Improvement of Digital Image Correlation for the analysis of the fracture behaviour of Refractories

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Abstract:

Refractories are heterogeneous materials designed to operate in harsh working environments which sometimes lead to their premature failure. Therefore, it is necessary to enhance their properties to ensure consistent furnace performance and operator safety. Among these properties, the thermal shock resistance of refractories is a parameter of significant interest which is known to be closely related to their mechanical behaviour. In fact, an existing network of micro-cracks within the microstructure of refractories often leads to non-linear phenomena around the crack tip which are beneficial for their crack propagation resistance and thus, their thermal shock resistance.
In this work, industrial refractory materials with a non-linear mechanical behavior, as magnesia hercynite, were chosen in order to highlight their fracture behaviour. Experimental tests are today commonly analysed with the help of DIC method which allows to easily provide the displacement field and, then, the strain field after post processing. Nevertheless, for application to fracture analyse, the data obtained by classical DIC can lead to some drawbacks since the assumptions of flow continuity and homogenous material transformation could be not strictly respected locally. In fact, in such case, several errors can appear in the vicinity of the crack. Therefore, the aim of this paper is to present a new DIC technique which has been specifically adapted to the studies of local discontinuities in refractories. In this purpose, this new DIC method, called 2-Parts DIC (2P-DIC) has been improved to take into account the potential local occurrence of such discontinuity. The material transformation, usually assumed homogeneous inside each subset for classical DIC, is thus here more complex and a discontinuity of displacement should be taken into account. Thus, each subset which is crossed by a crack can be cut in two parts with different kinematics. By this way, it is possible to automatically find the fracture paths and follow the cracks geometries (length, opening). Performances of this new procedure will be discussed in this paper and experimental Brazilian test commonly applied to refractories will be presented.

Mots clefs :

DIC, Optical technique, Refractories, Experimental Mechanics, Fracture

1 Introduction

Thermal shock resistance of refractory materials is among crucial properties that interest refractory researchers and industrials. Magnesia spinel materials present a complex microstructure made from a magnesia matrix and spinel inclusions which have different thermal expansion coefficients. During material processing, a network of micro-cracks is generated and allows improving the flexibility i.e. the strain to rupture and also increasing thermal shock resistance [1-5]. Stress-strain behaviour in tension is non-linear, depending on the degree of initial micro-cracking induced within the microstructure. This specific behaviour is a key point to enhance level of strain-to-rupture for a better accommodation to high level of strain. Among the different kind of spinel inclusions which can be introduced in the magnesia matrix to promote microcracks, the hercynite natural one (FeAl2O4 or iron aluminate spinel) has been chosen here.

Magnesia-Hercynite bricks are used in cement rotary kilns as a refractory lining. In operating conditions, the bricks are subjected to thermal shocks that induce not only compressive but also tensile loads which are critical for brittle materials. It is thus pertinent to investigate the tensile behaviour. Brazilian test (diametrical compression) is an indirect test which allows to investigate the tensile behaviour by limiting difficulties in sample preparation and in load alignment required for direct tensile test on brittle materials. The application of a vertical diametrical load on a cylindrical sample induces tensile stresses in the perpendicular direction that leads to the failure in the central part of the sample [6-11]. Brazilian test is not very well suited for the stress-strain law characterization because the mechanical fields are not homogeneous in the sample. It is also necessary to use full-field measurement techniques to achieve kinematic fields.

