Whiskers as perspective input material for production of high temperature resistant ceramic building materials

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Abstract. Production of electric power by nuclear power plants (NPP) in the world and in Russia accounts for about 17%. Much attention is currently paid to safe NPP operation and to enhancement of their reliability. Present-day nuclear power plants with high-temperature gas-cooled reactors require development and application of new composite materials capable to withstand high temperatures and mechanical stresses. Ceramic composite materials where whiskers of heat-resistant chemical compounds are used as reinforcement fibers look promising for those purposes. The paper investigates and analyses the opportunity of applying whiskers as reinforcement fibers for heat-resistant ceramic building materials. Studies revealed that whiskers of silicon carbide and aluminium nitride are resistant towards high temperature heating without notable change in their chemical composition. It was found out that mono crystals of silicon carbide have higher mechanical strength owing to lack of defects in its structure. Linear heat expansion factors of silicon carbide that are needed for thermo-chemical calculations of composite materials on its base were determined.

1. Introduction
About 17% of electric power generated in Russia and in the world fall on nuclear power plants. Design of nuclear reactors is continuously enhanced with focus on their safety, reliability, and efficiency. High-temperature gas-cooled nuclear reactors are thought to be more advanced units [1]. Temperature of their fuel elements may be as high as 1600°C [2, 3]. Correspondingly, temperature of the heat transfer medium and of pipes for its circulation, temperature of the gas turbine elements ensuring circulation of heat medium in the loop, and that of a heat exchanger may be higher than 1000°C. The structures of such reactors need high-temperature composite building materials of high chemical resistance and mechanical strength [4]. In this connection the ceramic materials of different structure and chemical composition arouse more and more interest. Whiskers have high mechanical strength owing to peculiarities of their structure, they are chemically inert towards many aggressive media, and have high temperature resistance [5-7]. Whiskers are used in industry as reinforcing fibers for a large range of composite materials. Development of ceramic temperature-resistant composite materials with the use of whiskers would allow production of composites capable to withstand high mechanical loads but maintaining high temperature and chemical resistance [8-11]. Creation of such materials requires studies on changes of whiskers properties under high temperatures.
2. Methods and materials
Mechanical properties and temperature resistance of silicon carbide (SiC) and of aluminium nitride (AlN) whiskers at different temperatures were studied using the IR spectroscopy. IR spectra were recorded by an IR spectrometer Specord. Factors of heat linear expansion of silicon carbide whiskers were determined using a dilatometer.

3. Results and discussion
Silicon carbide (SiC) and of aluminium nitride (AlN) whiskers demonstrated the highest temperature resistance. The main mechanical properties of whiskers of those compounds are given in Table 1.

Table 1. Mechanical properties of silicon carbide (SiC) and of aluminium nitride (AlN) whiskers

| Fiber material | Melting temperature, °C | Density, 10^12 kg/m^3 | Elasticity modulus, 10^9 N/m^2 | Ultimate resistance, 10^9 N/m^2 | Specific strength, 10^9 N-m/kg | Specific elasticity modulus, 10^6 N-m/kg |
|---------------|------------------------|-----------------------|-------------------------------|---------------------------------|---------------------------------|----------------------------------------|
| SiC           | 2665                   | 3.32                  | 580                           | 27                              | 8.4                             | 180                                    |
| AlN           | 2400                   | 3.30                  | 380                           | 15                              | 4.55                            | 115                                    |

Considered chemical compounds of whiskers have high melting temperature corresponding to a class of extremely-high temperatures (2000-3000°C). The 1.8 times difference in the values of ultimate resistance of mono crystals is due to difference of elasticity modulus of those compounds. This fact, in its turn, evidences the differences in the structure of a crystalline lattice of compounds at equal densities, and availability of such defects as brittle fractures in the aluminium nitride structure [12,13]. The data obtained prove more perfect (in terms of strength) structure of silicon carbide mono crystals.

Silicon carbide and aluminium nitride whiskers were also subjected to IR investigation at different temperatures of heating.

