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Fracture energy and thermal shock damage resistance of refractory castables containing eutectic aggregates

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Abstract

One of the main reasons to investigate fracture energy of refractory castables is their need for superlative performance in resisting to thermal shock damage, which is one of the most crucial thermomechanical requirements in face to their industrial application. The fracture energy depends on toughening mechanisms, which will vary according to the material's microstructure. Considering this, the addition of eutectic electrofused aggregates is an interesting choice to increase toughness, since eutectic microstructures can deflect cracks during the fracture process. In that case, the crack deflection is likely to occur inside the aggregates during the transgranular fracture, which would increase the fracture energy. In the work herein, castables containing eutectic electrofused aggregates were investigated by the means of a comparison to blank materials, based on aggregates of white electrofused alumina. The fracture energy results were sensible to the variation of aggregate type, pointing out that the eutectic ones have a better performance regarding thermal shock damage resistance.

Keywords: C. Thermal shock; Castable; Refractory; Eutectic; Fracture energy

1. Introduction

Fracture energy can be defined as the necessary energy to generate two new surfaces (a crack) per projected unit of area in a material. Thus, it would be wise to consider that the higher the fracture energy is, the higher is the thermal shock damage resistance of a material. The reason for that is the fact that a crack would have more difficulty to propagate in the material. In fact, a linear relation can be observed in the following equation for the parameter R'''':

$$R'''' = \frac{E\gamma_{\mathrm{WOF}}}{{\sigma_f}^2}, \qquad (1)$$

where γ_{WOF} is the fracture energy, σ_f is the tensile strength and E is the Young's Modulus. R'''', known as the parameter for thermal shock damage resistance, was introduced by Hasselman [1,2]. The higher the R'''', the better the thermal shock damage resistance of a material.

Considering the refractory ceramics area of knowledge, an interesting question would aim to discover how to enhance fracture energy in refractories. A possible answer for that could be to use eutectic microstructures because of their high number of interfaces between phases, which would increase the probability of a propagating crack to be deflected. Fig. 1 illustrates a crack that propagated through an eutectic microstructure of mullite–zirconia. It demonstrates that the crack finds many interfaces and encounters mullite and zirconia alternately. In the reference [3], other examples of this phenomenon and many applications for eutectics ceramics can be found.

Based on the subjects introduced up to this point, the concern of the current work is to investigate the fracture energy and the thermal shock damage resistance of eutectic aggregates containing refractory castables. It is important to

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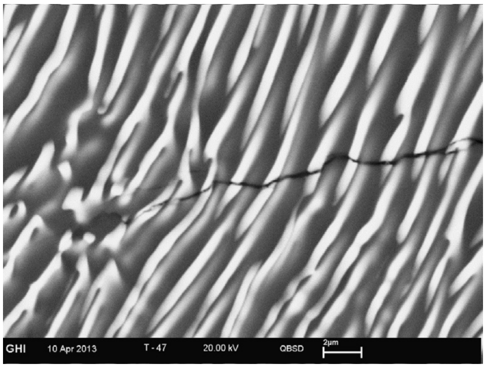

Fig. 1. A crack that propagated through an eutectic microstructure of mullite–zirconia.

address that the fracture energy was characterized by applying the wedge splitting test, which is suitable for testing refractory materials, according to Harmuth et al. [4,5]. Furthermore, the experimental thermal shock damage results were compared to R''''-values, in order to verify how good that correlation is.

In the following sections, a brief review of fracture mechanics is presented in order to contextualize the results.

1.1. Basic concepts about toughening in ceramics

A material is considered brittle if a crack propagates through it with almost no plastic deformation. Usually, at catastrophic failure, the elastic energy released during the fracture exceeds significantly the material's capacity to convert it into surface energy. In other words, if a brittle material is mechanically loaded to a point that a crack starts to propagate and, if the loading rate is kept constant, the crack is most likely to propagate unstably. In such cases, toughening mechanisms are desirable to shorten crack propagation. Therefore, the fracture energy, γ_{WOF}, represents all the consumed energy by mechanisms that act in order to produce two new surfaces.