In the last 30 years, Digital Image Correlation (DIC) has shown to be a valuable non-contact technique for measuring kinematic fields on the surface of samples in many experimental conditions [1], [12-15]. Nevertheless, a refined study of fracture mechanisms from data obtained by classical DIC is difficult due to the assumptions of flow continuity and homogenous material transformation which could not be strictly respected locally. As such, several errors can appear in the vicinity of the crack [21].A first improvement of DIC algorithm consists in defining a mask along the crack and adapting the subset shape and size automatically to avoid the crack area.[21-23]. A second solution is to introduce a new material transformation with a displacement jump. A subset can be split in two parts with different kinematics [24-25]. The aim of this paper is to present principle and performances of a new local DIC technique based on the split approach, specially adapted to study local discontinuities in refractories (crack orientation close to vertical, brittle material which allows to decrease calculation time). Furthermore, an originality of our approach is an automatic crack length calculation. In this new method named 2-Parts DIC (2P-DIC), the material transformation, usually assumed homogeneous inside each subset for classical DIC, can take into account a discontinuity of displacement: each subset crossed by a crack can be divided in two parts with different kinematics. In the present study, 2P-DIC has been combined to Brazilian test. By this way, it is possible to automatically find the fracture paths and follow the cracks geometries (length, opening). An application example of this new procedure will be discussed in this paper and different aspects have been studied such as crack's initiation and its propagation in order to evaluate energy release rate which allows an indirect characterization of thermal shock resistance.

2 Experimental Protocole

2.1 Material

In this paper, only magnesia hercynite refractory materials developed for cement rotary kilns are studied through the use of Brazilian test combined with Digital Image Correlation. Materials have been provided by RHI through a FIRE (Federation for International Refractory Research and Education) research program dedicated to dense refractories with enhanced flexibility for thermal shocks. Hercynite ($FeAl_2O_4$) aggregates are introduced in the magnesia (MgO) matrix to improve the flexibility of the material [16]. During the cooling stage after sintering, a network of micro-cracks appears because of the differences of thermal expansion coefficient between hercynite (8.3 10^{-6} K^{-1} in the 20-1000°C domain) and magnesia (13.7 10^{-6} K^{-1} in the 20-1000°C domain) [17]. By this way, the strain to rupture is enhanced and a non-linearity is introduced in the stress-strain law.

2.2 Brazilian test

Brazilian test was originally developed to determine the quasi-static tensile strength of concrete materials [18], [19]. As shown in Figure 1, a thin disk (typically 50mm in diameter and 10 mm in thickness) is vertically compressed by an imposed displacement speed. Stress fields in the sample are heterogeneous: the area close to the contacts (bottom and up) are mainly in compression whereas the central part is loaded by tensile stresses. In this zone, stresses are quite uniform along the vertical diameter and maximum stress is observed in the middle of the sample, leading to the final vertical mode-I rupture [11], [20] [21].

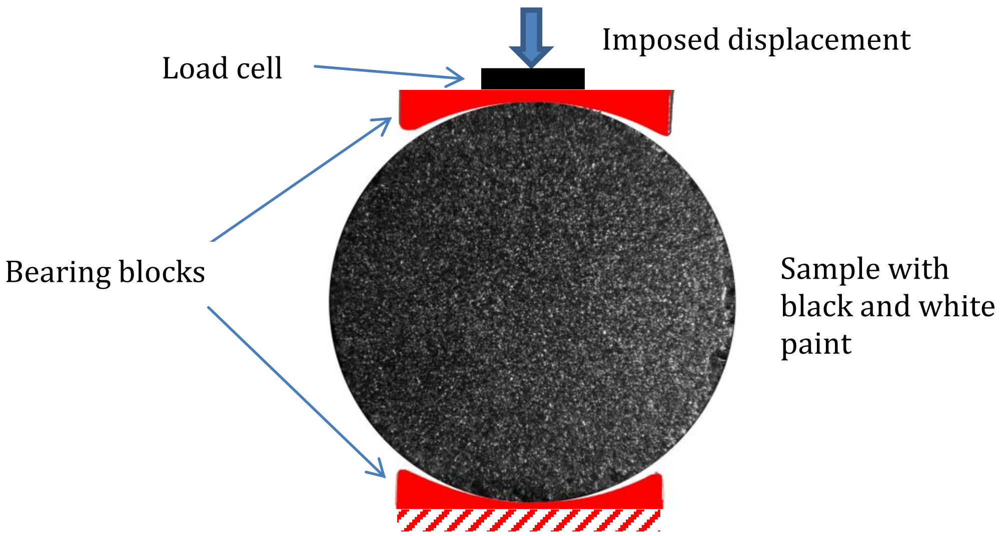

Figure 1: Principle of Brazilian test

2.3 2-Parts Digital Image Correlation

The new DIC technique, named two-parts DIC (2P-DIC) has been especially developed to detect the presence, the position and the opening of cracks in refractory brittle materials with a preferential direction of crack propagation (here vertical). As the studied material is considered to be quasi-brittle, the local displacement gradients can be neglected and only rigid-body displacements are calculated. It is based on the same principle of usual local DIC [20, 21], which consists in matching initial and final

