickness estimates.

Further, we proceed to the influence of the parameter \( K_0 \). The following three options were compared: 1. \( K_0 = 7.07 \text{ nm s}^{-0.5} \), 2. \( K_0 = 5 \text{ nm s}^{-0.5} \), 3. \( K_0 = 9 \text{ nm s}^{-0.5} \).

Once again, the procedure for calculating the parameters was repeated. For the three variants the following values of this parameter were found: 0.2356144, 0.190418; 0.267104.
After that the time dependences for the interfacial layer were plotted. The results are shown in Figure 3:

![Figure 3](image)

**Fig. 3.** Influence of the accuracy of the parameter determination $K_0$ to predict interfacial layer thicknesses: solid thick line - $K_0 = 9$ nm with $0.5$, dotted line - $K_0 = 7.07$ nm s$^{-0.5}$, thin line - dashed line - $K_0 = 5$ nm s$^{-0.5}$.

It is essential to note that the accuracy of the prediction is affected by the accuracy of the parameters in formula (*). Therefore, the problem of extending the experimental data that can be used to determine (and refine) the parameters included in (*) is very important. Having these data and solving the problem of identification of model parameters (*) by minimizing the target function (the theoretical dependence error) in a norm selected after testing, we can significantly refine the forecast data on the interfacial layer thickness.

According to some sources the growth of spinel interphase zone can begin only after passing an "incubation" period which is up to 1000 K - 2000 s and decreases to 500 s for temperatures above 1000 K. Thus, the investigated treatment time interval of 3 min may not be sufficient to initiate the growth of interphase zones in the aluminium composite. Fig. 4 shows revised dependence of interface thickness as a function of process temperature and incubation time. Here it was assumed that the incubation time decreases linearly with increasing temperature from 970 to 1020 K from an initial value of 2000 s to a value of 500 s.

![Figure 4](image)

**Fig. 4.** Dependence of interface thickness on time with consideration of incubation period (solid line $T=1020K$, dashed line - $T=1000K$, dotted line - $T=970K$).
3 Conclusions

Simulations show that an interfacial layer thickness of 60-120 nm can be achieved within a given range of temperatures and pressures. Neither temperature nor pressure (in the given ranges) have a significant influence on the thickness. Optimal thickness can be achieved only by changing the exposure time. Based on the preliminary calculations made (which may need to be refined during the experiments), it can be recommended that the process of obtaining samples at 750 °C is carried out to ensure the shortest growth incubation period. Pressure should be minimum in the chosen range - 30 atm. to increase the growth rate of the interfacial zone. The process time should be 10-20 min. to obtain an interfacial zone thickness of 80-150 nm. In the event that the phenomenon of interfacial growth onset in the incubation period is not confirmed, the dwell time shall be 3-5 min.

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