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Modified formula for the assessment of the thermal response of neutron irradiated CFC

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Abstract

The available thermal conductivity data for various neutron-irradiated 2–3 dimensional carbon fibre composite materials have been collected and have been critically reviewed with respect to possible application in the ITER divertor. The empirical correlations are proposed that match the thermal conductivity data and allow interpolate or extrapolate of the behaviour in the wide temperature (~150–3000 °C) and fluence (0–0.1 dpa) ranges of interest for ITER. These include the correlations for materials with 'high' ($\gtrsim$ 200 W/m K) initial thermal conductivity and for materials with moderate (~100 W/m K) thermal conductivity. Using the proposed formula the thermal performance of CFC armoured ITER divertor is assessed.

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1. Introduction

Carbon fibre composites (CFCs) are considered as armour material for the plasma-facing components of next step fusion facilities (e.g. ITER divertor [1]). The main advantages are high thermal conductivity, high thermal shock resistance, and absence of melting. To predict the erosion lifetime of the CFC-armoured components (due to chemical erosion and evaporation during transient events), information about surface temperature and bulk thermal conductivity must be known.

It is well known that for carbon-based materials the thermal conductivity under neutron irradiation degrades, starting at low fluence, especially at low irradiation temperature. This degradation is primary due to formation of vacancies, or vacancy clusters, due to neutron irradiation. As the surviving concentration of vacancies following a neutron cascade is a strong function of temperature, the level of neutron-degraded thermal conductivity is also a strong function of irradiation temperature.

To assess the thermal performance of neutron irradiated CFC-armoured components, a correlation that describe the thermal conductivity changes was proposed [2]. However, that correlation does not cover degradation effects at irradiation temperatures less than 300 °C; also, as was shown [3], the level of the degradation depends on the initial thermal conductivity. Recently, more data on the effect of neutron irradiation on the thermal conductivity were published [4,5] and these data, especially at low irradiation temperature ($\lesssim$300 °C) provide a good basis for proposing a modified correlation.

This paper proposes an empirical formula describing thermal conductivity changes as a function of the neutron fluence over a wide temperature range (~100–1500 °C). Based on the recommended correlation the thermal performance of CFC-armoured ITER divertor components has been assessed, and, the possible influence on the lifetime is discussed.

2. Analysis of the data

The available data on neutron irradiation effects on the thermal conductivity of different carbon fibre

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composites have been collected from a number of Refs. [3–15]. Detailed information about the collected data is included in Table 1. The data were collected for CFC grades with thermal conductivity in the range of 200–400 W/m K. The data were collected for cases where the test temperature after irradiation (T_{test}) is equal to the temperature of irradiation ($T_{\text{irr.}}$). Refs. [4,7,9] report the thermal conductivity measured at room temperature. These data were also included in the assessment because, as shown in [5], an increase of testing temperature leads to non-significant changes in the thermal conductivity after irradiation.

The values of the ratio of thermal conductivity after irradiation ($K_{\text{irr.}}(T)$) to initial thermal conductivity ($K_{\text{o}}(T)$) as a function of irradiation and test temperature and neutron damage in dpa are plotted in Fig. 1. The data collected were grouped together for the following temperatures: <90, 150, 200, 335, 370–430, 600–620, 775–820, 1000 and 1500 °C. The analysis of the available data leads to the following conclusions:

- irradiation temperature plays an important role in reduction of the thermal conductivity even at very low neutron fluence (<0.001 dpa), e.g. [4];
- the dose dependence of the ratio $(K_{\text{irr.}}(T)/(K_{\text{o}}(T))$ in the temperature range 200–1200 °C varies logarithmically, as pointed out in [2];
- saturation of the value of $(K_{\text{irr.}}(T)/(K_{\text{o}}(T))$ is observed; the lower the irradiation temperature, the lower the saturation dose required;
- at irradiation temperature ~1500 °C there are no changes in the thermal conductivity;
- at very low irradiation dose (<10^{-3} dpa) the thermal conductivity changes are in the scatter band of the experimental measurements.

Analysis of the data allows the following semi-empirical equation to be proposed:

$$K_{\text{irr.}}(T,F) = K_{\text{o}}(T) * (1 - A(T) * \log(F/0.0008)), \qquad (1)$$

where $K_{\text{irr.}}(T,F)$, W/m K is the thermal conductivity of irradiated material; $K_{\text{o}}(T)$, W/m K, thermal conductivity of unirradiated material; T, °C, irradiation and testing temperature, $100 \leqslant T \leqslant 1450$ °C; F, fluence, dpa; $0.0008 < F < 0.1$ dpa;

$$\begin{aligned} A(T) = {} & -2.56\text{E–}10 * (T+50)^3 + 9.31\text{E–}07 \\ & * (T+50)^2 - 1.22\text{E–}03 * (T+50) \\ & + 6.04\text{E–}01. \end{aligned}$$

It is assumed that there are no changes in the thermal conductivity at damage doses less than 0.0008 dpa. There is no special meaning in this value.