2D images linked by a plane material transformation ϕ. ϕ is locally searched as an affine transformation at each point of a regular grid defined in the reference image. The best values of parameters of this transformation, i.e. two components of displacement and four components of local gradients, are obtained for the best resemblance of grey levels between initial and deformed subsets by an iterative Newton scheme [19]. A bi-linear interpolation of grey levels of deformed image is used in order to overcome the discrete features of digital images.

In 2P-DIC, each subset D (of size n by m pixels) is divided at the position x=XC in two parts D1 (x < XC) and D2 (x > XC) as shown Figure 2 with an orientation θ of the boundary. The pixels of the boundary are not taken into account in the matching process. The matching also consists in searching the best values of XC, θ and material transformation parameters in each part Di.(i=1,2) which are different. For each value of XC varying by one-pixel step from -n/4 to n/4 and θ varying between -50° to 50°with a pitch of 10°, the same minimization process that for standard DIC is used to achieve the best estimation for each transformation. The values of XC smaller than -n/4 and larger than n/4 are not considered because they lead to a small part Di giving a displacement with an insufficient accuracy. This procedure is repeated on the whole image by shifting the subset with the pitches px and py. Where px is fixed to n/2 in order to bypass dead zones that cannot be analysed (XC $\in$[-n/4,n/4]) and py can be chosen equal to m to avoid recovery.

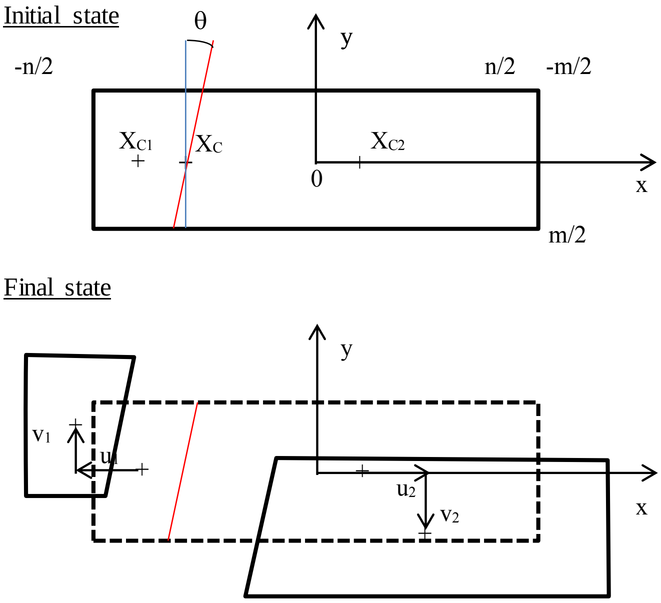

Figure 2: Approached material transformation on a 2P-DIC subset

2.4 Crack length measurement

The 2P-DIC method previously presented searches the best approximate discontinuous transformation in each subset of the grid of measurement points. The found solution is not always physical, in particular when images are noisy. It is also necessary to separate physical discontinuities to artificial ones by using a thresholding of the displacement differences between the two parts of the subset. This criterion can also be expressed in terms of strain: a pseudo strain can be calculated as the ratio between the initial distance between the centres of the two subset parts and the same distance evaluated in the deformed state:

$$\varepsilon = \frac{\sqrt{(XC_2-XC_1+u_2-u_1)^2+(v_2-v_1)^2}}{XC_2-XC_1} - 1 = \frac{2\sqrt{(n/2+u_2-u_1)^2+(v_2-v_1)^2}}{n} - 1 \quad (1)$$

Crack presence corresponds to local higher strain values. A threshold ε_L is set in order to extract the signal corresponding to reliable mechanical strains from fluctuations only due to 2P-DIC uncertainty. This threshold is also linked to material properties, as elastic limit for example. An automatic measurement of crack length can be done. So the naked eye evaluation currently used before is not useful now [26].
We have chosen to highlight this step with the help of the Brazilian test presented in the next section.

