COMPRESSIVE BEHAVIOUR OF ACS TORPEDO BRICKS

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INTRODUCTION

In torpedo ladles of the steel industry the shell constrains thermal expansion of refractories and compressive stresses develop in the bricks [1, 2]. If the refractories response is stiff, spalling can occur. A soft material can develop irreversible plastic strains, which cause joint opening and penetration during consecutive cooling and filling cycles. Both spalling and joint penetration are out-comes of one and the same thermo-mechanical process. This process is influenced by a number of factors, many of which are plant specific. These include the duration of the filled and idle phases of the service cycle, temperature in the shell and refractories and the shell geometry. It is not so inconceivable that the same material will fail due to spalling at one plant, and will have joint wear and penetration at another. In these conditions the process of the material selection demands a special approach. This paper illustrates an attempt of systematic investigation of ACS bricks used in torpedo wear linings. The investigation involves determination of material properties, compressive strain quantification in post mortem analysis and computer modelling. The main purpose of the paper is to discuss utilised analysis approaches.

EXPERIMENTAL PROCEDURE

Several qualities of ACS materials are investigated. Test results discussed in the paper are obtained on a resin bonded sinter Bauxite quality with additions of metallic anti-oxidants.

The coefficient of thermal expansion (CTE) is measured in an Anter 1161 Dilatometer (Argon, 4 K/min). Flexial dynamic E-modulus is measured at the Department of Ceramics, University of Leoben using RFDA impulse excitation measurements system supplied by IMCE (3 K/min, 10 % CO 90 % CO2, 25x12x72 mm). Polished samples are analysed using Zeiss optical microscope and the software AxioVision.

Compressive tests are performed on Zwick 250 test frame on samples immersed in coke particles. The displacement is measured at the cross-head. That is calibrated with filler arm extensometer measurements performed with ACS samples at room temperature and with "white" refractories at higher temperatures. The sample is heated with the rates of 4 K/min and the constraint of 100 N. Stress-strain measurements are conducted with constant rate of either 0,002 mm/sec or 0,02 mm/sec. The latter rate is used to reach the aimed creep stress. During the creep test deviations from an aimed constant stress are +/- 7 Pa. Cylindrical plan-parallel polished samples with the diameter of 30 mm and the height of 50 mm are used. To support the test results samples of other geometries (30 mm/75 mm and 50 mm/50 mm) are tested. In agreement with [3] the only significant differences between the geometries are found in the post-failure part of the stress-strain curve.

RESULTS AND DISCUSSION

Material behaviour

The tests are to deliver information on the material behaviour in the whole service temperature range and under various loading conditions. In this respect the combination of the continuous measurements (CTE, dynamic E-modulus) conducted in wide temperature range with loading tests performed at certain key temperatures seem to be of especial use.

Green ACS material shows very non-linear response to the rising temperature (figure 1). Below 1100 ºC the changes in the material are caused mainly by the changes in the binder. In this interval the maxima on the CTE curve correspond with the minima of the dynamic stiffness and vice versa. Above 1100 ºC simultaneous stiffening and increase in CTE is observed and attributed to the transitions of anti-oxidants.

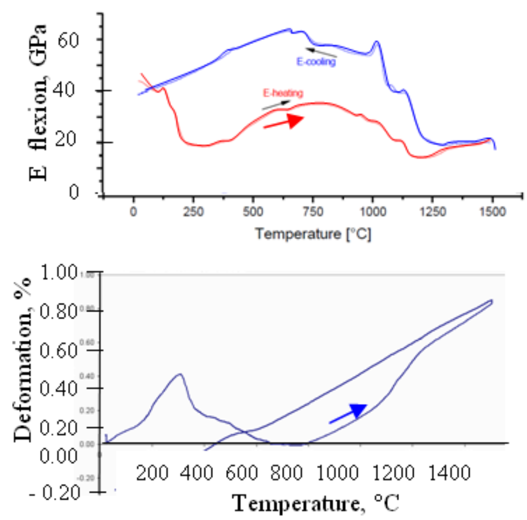

Fig. 1 Dynamic Young's modulus (a) and thermal expansion (b) of green ACS brick.

