SUMMARY

Graphite reactor components are parts which are moulded from graphitized coke-binder mixtures. Due to the moulding operation (die pressing or extrusion), necessary during the manufacturing procedure, the graphite grains obtain a preferred orientation with respect to the direction of the moulding pressure. This orientation of the graphite grains results in an anisotropy of the macroscopic properties of the moulded graphite component, since the structure of the crystallites is anisotropic. This anisotropy occurs for the elastic properties (modulus of elasticity and Poisson’s ratio), for the coefficient of thermal expansion, and for the dimensional changes during irradiation with fast neutrons, observed in all graphites. The preferred orientation of the graphite grains in a certain direction results in an orthogonal anisotropy of the material properties, which is characterized by the effect that the properties in one direction substantially differ from the properties in the directions perpendicular to it.

During reactor operation, stresses are accumulated in the components, which are caused in their greater part by the neutron-induced dimensional changes (shrinking) and by thermal expansion. Thus it is desirable to have a possibility to consider the anisotropy of the shrinking behaviour and of the coefficient of thermal expansion in the calculation of such stresses.

Thus, from the two-dimensional Finite-Element-Program SIGMA, which considers only the isotropic behaviour of materials, the Program SIGMA-ANISO was developed for the calculation of deformations and stresses in graphite reactor components under consideration of the anisotropy of thermal expansion and shrinkage under neutron irradiation. For the analysis it is assumed, that the maximum differences in material behaviour occur in the plane being analyzed. The anisotropy of shrinkage is taken into account by introduction of two different shrinkage curves for the two perpendicular main directions of anisotropy in this plane. These main directions coincide with those of the anisotropy of thermal expansion, which is taken into account by two different coefficients of thermal expansion. The elasticity characteristics and creep behaviour of the material are assumed to be isotropic.

This program has been applied for stress calculations on various reactor components (HTR reflector blocks and HTR fuel elements), the results of which were then compared to results obtained under the assumption of an isotropic material behaviour.
1. Introduction

The core of a high-temperature reactor is constructed mainly out of artificial graphites which serve simultaneously for structural purposes and for the moderation of fast neutrons. During reactor operation, the core-components are subjected to a high flux of fast neutrons. This results in dimensional changes of the graphite and induces strains which are added to the thermal strains. Due to the non-uniformity of flux- and temperature distribution, internal stresses are generated which are the main loading of the components.

For an assessment of the structural behaviour of the core components during reactor operation, knowledge of stress levels and distributions is necessary. Graphite is an anisotropic material whose anisotropy is increased during irradiation with fast neutrons. It is therefore desirable to consider anisotropy in the stress calculations. The purpose of the presented paper consists in examining the influence of the anisotropy of material properties on stress levels and distributions in reactor components during reactor operation.

2. Material Behaviour

The stratified structure of the graphite crystallites results in a distinct anisotropy of their mechanical properties. The different strengths of bonds within and between the layers cause very different properties parallel and perpendicular to the grain orientation. The processes used for manufacturing the graphitic components result in a characteristic orientation of the graphite grains within the component. In extruded material, the grains have a preference orientation in the direction of extrusion which gives a marked difference between the properties in extrusion direction compared with directions perpendicular to it. Likewise for molded components a preference direction develops which is perpendicular to the pressing direction.

The orientation of the graphite grains is the reason for the fact that the mechanical properties of the artificial graphites become anisotropic. The anisotropy can be measured for nearly all physical properties. E.g., the coefficient of linear thermal expansion of the graphite crystallite has in c-direction, i.e. perpendicular to the graphite layers, a value of about \(3 \cdot 10^{-5} \, {^\circ}C^{-1}\), parallel to the layers however only \(1 \cdot 10^{-6} \, {^\circ}C^{-1}\). This anisotropy of the coefficient of thermal expansion can be measured with reduced magnitude also for the artificial graphite.
The elastic properties such as Youngs modulus and Poissons ratio as well as the strength properties are anisotropic in the same manner. Especially pronounced however is the anisotropic behaviour of the dimensional changes of the graphite which are induced by irradiation with fast neutrons. These dimensional changes (Wigner strains) which are strongly dependent on the temperature during irradiation, cause strains which are equivalent to a thermal loading which is generally much more severe than the thermal loading due to the actual temperatures. Fig. 1 shows the neutron induced strains and their dependence on the orientation of the test sample with respect to the grain orientation for a needle-coke graphite which exhibits an extremely strong anisotropy.

The stresses induced by the irradiation strains are fortunately considerably reduced by neutron induced creep whose magnitude depends on the stress level, the fast neutron flux, and temperature. This creep is also dependent on the grain orientation.

3. Analytical Treatment

For the analytical treatment of the behaviour of graphite reactor components, the graphite is, in good agreement with experimental results, considered as a material whose creep response is linearly proportional to the applied stress, and for which therefore the linear superposition principle [1] can be used.