3 Results

Figure 3 shows the applied load curve versus time. The curve can be divided into several stages: The first one, time <260s, corresponds to the elastic domain of the mechanical behavior, the second one, between 260s to 360s, corresponds to the damage progression. The last one corresponds to the complete failure of the disk, which is divided in two parts.

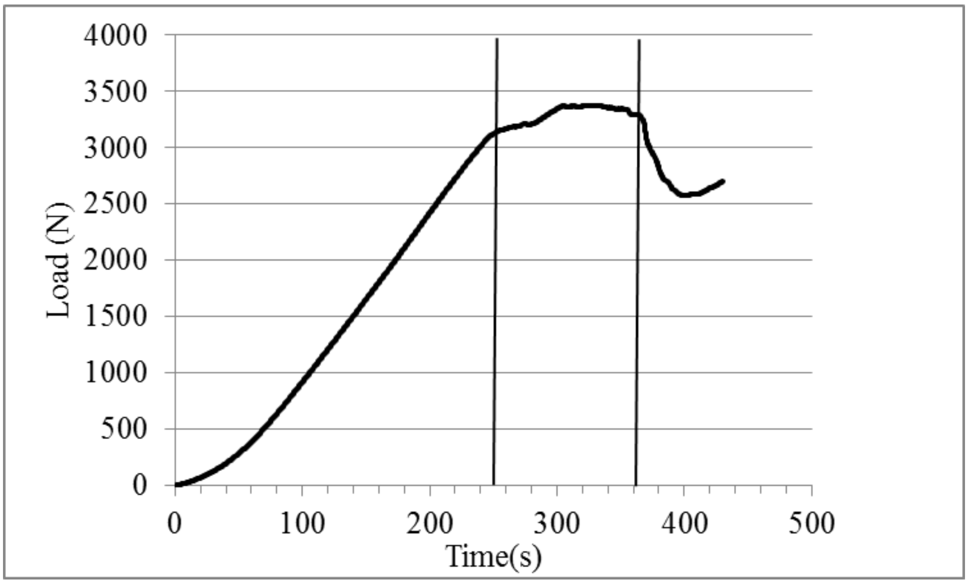

Figure 3: Load curve during Brazilian test on a magnesia hercynite refractory.

To study the damage propagation, the threshold ε_L has to be determined. As presented in the previous section, the choice is done by selecting a value superior to the measurement uncertainty. The 2P-DIC parameters are n=64 pixels, m=16 pixels, px=32 pixels and py=8 pixels. On Figure 4, we can see that a threshold equal to 0.001 is too small because non-physical cracks appear with the real ones. Then the length curve is noisy and overstated. For the next value 0.002, the same phenomenon occurs even if variations are smaller. ε_L=0.003 is a good compromise and the curve is less noisy. The next threshold values give close lengths but the procedure detects crack initiation with a lag for values of threshold higher than 0.003.