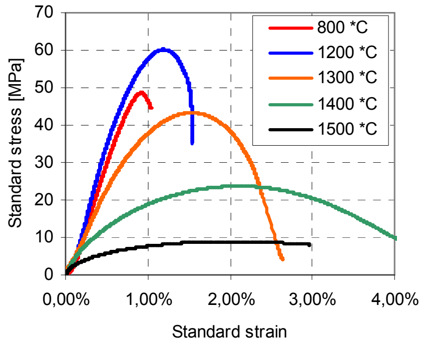

Fig. 2 Compressive curves of ACS brick, the loading rate is 0,002 mm/sec.

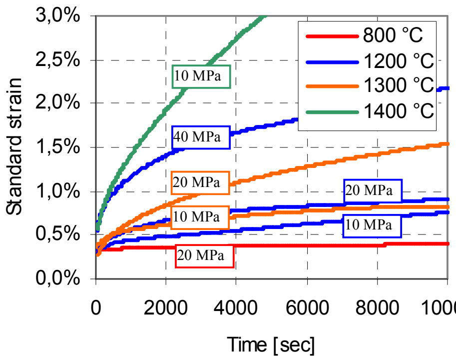

Fig. 3 Compressive creep strain of ACS brick, the strain at 0 sec is the strain developed during the loading to reach the stress of the creep test.

In compressive loading (Table 1, figure 2) the stiffest material behaviour and the highest strength values are registered at RT and at 1200 ºC. Above 1200 ºC the weakening of the material is observed. It is remarkable that the weakening is not seen in the dynamic measurements. Apparent static Young's modulus (Table 1) is calculated from the slope of the stress-strain curves between 30 and 70 % of the maximal force. In this part of the curve the material behaviour is already influenced by micro plastic events, which are responsible for the greater part of the deviation between the static and dynamic moduli [3, 10]. Material stiffness can be influenced by viscous flow or creep, when compressive strain grows under constant stress. Viscous behaviour can be measured in a direct test [4-6] or indirectly by performing stress-strain measurements with different loading rates [7]. No effect of the loading rate is seen in the tests conducted at RT and 300 ºC (Table 1). The tests at 800 ºC and especially those at 1400 ºC show that higher loading rates deliver higher Young's moduli. Slow loading rate promotes the viscous flow which results in lower apparent material stiffness. The material strength stays un-affected by the rate even at the higher temperatures.

There are three factors influencing the creep – temperature, stress and time. Parameters for the direct creep tests (figure 3) are chosen so that the test would simulate the loading conditions of a torpedo. In a torpedo the brick is exposed to the stresses of several dozens MPa [2] which develop during relatively short time interval when the torpedo is filled. The material starts to creep in the range of 800-1000 °C. Above 1200 °C it develops very significant creep rates, e.g. $1*10^{-6}$ 1/sec at 1300 °C/20 MPa, $3*10^{-6}$ 1/sec at 1400 °C/10 MPa. Higher stresses results in more intensive creep. All the creep curves show primary and secondary creep regimes, which are characterised, respectively, by decreasing and constant strain rates. Some samples also enter the ternary regime, recognised by growing strain rates. Upon cooling these samples are found to be cracked. An attempt is undertaken to assess the creep activation energy needed to define the material behaviour in computer models (figure 4). Used methods are described in [8].

Compressive strain quantification

To quantify the compressive strains sustained by the material in service a final strain quantification method (Fry method) is used [9]. The technique involves determining particle centres which were originally statically nearest neighbours, finding nearest neighbour

Table 1 Results of compressive stress-stain measurements of ACS brick.

	30-70% Young's modulus [GPa]		Strength [MPa]	
	0,002 mm/sec	0,02 mm/sec	0,002 mm/sec	0,02 mm/sec
20 °C	**7,9**+/-0,4	**8,1**+/-0,7	**55**+/-1,8	**52**+/-1,2
300 °C	2,3	-	34	-
800 °C	7,3+/-1,2	9,6+/-1,9	49+/-2	51+/-3,2
1200 °C	7,4+/-1,6	8,4	60+/-4,2	58
1300 °C	4,2	-	44	-
1400 °C	**2,3**+/-0,4	**4,5**+/-0,6	**23**+/-1,5	**20**+/-0,8
1500 °C	2,1	-	10	-