For a uniaxial stress state with variable stress history, the strain as a function of neutron dose (excluding thermal and irradiation strains) is expressed by the integral relation [2, 3]:

$$\varepsilon(D) = \int_0^D J(D - D', T) \frac{dS'(D')}{dD'} dD'$$  \hspace{1cm} (1)

where D is the accumulated dose and D' an integration variable. J(D,T) is the dose- and temperature-dependent creep function which has to be obtained by experiment.

Results of experiments [4, 5] indicate that for uniaxial loading conditions the creep function for graphite, to a good approximation, can be written in the form [3]:

$$J(D,T) = \frac{1}{E} + K(T)D + \frac{1}{\tau(E)} (1 - e^{-A_0 D})$$  \hspace{1cm} (2)

which accounts for the elastic response, the primary and the secondary creep.
The secondary creep which is mainly responsible for the behaviour of the components under long term loading, is linearly dependent on the neutron dose. The creep coefficient, $K_1$, is a function of temperature. The primary creep term which results in strains in the order of magnitude of the elastic strains is usually neglected, if the long term behaviour of the graphite is considered.

A three dimensional strain-stress law, which generalizes Eq. (1) and includes thermal and irradiation strains may in matrix notation be expressed as follows [2]:

$$\{\epsilon\} = \int_0^D \{\tilde{J}(D',T)\} \frac{\partial}{\partial D} \{\epsilon(D')\} dD' + \{\epsilon_1\} + \{\epsilon_5\}$$

(3)

where $\{\tilde{J}(D,T)\}$ is the matrix of creep compliances and $\{\epsilon_1\}$ and $\{\epsilon_5\}$ represent the thermal and irradiation strains respectively.

As the anisotropy, which is induced to the material by the manufacturing process, results generally in a distinct difference of the material behaviour for one direction (e.g. the extrusion direction) compared to directions perpendicular to it, the material can be considered as orthotropic in planes which contain this preference direction.

The strain-stress law Eq.(3) in its general form represents an anisotropic material. The anisotropy of thermal expansion and irradiation induced strains can readily be considered by choice of appropriate tensors for the thermal and irradiation strains. If a Cartesian coordinate system is chosen so that its $x_1$-axis coincides with the principal direction of anisotropy (e.g. the extrusion direction), the tensors of thermal and irradiation strains are, for orthogonal anisotropy given by

$$\epsilon_1: \begin{pmatrix} \alpha_1 \Delta T & 0 & 0 \\ 0 & \alpha_1 \Delta T & 0 \\ 0 & 0 & \alpha_2 \Delta T \end{pmatrix}; \quad \epsilon_5: \begin{pmatrix} \epsilon_{15} & 0 & 0 \\ 0 & \epsilon_{25} & 0 \\ 0 & 0 & \epsilon_{35} \end{pmatrix}$$

(4)

where $\alpha_1$ and $\alpha_2$ are the coefficients of thermal expansion for the $x_1$-direction and the perpendicular directions respectively, $\Delta T$ is the temperature increase, and $\epsilon_{15}$ is the neutron induced strain for the $x_1$-direction. $\epsilon_{25}$ are the neutron induced strains for the perpendicular directions. If the coordinate system is differently orientated with respect to the principal direction of anisotropy, the strain tensors are obtained from Eqs.(4) by an appropriate tensor transformation.

For the consideration of the anisotropy of the viscoelastic properties, creep functions dependent on different directions have to be obtained
by experiment. However, experimental results concerning the anisotropy of irradiation induced creep of graphitic reactor materials are not available to an extent that the matrix of creep compliances in Eq. (3) could be established in a general manner.

If it is assumed that the creep response for different directions is proportional to one single function (such as given by Eq. (2)) and the Poisson ratios of the material for the different directions are constants, the tensor of creep compliances can be written in the form [2]:

$$[\tilde{J}] = [H] \cdot J$$  \hspace{1cm} (5)

where $[H]$ is a matrix which contains functions of the direction-dependent Poisson ratios and $J$ is the creep function obtained from an uniaxial test.

For the numerical calculation of stresses in reactor components under consideration of a material behaviour according to Eq. (3), Eq. (4), and Eq. (5) the finite element method was used.

As it is expected that the anisotropy of the material behaviour will show the most marked influence on the stress distribution in those planes which contain the direction parallel to the grain orientation as well as the direction perpendicular to it, a two dimensional computer program is used which allows plane strain or plane stress calculations, where the material is orthotropic in the plane of consideration.

The viscoelastic behaviour of the graphite is considered according to Eq. (5) as dependent on one single creep function of the form of Eq. (2), neglecting the primary creep term. The anisotropy of thermal expansion is taken into account by choosing two different coefficients of thermal expansion for the principal direction of anisotropy and the directions perpendicular to it. The irradiation induced strains for the two directions are obtained as a function of neutron dose and temperature from experimental results, as given in Fig. 1, by interpolation.

