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Demonstrating the self-healing behaviour of some selected ceramics under combustion chamber conditions

A Farle, L Boatema, L Shen, S Gövert, J B W Kok, M Bosch, S Yoshioka, S van der Zwaag and W G Sloof

1 Department of Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628CD, Delft, The Netherlands
2 University of Twente, Laboratory of Thermal Engineering, PO Box 217, 7500 AE Enschede, The Netherlands
3 Graduate School of Engineering, Yokohama National University, 79-5, Tokiwadai, Hodogaya-ku, Yokohama, Japan
4 Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS, Delft, The Netherlands

E-mail: A.M.Farle@TuDelft.nl

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Abstract

Closure of surface cracks by self-healing of conventional and MAX phase ceramics under realistic turbulent combustion chamber conditions is presented. Three ceramics namely; Al₂O₃, Ti₂AlC and Cr₂AlC are investigated. Healing was achieved in Al₂O₃ by even dispersion of TiC particles throughout the matrix as the MAX phases, Ti₂AlC and Cr₂AlC exhibit intrinsic self-healing. Fully dense samples (>95%) were sintered by spark plasma sintering and damage was introduced by indentation, quenching and low perpendicular velocity impact methods. The samples were exposed to the oxidizing atmosphere in the post flame zone of a turbulent flame in a combustion chamber to heal at temperatures of approx. 1000 °C at low pO₂ levels for 4 h. Full crack-gap closure was observed for cracks up to 20 mm in length and more than 10 μm in width. The reaction products (healing agents) were analysed by scanning electron microscope, x-ray microanalysis and XRD. A semi-quantification of the healing showed that cracks in Al₂O₃/TiC composite (width 1 μm and length 100 μm) were fully filled with TiO₂. In Ti₂AlC large cracks were fully filled with a mixture of TiO₂ and Al₂O₃. And in the Cr₂AlC, cracks of up to 1.0 μm in width and more than 100 μm in length were also completely filled with Al₂O₃.

Keywords: combustion environment, ceramics, MAX-phase ceramics, self-healing

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years the possibility to oxidatively heal surface cracks in high temperature ceramics and metallo-ceramics and to restore mechanical strength at least once has been demonstrated in quite a number of laboratory studies [1–3]. In these laboratory studies relatively high oxygen potentials (comparable to those in heated air) and stagnant air were imposed and the samples were not exposed to any mechanical vibration during the healing treatment. These conditions differ significantly from the prevailing conditions (low partial pressure, very high gas flow velocities and extensive mechanical vibrations) in combustion chambers, where such self-healing ceramics are supposed to be used [4]. The work presented here describes the self-healing behaviour of three
grades of self-healing ceramics under realistic combustion chamber conditions. The materials to be tested are an extrinsic self-healing system (alumina containing TiC particles as healing agent) and two intrinsic self-healing metallo-ceramics (Cr$_2$A1C and Ti$_2$A1C), for which attractive self-healing behaviour under laboratory conditions had been demonstrated previously.

The early research on self-healing high temperature ceramics focussed on so-called extrinsic self-healing concepts, in which the crack filling reaction is due to the presences of discrete reactive particles homogeneously distributed in an inert ceramic matrix [4–6]. When a crack is formed in the matrix, the reactive particles in the path of the crack are dissected and oxygen from the environment flowing through the crack can react with the healing particle. In case the reaction product has a larger specific volume than the original particle the excess volume can fill the crack and restore mechanical contact between both opposing crack faces. In case the reaction product adheres relatively well to the matrix material, the filling of the crack not only leads to its sealing but also to the restoration of the tensile strength of the once broken sample. The early work focused on the use of SiC particles or fibres to heal Si$_3$N$_4$, mullite and alumina matrices [5, 7, 8] as SiC has a desirable oxidation behaviour leading to the formation of SiO$_2$ which has a good bond strength to many ceramic matrices. By using SiC particles with a size of about 0.3 μm the bending strength of Si$_3$N$_4$/SiC composites could be recovered more or less completely by heating between 900 °C and 1400 °C for 1 h in air. For the optimum healing temperature of 1300 °C the specimen fractured even outside the healed zone [5]. Similarly, surface cracks of diameter 100–200 μm in mullite were completely healed after heat treatment at 1300 °C for 1 h in air. The crack-healed zone even had a bending strength of 150 ± 30 MPa higher than that of the as received material [7].