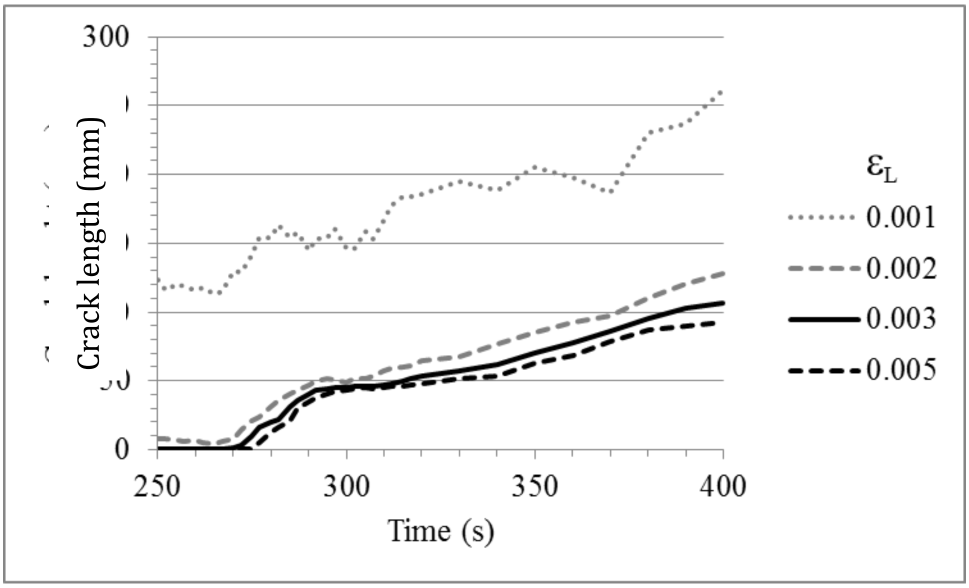

Figure 4: Crack length versus time for different threshold limits

Figure 5 represents the crack length versus time curve and Figure 6 gives the crack path by plotting the boundary lines between the two parts of the split subsets with a color given by the value of the pseudo strain. With the help of these two figures, it is possible to follow crack propagation during loading and to describe the mechanical behavior of the material

Before 270s, no crack is detected. The load curve of Figure 5 suggests that damage should occur 10 seconds before but it is not visible on the surface. At 270 seconds, a crack starts from the sample centre and propagates symmetrically close to vertical direction (Figure 6-a,b). We observe one crack with a propagation path driven by the microstructure. After 300s, the maximum load is reached; the crack tips are close to the bearing blocks (see Figure 6-c). Multiple tensile cracks appear in the vicinity of the contacts. The point (d) corresponds to the fracture of the disk in two halves.