IR absorption spectrum of SiC crystals is given in Fig. 1. The main absorption band of silicon carbide is observed at a frequency of (840-920) 10^2 m^-1. Moreover, silicon carbide has two low-intensity bands at 670 10^2 m^-1 and 1090 10^2 m^-1, the latter characterizing the variation in Si-C bonds. The band of 920 10^2 m^-1 rapidly loses its intensity and shifts towards a short-wave area when heated up to 200°C. At the same time a fuzzy band emerges in the range of (1100-1300) 10^2 m^-1. At 800°C the band of 920 10^2 m^-1 grows in intensity, whereas the band of 840-10^2 m^-1 extends towards a long-wave area. During heating for one hour at a temperature of 1200°C new peaks emerge in the area of (1200-1260) 10^2 m^-1.
IR spectra of SiC whiskers are given in Fig. 2. They constitute a system of intense fuzzy bands in the area of KBr and NaCl. Peaks are obvious at 625·10^2 m\(^{-1}\) and 815·10^2 m\(^{-1}\). With the temperature growth during heating, these bands practically do not change. During further heating the weak bands in the areas of 1160·10^2 m\(^{-1}\) and 1330·10^2 m\(^{-1}\) gradually disappear.

Fig. 1. IR spectra of SiC whiskers at different temperatures.

IR spectra of SiC whiskers are given in Fig. 2. They constitute a system of intense fuzzy bands in the area of KBr and NaCl. Peaks are obvious at 625·10^2 m\(^{-1}\) and 815·10^2 m\(^{-1}\). With the temperature growth during heating, these bands practically do not change. During further heating the weak bands in the areas of 1160·10^2 m\(^{-1}\) and 1330·10^2 m\(^{-1}\) gradually disappear.

Fig. 2. IR spectra of AlN whiskers at different temperatures.
Under relatively small changes in the spectrum absorption bands at different temperatures of heating the whiskers of investigated chemical compounds, the silicon carbide demonstrates better mechanical strength and has more perfect structure of mono crystals.

When developing a composite material, the thermal expansion factors of materials constituting the composite shall be taken into account along with temperature-dependent changes in its composition [14-18]; for thermo-mechanical calculations of temperature-resistant composite materials the thermal expansion factors of its components shall be considered in a wide range of temperatures. SiC is known to have a wide variety of crystalline structure types. Authors determined the thermal linear expansion factors for two main SiC modifications, namely for cubical (β-SiC) and for hexagonal (α-SiC) ones. Results of studies are given in Table 2.

### Table 2. Thermal linear expansion factors for different modifications SiC crystalline structure

| Material | Temperature, °C | Thermal expansion coefficient $\alpha \times 10^{-6}$ degree$^{-1}$ |
|----------|-----------------|---------------------------------------------------------------|
| Mono crystal $\alpha$-SiC | 25-1000 | 5.12 |
| Mono crystal $\alpha$-SiC | 25-1500 | 5.48 |
| Mono crystal $\alpha$-SiC | 25-2000 | 5.77 |
| Mono crystal $\alpha$-SiC | 200 | 3.8 |
| Mono crystal $\alpha$-SiC | 400 | 4.3 |
| Mono crystal $\beta$-SiC | 600 | 4.8 |
| Mono crystal $\beta$-SiC | 800 | 5.2 |
| Mono crystal $\beta$-SiC | 1000 | 5.8 |
| Mono crystal $\beta$-SiC | 1400-1800 | 5.5 |

Optimum composition of bonding material is selected based on the equality of numerical values of linear heat expansion factors for whiskers applied as reinforcement fibers of composites.

### 4. Conclusion

Thermal studies of silicon carbide (SiC) and of aluminium nitride (AlN) whiskers confirm the suitability of whiskers for creation of high temperature resistant ceramic building materials and coatings. IR studies of mono crystals have shown that there is no notable change in the chemical composition of the substance during heating. Considerable differences in the mechanical strength of mono crystals have been observed. Silicon carbide whiskers have lesser number of structural defects than aluminium nitride whiskers. Numerical values of linear heat expansion factors have been determined for silicon carbide whiskers that have higher mechanical strength and melting temperature that are needed for thermo-mechanical calculations of composite materials.

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