### 4. Examples

As an example for the influence of the anisotropy of neutron induced dimensional changes on stress distributions and distortions of graphite reactor components, a plane section of a reflector block as shown in Fig. 2 was chosen. Fig. 2 gives the initial dimensions (unirradiated, temperature = 200 C) and the temperature distribution used for the calculations. The x-axis is the line of symmetry for the block as well as
for the temperature and flux distributions. The boundary conditions are therefore chosen so that for the line \( y=0 \) the displacements in \( y \)-direction are prevented whereas the displacements in \( x \)-direction are only restricted for the point \( x=50 \) cm, \( y=0 \).

The Young's modulus of the unirradiated material was assumed to be 7.5 \( \cdot 10^8 \) kPa/cm\(^2\). The creep coefficient for 600° C is 2.0 \( \cdot 10^{-12} \) (dyn cm\(^{-2}\))\(^{-1}\) (10\(^{20}\) n cm\(^{-2}\))\(^{-1}\), and the coefficients of thermal expansion are 1.9 \( \cdot 10^{-6} \) °C\(^{-1}\) for the direction parallel to the grain orientation and 3.4 \( \cdot 10^{-6} \) °C\(^{-1}\) perpendicular to it. The neutron induced dimensional changes given in Fig. 1 belong to a highly anisotropic graphite. This material behaviour was chosen for the example in order to obtain a distinct difference of the irradiation strains for the main axes of anisotropy.

The neutron flux, \( \Phi \), was assumed to decrease exponentially in \( x \)-direction according to

\[
\Phi = 5.0 \cdot 10^{13} \cdot e^{-0.118x} \text{n/(cm}^2\text{sec)} \quad (\text{EDN})
\]

The results given in Figs. 3 to 6 were calculated for the point in time where the neutron dose for \( x=0 \) reached the value of 4.5 \( \cdot 10^{21} \) n/cm\(^2\).

Figs. 3 to 6 show the distortions of the block and the distribution of the maximum principal stresses calculated under the assumption that the material is isotropic with the properties valid for the direction parallel to grain orientation (Figs. 3a and 3b) and perpendicular to it (Figs. 4a and 4b). Figs. 5a and 5b give the corresponding results for the anisotropic material with grain orientation parallel to the \( x \)-axis and Figs. 6a and 6b with grain orientation parallel to the \( y \)-axis.

Whereas the distortions reflect clearly the influence of the different assumptions concerning the material behaviour, the stress distributions are very similar for those isotropic and anisotropic cases for which the material properties in \( y \)-direction agree. This is due to the fact that for the assumed flux distribution, the stresses are mainly generated due to the neutron induced shrinking in \( y \)-direction.

As a further example for the influence of the orientation of the material properties with respect to the flux distribution, the maximum principal stresses calculated for a rectangular section are given in Fig. 7 and Fig. 8. The line \( y=0 \) was again supported in a manner that displacements in \( y \)-direction were prevented. Material properties and flux distribution are the same as for the previous example. The temperature was assumed constant.
at 1000° C. The neutron dose at x=0 for the calculations was again $4.5 \times 10^{21}$ n/cm$^2$.

Fig. 7 shows the distribution of the maximum principal stresses for the anisotropic material with grain orientation parallel to the x-axis; Fig. 8 gives the stress distribution if the grain orientation includes an angle of 45° with the x-axis. The results show considerably lower stresses for the 45° orientation.

5. Conclusions

The reported results indicate that the anisotropy of the material behaviour and especially of the neutron induced strains shows an effect on the stresses in graphite components subjected to neutron irradiation which depends strongly on the orientation of the material properties with respect to the flux distribution and the existing boundary conditions. For materials with marked anisotropy, the magnitude of the stresses during reactor operation can be considerably influenced by an appropriate choice of the grain orientation in the component.

References


Fig. 1: Neutron induced dimensional changes for a needle-coke graphite.

Fig. 2: Reflectors-block: Temperature distribution
Fig. 3a: Dimensional changes of the block for isotropic material with properties "parallel to grain orientation" according to Fig. 1.

Fig. 3b: Distribution of maximum principal stresses for isotropic material, "parallel to grain orientation".

Fig. 4a: Dimensional changes of the block for isotropic material, "perpendicular to grain orientation".

Fig. 4b: Distribution of maximum principal stresses for isotropic material, "perpendicular to grain orientation".
Fig. 5a: Dimensional changes of the block for anisotropic material. Grain orientation parallel to the x-axis.

Fig. 5b: Distribution of maximum principal stresses for anisotropic material. Grain orientation parallel to the x-axis.

Fig. 6a: Dimensional changes of the block for anisotropic material. Grain orientation perpendicular to the x-axis.

Fig. 6b: Distribution of maximum principal stresses for anisotropic material. Grain orientation perpendicular to the x-axis.