The alternative approach to extrinsic self-healing systems in which the healing reaction is due to the intentional addition of a sacrificial phase is that of intrinsic self-healing systems in which the material itself can locally undergo healing reactions. In 2008 metallo-ceramic MAX phases, in particular Ti$_3$A1C$_2$, were shown to demonstrate significant self-healing when exposed to high temperatures in oxygen containing atmospheres [16, 17]. The underlying mechanism in the healing reaction is the selective oxidation of the A element in the MAX phases, such as Ti$_3$A1C$_2$ and Ti$_2$A1C as well as Cr$_2$A1C [16, 18, 19]. Cracks in Ti$_2$A1C MAX phase ceramics of up to some millimetres in length and about 5 μm in width can be healed by oxidation at 1100 °C in air within 2 h [17, 20] leading to full strength recovery. Also cracks running along the same path as previously healed cracks can be restored several times [17]. The healing is due to the extensive formation of Al$_2$O$_3$ in the crack with minor amounts of the weaker TiO$_2$ phase. Cr$_2$A1C MAX phase also shows good self-healing behaviour but the reaction rates are a bit slower. Yet the guaranteed absence of the weak TiO$_2$ in the healed cracks may lead to higher strength values for the healed material [21]. Hence Ti$_3$A1C and Cr$_2$A1C were selected for testing under combustion chamber conditions as both materials meet all requirements postulated for successful healing of crack damage [22], e.g. preferential oxidation and fast diffusion of the A-element, volume expansion upon oxidation and adhesion of the healing product to the matrix. As earlier studies [19, 23] on the MAX phase materials have shown that the healing kinetics and the mode of filling of the cracks depends on the grain size, Cr$_2$A1C samples were produced having two different average grain sizes. The influence of commonly present impurities, such as TiC and Ti$_4$Al, in Ti$_2$A1C are considered by producing MAX phases of different purity grades.

Apart from their self-healing potential MAX phases have interesting mechanical and physical properties, which make them interesting materials for combustion chambers: They are stable up to high temperatures and corrosion resistant [1–3, 24]. Their high thermal conductivity makes them thermal shock resistant [25] and their static strength is maintained up to high temperatures, above which creep will become the limiting factor [26, 27].

In the present work we will demonstrate the self-healing behaviour of three promising self-healing ceramics (alumina
Discs of the self-healing ceramics Al$_2$O$_3$, Ti$_2$AlC, and Cr$_2$AlC were directly synthesised by SPS using a graphite mould with an inner diameter of 20 mm under an Ar atmosphere or in vacuum. The Al$_2$O$_3$, TiC, Ti$_2$AlC and Cr$_2$AlC samples were sintered from ball milled powders, details can be found in table 2. Finally, the surfaces of the sample were ground using emery paper up to grit 4000, ultrasonically cleaned in ethanol and dried by blowing with pure and dry nitrogen gas.

2. Materials and methods

2.1. Synthesis

Discs of the self-healing ceramics Al$_2$O$_3$/TiC, Ti$_2$AlC and Cr$_2$AlC with a diameter of 20 mm and a thickness of about 5 mm were prepared by spark plasma sintering (SPS). The powders used to sinter the materials are listed in table 1. These powders were mixed with molar ratios specified in table 2 using a Turbula T2C Mixer (Willey A Bachofen, Switzerland), for 24–48 h using 5 mm alumina balls. The ball to powder weight ratio was about 3:1. The powder mixtures for Ti$_2$AlC and Al$_2$O$_3$/TiC were sintered directly in the SPS furnace (HP D 25 SD, FCT Systeme GmbH, Germany) using a graphite mould with an inner diameter of 20 mm under Argon atmosphere or in vacuum.

The Al$_2$O$_3$/TiC composite was sintered at 1500 °C in Ar and cooled naturally to avoid cracking due to thermal shock. Ti$_2$AlC samples were directly synthesised by SPS using the settings specified in table 2 and a heating rate of 80 °C min$^{-1}$. The experiments were performed in vacuum. Cr$_2$AlC was prepared by a two-step sintering process described elsewhere [28]. The coarse grained material was densified directly from pulverized pressureless sintered powder and fine grained sample was sintered from ball milled powders, details can be found in table 2.

2.2. Characterisation

The density of the sintered materials was measured with the Archimedes method using an analytical balance (Mettler Toledo AG-204, Switzerland) according to ASTM B 311-93 [29]. The Vickers hardness was determined by averaging the results from 10 to 50 N indents using a hardness tester (Zwick/Z2.5, Germany). The indents were created by loading the indenter with 5 N s$^{-1}$ and a holding time of 20 s.