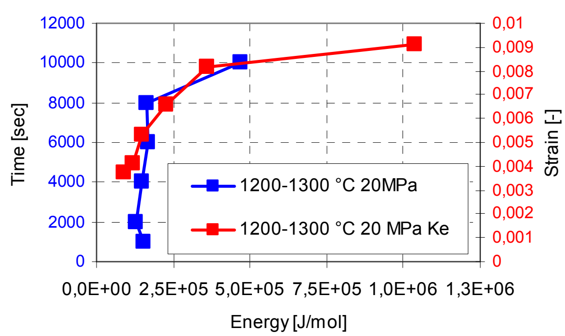

Fig. 4 Creep activation energy of ACS brick: blue curve – standard method, red curve – Ke's method [8].

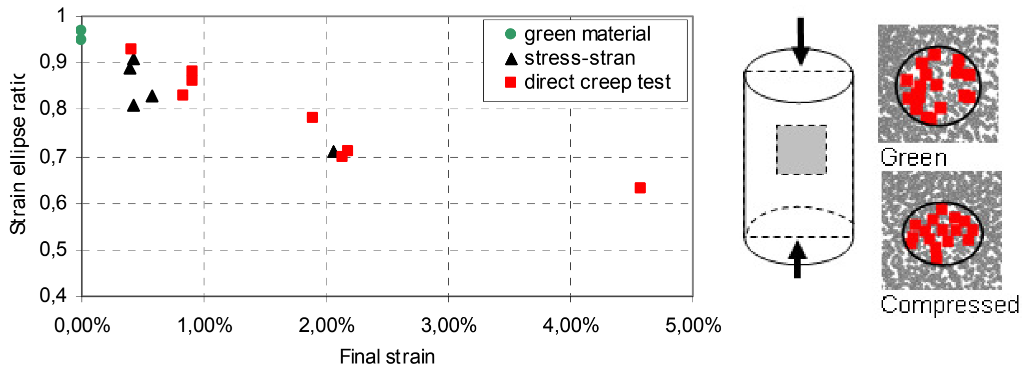

Fig. 5 Correlation between the ratio characterising the position of the grains and the maximal strains registered during the compressive tests of ACS bricks.

tie lines, and analysing the changes of length of these tie lines. In the ACS material bigger Bauxite grains (d > 1 mm) are used as the structural element to measure the deformations. At first, measurements of the un-compressed and compressed laboratory samples are performed. A sample is cut along the main axis and the surface image is obtained and processed. In un-compressed samples the grain centres forms a circle (figure 5). In compressed samples an elliptic form is observed. The shorter axis of the ellipse corresponds with the axis of compression. The ratios between the ellipse axes, that parallel to the direction of compression to that perpendicular to it, are charted against the maximal strains measured during the compression test. In spite of some data distribution there is a clear correlation.

The obtained correlation is used to assess the condition of a brick taken during demolishing of an old torpedo lining. The brick is of the same quality as the samples measured in the laboratory. Near the hot face brick samples showed an ellipse with the ratio of 0,83. The longer axis of the ellipse is directed towards the hot face, which means that the compressive thrust is directed parallel to the hot face. Samples from the middle and the cold end of the brick have the ellipse ration close to 1. For the comparison a new brick of the same format is measured. In the new brick in all three locations the ratio is about 1. The measurements are repeated with another face of the brick, which is also perpendicular to the hot face. The results are quite similar. The ratio at the hot face was 0,81.

From the ratio values obtained from the old brick and the diagram of figure 6 one can conclude that the brick near the hot face experienced the strain of about 1 %. This result will be compared with the results of the model, which is being constructed at the time the paper is written.

Numerical FEM modelling

Creep behaviour is introduced into computer models to investigate the wear mechanisms and to choose the material most suitable for the specific torpedo (design and service conditions). Behaviour of ACS bricks is compared with "white" non-carbonaceous refractories. In this chapter, results of a model featuring phosphate bonded Bauxite brick are given. The material has static Young's modulus of 5-10 GPa, the strength of about 55 MPa, CTE of about 5*10-6 1/K and heat conductivity of about 2,2 W/m/K. At 1100-1200 ºC material transforms to viscous condition.