For materials with lower initial thermal conductivity (~100 W/m K at room temperature) the level of degradation of thermal conductivity $(K_{\text{irr.}}(T))/(K_{\text{o}}(T))$ is typically lower ([3]). For example, the value of $(K_{\text{irr.}}(T))/(K_{\text{o}}(T))$ for 'high' thermal conductivity material at 800° and 1 dpa is ~0.75–0.8, whereas this ratio is ~0.85–0.9 for 'low' thermal conductivity material. This can be explained if one considers that the phonon scattering is higher initially in the lower conductivity materials.

This is also relevant for thermal conductivity of CFCs in direction other than the maximum thermal

Table 1
Summary of the collected data for different CFC materials

Material grade	Damage dose (dpa)	Irradiation and test temperature (°C)	Ref.
CX-2002U	0.42–0.85	385, 430	[3]
SEP NB31, SEP NS31	0.0021–0.13	<90[a]	[4]
SEP NB31, SEP NS31	0.2, 1	200	[5]
FMI-222, Hercules 3-D	0.01–0.24	150–200[a]	[6]
Dunlop C1, Dunlop C2, SEP N112, SEP N312B, SEP NS11	0.31–0.35	335, 775	[7]
CX-2002U	0.01–0.82	200, 400	[8]
CX-2002U	0.1	400, 600	[9]
CX 2002U, SEP N112, DMS678, A05	1.3, 1.8	620, 820, 1000	[10]
A05, SEP N11, SEP N112, FMI A27–130, DMS 678, CX-2002U	0.41, 0.57, 0.83	385, 395, 420	[11]
CFC223, CFC222	1.2–4.6	600	[12]
UAM	0.1, 0.12, 0.2	200, 370, 600	[13]
A05, DMS 678, FMI 4D	0.00074–0.091	400, 600	[14]
A05, FMI 4D, DMS 678, FMI 222	0.00009–3.1	400, 600, 1500	[15]

[a] Tests after irradiation were performed at room temperature.

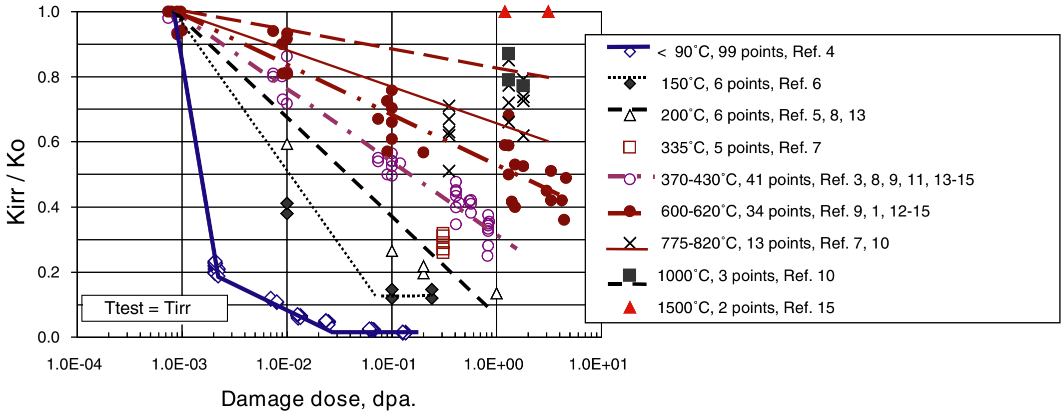

Fig. 1. Available database on the reduction of the thermal conductivity of different CFCs grouped in different temperatures ranges as a function of neutron damage dose.

conductivity direction. Taking into account empirical recommendations [3], a similar equation is proposed for describing these thermal conductivity changes:

$$K_{\mathrm{irr.}}(T,F) = K_{\mathrm{o}}(T) * (1 - B(T) * \log(F/0.0008)), \qquad (2)$$

where $K_{\mathrm{irr.}}(T,F)$, W/m K is the thermal conductivity of irradiated material; $K_{\mathrm{o}}(T)$, W/m K, thermal conductivity of unirradiated material; T, °C, irradiation and testing temperature, $100 \leqslant T \leqslant 1450$ °C, F, fluence, dpa; $0.0008 < F < 0.1$ dpa;

$$\begin{aligned} B(T) = {} & -2.56\mathrm{E}{-}10 * (T+100)^3 + 9.31\mathrm{E}{-}07 \\ & * (T+100)^2 - 1.22\mathrm{E}{-}03 * (T+100) \\ & + 6.04\mathrm{E}{-}01. \end{aligned}$$

Fig. 2 shows the calculated thermal conductivity of CFC SEP NB31 for two directions: x-direction with maximum thermal conductivity, and y-in plane direction. The values for unirradiated materials were taken from [16].