The Al$_2$O$_3$/TiC composite was characterised using the x-ray diffractometer with a Lynxeye position sensitive detector and Cu K$_\alpha$ radiation. The phase purity of the MAX-phase samples was determined via x-ray diffraction using a Bruker D8 Advance diffractometer (Bruker, Germany) in the Bragg–Brentano geometry with graphite monochromator and Co and Cu K$_\alpha$ radiation. The recorded x-ray diffractograms were processed with Bruker software Diffrac.EVA 4.1 software.

Microstructure, crack morphology and crack filling were investigated using a scanning electron microscope (SEM), type JSM 6500F (JEOL Ltd, Tokyo, Japan) equipped with an energy dispersive spectrometer (EDS, type: ThermoFisher UltraDry 30 mm$^2$ detector) for x-ray microanalysis (XMA) and with Noran System Seven software package for data acquisition and analysis.

Finally the surfaces of the sample were ground using emery paper up to grit 4000, ultrasonically cleaned in ethanol and dried by blowing with pure and dry nitrogen gas.

### Table 1. Starting powders for synthesis and sintering.

| Powder | Purity (%) | Particle size (µm) | Supplier |
|--------|------------|--------------------|----------|
| Al$_2$O$_3$ | ≥99.99 | 0.2 | Sumitomo Chemicals, Japan |
| TiC | 98 | 4.5 | Alfa Easer, UK |
| Ti | >99.5 | 100 | TLS Technik GmbH & Co., Germany |
| Al | 99.8 | 45 | TLS Technik GmbH & Co., Germany |
| Cr | 99.2 | 100 | TLS Technik GmbH & Co., Germany |
| C (Graphite) | >99.5 | 6 | Graphit Kropfmühl AG, Germany |

### Table 2. Powder composition and sintering conditions for preparing the self-healing ceramics.

| Sample | Powder | Ratio | Temperature (°C) | Pressure (MPa) | Duration (min) |
|--------|--------|-------|-----------------|---------------|---------------|
| Al$_2$O$_3$/TiC | Al$_2$O$_3$ TiC | 0.8:0.2 mass % Al$_2$O$_3$:TiC | 1500 | 30 | 10 |
| Ti$_2$AlC-P | Ti Al TiC | 0.85:1:0.15 | 1400 | 50 | 30 |
| Ti$_2$AlC-LP | Ti Al TiC | 0.85:1:0.15 | 1400 | 50 | 60 |
| Cr$_2$AlC_FG | Cr Al C | 2:1:1.5:1 | 1250 | 50 | 60 |
| Cr$_2$AlC_CG | | | | | |
measured peak temperature \((T_p)\) is given by the Kissinger–Sunose–Akahira equation [30]:

\[
\ln \left( \frac{\beta}{T_p^2} \right) + \frac{E_A}{RT_p} = \text{constant},
\]

where \(E_A\) is the activation energy and \(R\) is the gas constant. The slope of a straight line fitted to the data points for \(\ln (\beta/T_p^2)\) versus 1/\(T_p\) yields the activation energy of the oxidation reaction. This relation is based on first order reaction kinetics, hence:

\[
k = A \exp \left( -\frac{E_A}{RT} \right),
\]

where \(k\) is the reaction rate and \(A\) the frequency factor. Earlier studies [31] have shown that a reaction rate, \(\ln k\), corresponding to \(-13\) generally leads to full healing of cracks of micron sized width within a time span of 1 h, whereas a value of \(-15\) requires 10 h.

2.3. Initiation of local crack damage

As a result of the large differences in hardness and toughness different methods had to be applied to the three materials selected to induce local cracks whose healing behaviour could be studied under the combustion chamber conditions.

In the case of the alumina–TiC composite material Vickers indentation (Zwick/Z2.5, Germany) at a load of 20 N were used to induce penny-shaped cracks. The relationship between the applied load and the length of crack generated was investigated; see figure 1. The indent size (2a) is defined by the average of the diagonals of the imprint made, whiles the crack length (2c) is defined as the average of the horizontal and vertical cracks formed in addition to the indent size. The fracture toughness was calculated to be 4.3 ± 0.1 MPa m\(^{1/2}\) [32]. This is slightly higher than the reported values for the constituents, i.e., 4.0 ± 0.1 MPa m\(^{1/2}\) for monolithic Al\(_2\)O\(_3\) [33] and 3.8 MPa m\(^{1/2}\) for TiC [34]. When applying a load of less than 5 N the Vickers indenter did not generate any crack. However, at 20 N an appreciable surface crack of length 100 \(\mu\)m forms. The cracks opened up to a width of about 1 \(\mu\)m, see figures 5(a) and (b).