According to Sakai and Ichikawa [6] γ_{WOF} can be represented by the following expression:

$$\gamma_{WOF} = \gamma_0 + \gamma_P + \overline{\Delta\gamma}, \tag{2}$$

where γ_0 is the energy consumed to break the chemical bond between atoms or ions; γ_P is the energy consumed by plastic micro deformations at the crack tip, which is not significant in ceramics at room temperature; and $\overline{\Delta\gamma}$ is the energy consumed by the crack due to its interaction with the material's microstructure.

If one considers the Griffith's Theory of Fracture [7] and Irwin's modification [8], the terms γ_0 and γ_P take part on the K_{IC} equation below:

$$K_{IC} = \sqrt{2(\gamma_0 + \gamma_P)E}, \tag{3}$$

where K_{IC} is the critical stress intensity factor at the flaw tip. In that case, the flaw is elliptical and passes through the thickness of a long plate shaped-like specimen.

As aforementioned, ceramic materials have a non-significant γ_P. Therefore, the term in brackets in Eq. 3 is more closely related to toughening at crack initiation than at crack propagation. If a material that contains a flaw is mechanically loaded to a point at which the K_{IC} value is reached, the crack initiates its propagation. Hence, in ceramics, if the elastic strain energy release rate, G, is higher than the absorption rate as surface energy, the crack tends to propagate unstably. Therefore, it is up to the toughening mechanisms (represented by $\overline{\Delta\gamma}$) to play their role after the crack initiates propagation.

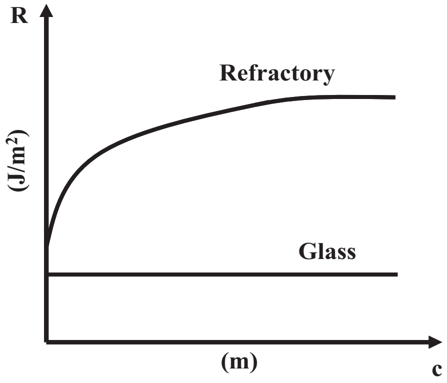

Fig. 2. Schematic examples of typical *R*-curve shapes for glasses and ceramic refractories.

The importance of accounting for $\overline{\Delta\gamma}$ in the equation of γ_{WOF} becomes evident when R-curves of glassy materials and ceramic refractories are compared to each other. The *R*-curve test [9,10] determines the variation of the crack propagation resistance, *R*, as a function of the crack length, *c*. A crack propagates when G equals the crack resistance energy, *R*. In order to obtain the *R*-curve, a condition for crack propagation stability must be fulfilled, which is $\partial G/\partial c \leq \partial R/\partial c$ [8], in which *c* is the crack length. Typical *R*-curve shapes for glasses and refractories are presented in Fig. 2.

By looking at Fig. 2, it is possible to notice that the crack propagation resistance, *R*, of a refractory increases as a function of c until it reaches a constant value. The same, however, is not observed in the case of a glass, whose *R*-curve is flat, which means it does not depend on the crack length. The main reason for these two materials to behave in such different ways is the fact that refractories have microstructure constituents and glasses do not. By defining that $G = K_I^2/E$ [8], where K_I is the stress intensity factor at crack tip, and considering that $G = R$ during stable crack propagation, it is observed that K_I increases as a function of c in refractories, but it is constant for glasses (E was assumed to be constant for both types of materials). Moreover, it is clear that *R* increased due to extrinsic factors, such as the interactions of the crack with the refractory microstructure. Depending on the microstructure type and on its phases, several toughening mechanisms can be activated during the crack propagation in a material. Hence, when the refractory's *R*-curve reaches its plateau, it signifies that the toughening mechanisms activation rate is constant and the consumed energy rate, by the propagating crack as a function of *c*, is a constant. It must be mentioned that there are other types of rising *R*-curve shapes and the example in Fig. 2 should not be taken as a rule [11].