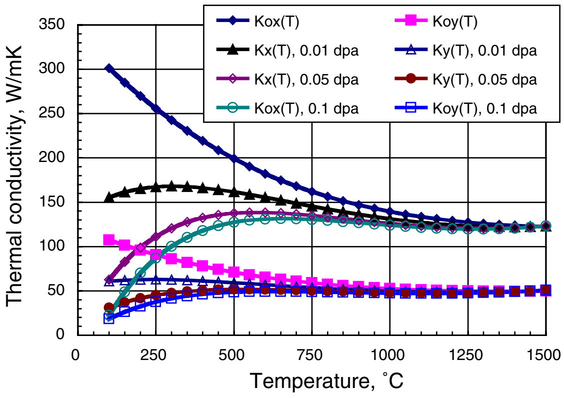

Fig. 2. Calculated thermal conductivity of CFC SEP NB31 in x- and y-directions at damage dose 0.01, 0.05 and 0.1 dpa.

3. Thermal performance of CFC armoured divertor

To assess the erosion lifetime of CFC-armoured components in fusion reactors, the surface temperature during operation must be known. This is particularly important for calculation of the chemical erosion, which is strongly temperature-dependent.

The thermal performance of CFC-armoured components at different neutron fluences levels was assessed using the proposed correlations. A 1-D model was used and SEP NB31 was selected as armour with thickness was 20 mm. The CFC/Cu alloy joint temperature was calculated, assuming the coolant inlet temperature (100 °C), water pressure (4 MPa), water velocity (10 m/s) and additional thermal gradient through the 3 mm thick CuCrZr alloy heat sink. For this cooling condition the heat transfer coefficient was assumed to be equal approximately of $\sim 5 \times 10^4$ W/m^2 K.

During operation under heat flux and neutron irradiation the CFC armour will have a temperature distribution through the thickness. Since neutron irradiation will lead to a decrease of the thermal conductivity, over time each piece of material will be irradiated at increased temperatures. However, the radiation defects, which were generated at low irradiation temperature, will be at least partially annealed as the material temperature increases with irradiation [6]. This means that the resultant thermal conductivity will be determined by the highest irradiation temperature. Consequently, the proposed equations can be directly used for calculation of the temperature distribution at the required neutron fluence.

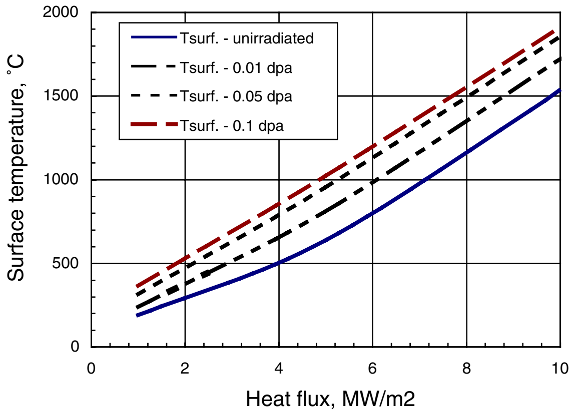

Fig. 3. Calculated surface temperature of CFC armoured component (material – SEP NB31, thickness – 20 mm) as a function of heat flux at different damage dose.

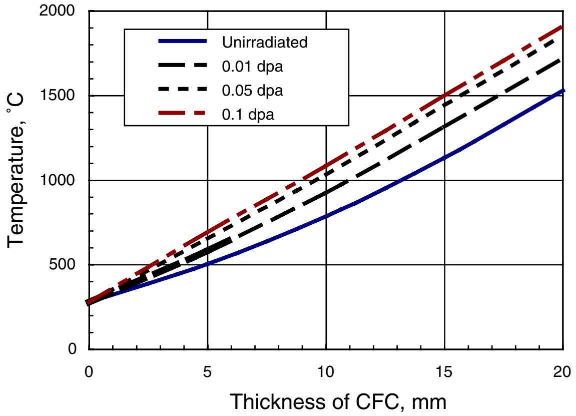

Fig. 4. Calculated temperature of CFC as function of thickness (material – SEP NB31, thickness – 20 mm) for heat flux of 10 MW/m^2 at different damage dose.

Fig. 3 shows the calculated surface temperature of CFC as a function of heat flux at damage doses of 0.01, 0.05 and 0.1 dpa. The dose of 0.1 dpa is considered to be the maximum expected dose for the ITER divertor. Fig. 4 shows the temperature distribution through the thickness of 20 mm CFC armour at 10 MW/m^2 for different damage doses. With decrease of the CFC thickness, which is expected due to erosion, the surface temperature could decrease, but the neutron irradiation in any case will dominate, leading to an overall increase of the surface temperature.

4. Conclusions

The available data on the effect of neutron irradiation on thermal conductivity of different CFC grades have been collected and assessed. The empirical formulas describing the thermal conductivity of CFC as a function of irradiation temperature and neutron fluence for material with high (~200–400 W/m K) and low (~100 W/m K) room temperature thermal conductivity have been proposed. These correlations allow to calculate the surface temperature of CFC as a function of neutron fluence and heat flux, which is needed for the assessment of the erosion of CFC armour during operation in fusion devices.

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