A unit-cell model is built using the software ANSYS. It features the steel shell, the wear and back-up (fire-clay brick) lining. The wear lining material behaviour is described by combining creep with compressive failure and following plastic flow (figure 6). The creep is described by the time hardening model:

$\dot{\varepsilon}_{cr} = a*\sigma^b*t^c*e^{(-d/T)}$,

where $\dot{\varepsilon}_{cr}$ – creep strain rate, σ - equivalent stress, t – time, T – temperature. The material constants (a, b, c, d) are determined by fitting the creep test data. Different sets of constants define the creep at different temperatures. Available test data is not enough for direct determination of the creep constants, which would be an option preferred to fitting. E.g. creep activation energy (related to the constant d) can only be reliably calculated for the range 1200-1300 ºC (figure 4).

The modelling results (figure 6) demonstrate that the danger of joint opening realises when the hot face of the torpedo cools below 1240 ºC. Besides the creep strains, the shell temperature influences the joint opening. During the service the shell heats up and expands. The shell temperature is hardly affected by the thermal cyclic variations on the hot face.

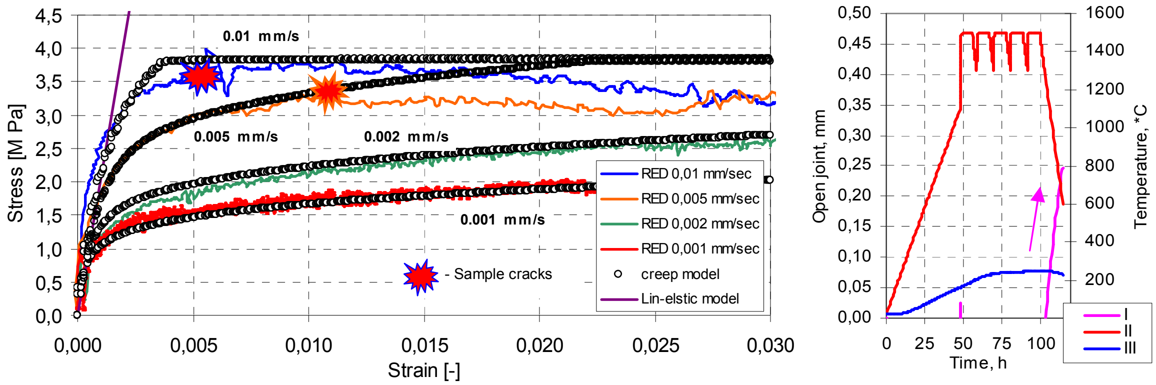

Fig. 6 FEM modelling of creep (a) lab compressive tests at 1400 °C and their simulation, the parameters of the model were obtained by fitting the stress-strain curve of 0,01 mm/sec, all other calculated curves were predictive, (b) results from computer unit cell model of 300 t torpedo, I – joint opening at the hot face, II – Temperature at the hot face, III – temperature at the shell.

when the hot face cools expansions mismatch occurs in the shell and refractories and the joints open. In this situation replacing the non-carbonaceous Bauxite bricks with ACS will have a negative effect. The conductivity of the latter bricks is 3-4 times higher than that of the "white" bricks. The introduction of ACS bricks will cause higher shell temperatures and shell displacements. In ACS lining the joint opening is predicted to be twice of that in the non-carbonaceous lining, provided that the back-up lining is the same in both cases. Adjustments of the back-up lining to compensate for the higher conductivity of ACS should be supported by careful analysis. More insulating back-up lining will raise the temperatures in the wear-lining and, potentially, increase the creep. In this case measures need to be taken to reduce the creep effects.

CONCLUSIONS

The wear of the torpedo lining due to compressive loads is determined by the material behaviour, the vessel design and plant specific service parameters. The material behaviour has very non-linear nature. At higher temperatures material stiffness is not only influenced by the temperature, but also by the loading rate and the level of stress. The material strength does not seem to be influenced by the loading rates. Material constants to describe creep in FEM models can be obtained by fitting stress-strain curves of different loading rates. Direct determination of the creep constants is difficult as great amount of test data and high quality equipment is needed for the purpose. To validate modelling results quantitative strain measurements techniques can be used. These techniques are used in various fields of material science. More research is needed to guaranty their successful utilisation in refractories engineering.

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