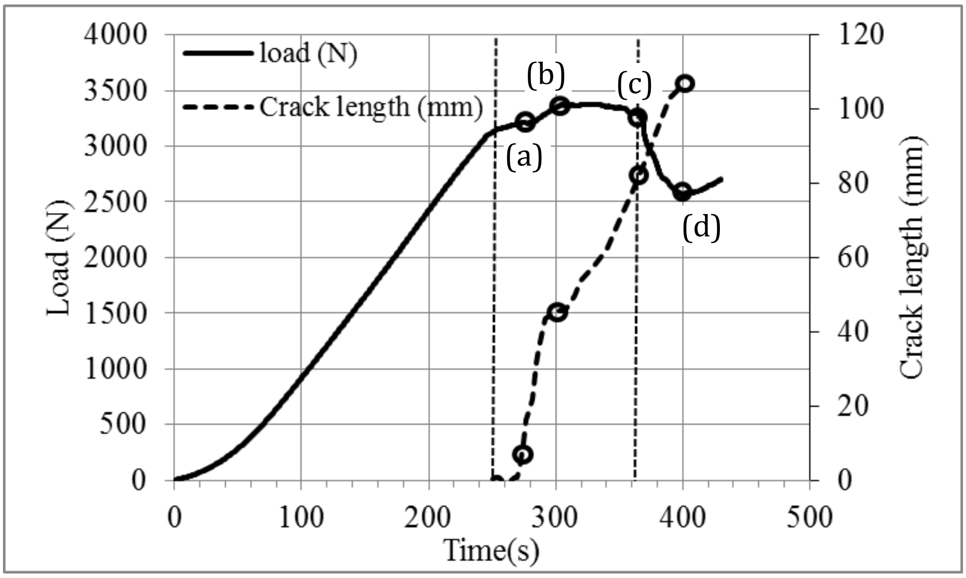

Figure 5: Load and crack length (for ε_L =0.003) versus time

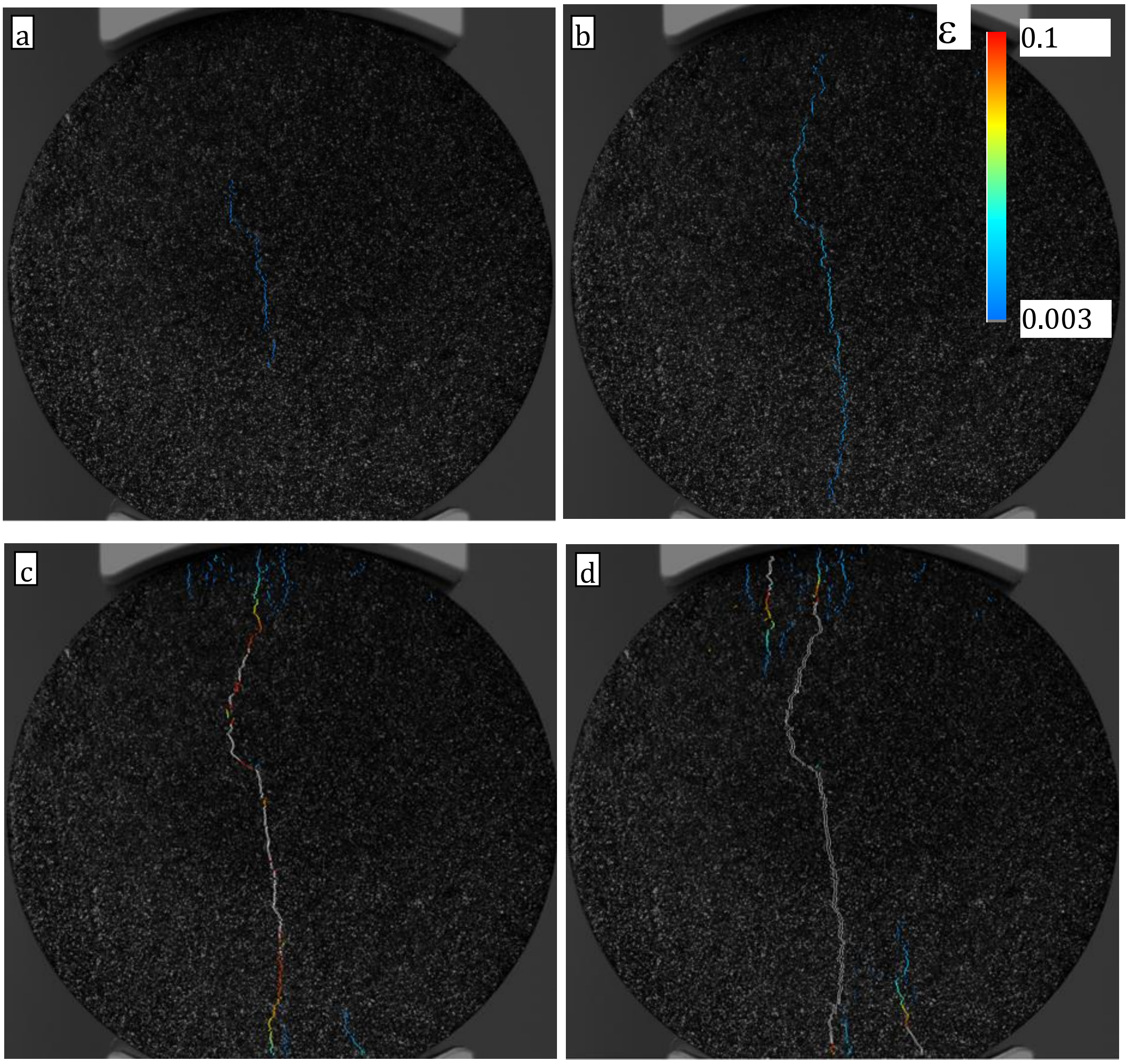

Figure 6: Visualization of cracks propagation and opening (pseudo strain ε) for ε_L =0.003

4 Conclusion

The new technique, 2P-DIC recently developed for kinematic field measurement with discontinuities is a promising tool for improving the understanding of fracture mechanisms in refractory materials. The obtained results highlighted in particular the efficiency of this new technique to detect the early presence of a crack and its path with an optimal spatial resolution. For the studied materials, it allows to underline that there is no multi-crack branching phenomenon. Besides, this optimized 2P-DIC method that allows to automatically determining the crack path with an interesting spatial accuracy, opens new way to correlate actual crack(s) length with the so-called specific fracture energy which plays a key role in the thermal shock resistance of refractories.

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