In the case of Ti\(_2\)AlC samples neither indentation nor an impact method resulted in finite cracks within the samples. In this case thermal shock treatments were applied. Crack formation due to thermal shock first occurred at a temperature difference between heating and cooling of 450 °C. Microcracks of less than 2 \(\mu\)m in width were formed. For maximum temperatures between 450 °C and 950 °C cracks between 5 and 20 mm in length were formed by quenching in water. Based on 16 experiments the results were reproducible. Crack widths remained between 1 and 15 \(\mu\)m in this temperature range.

The Ti\(_2\)AlC samples used in the combustion study were quenched from 850 °C. This led to a large crack of 10 \(\mu\)m width and 20 mm length in the pure Ti\(_2\)AlC disk through the sample thickness. The second Ti\(_2\)AlC sample, containing TiC, Ti\(_3\)AlC and Ti\(_3\)Al impurities formed a crack of 5 \(\mu\)m in width and of approx. 0.5 mm in depth.

In the fine grained Cr\(_2\)AlC samples microcracks could be created with the Vickers indenter by applying a load of 300 N for 12 s. Cracks of about 140 \(\mu\)m, having a width of less than 1 \(\mu\)m were obtained. Per disc 10 of such cracks were produced in the samples to be tested in the combustion chamber. The fracture toughness value was estimated to be 8.7 MPa m\(^{1/2}\) using the load dependence of the indentation crack length.

In the case of the coarse grained material indentation loading did not result in radial cracks and only caused local plastic deformation. To induce local cracks of finite dimensions, coarse grained Cr\(_2\)AlC discs were clamped to a steel plate and subjected to low velocity perpendicular impact using 10 mm tungsten carbide balls. Beyond a critical impact energy, cracks were initiated at the crater edge and then propagated in the radial direction [35–37]. The correlation between impact energy and inducing cracks is depicted in figure 2. The threshold impact energy for Cr\(_2\)AlC is about 50 mJ. A crack with a length of 700 \(\mu\)m and a maximum

![Figure 1](image-url). Vickers Indent size and crack length versus applied load of (a) Al\(_2\)O\(_3\) with 20 vol% TiC composite and (b) fine grained Cr\(_2\)AlC.
crack opening of 2.5 μm is observed in the coarse grained sample tested in the combustion chamber. Samples tested in the combustion chamber contained cracks initiated by methods described above. Al$_2$O$_3$/TiC composites and both the fine and coarse grained Cr$_2$AlC had more than 5 cracks with lengths up to 1 mm and an average width of less than 2 μm. The through crack produced by thermal shock in the high purity Ti$_2$AlC sample was 10 μm wide and 20 mm in length, while the impurities of the second Ti$_2$AlC sample resulted in a thinner 5 μm crack with of approx. depth of 0.5 mm, while comparable in length.

2.4. Crack healing in combustion chamber

To investigate healing of crack damage at conditions encountered in a real combustion chamber, samples were placed in a combustor setup (Limousine Combustor, UTwente, The Netherlands [38]); see figure 3. The flow in the combustor is turbulent, as the Reynolds number is well above 4000 for all conditions. The combustor is operated at atmospheric pressure and the gases are injected at room temperature. The fuel used is 100% methane at room temperature. The air and fuel flow are controlled from a PC with control software and mass flow controller valves. The air and fuel mass flow are about 24.62 g s$^{-1}$ and 0.8 g s$^{-1}$, respectively resulting in an average gas flow speed of 16 m s$^{-1}$ at the location of the samples. The combustor is operated at an operating point with a thermal power of 40 kW and an air excess factor of 1.8. The air factor is the ratio of the actual

![Figure 2. Crack length versus impact energy for cracks created in coarse grained Cr$_2$AlC by impact of WC balls.](image)

![Figure 3. Combustion setup: (a) schematic side view with arrows indicating gas flow direction, (b) front view showing the position of the sample holder and thermocouples and (c) actual experimental setup.](image)
fuel-to-air flow rate ratio to the fuel-to-air flow rate ratio necessary for stoichiometric combustion and indicates the excess of air in the chemical reaction. The combustor can operate in a stable or unstable regime. In the unstable regime pressure oscillations are amplified by the combustion process and they grow in a limit cycle to amplitudes of 160 dB sound pressure level. This phenomenon can happen in gas turbine engines but is to be avoided with a view to fatigue damage. Under the conditions mentioned before, the combustor is running stable and the observed pressure oscillations are lower (about 100 dB) and representative for normal operation of a gas turbine engine. The adiabatic flame temperature and oxygen concentration at equilibrium conditions can be estimated using Chemkin Equil [39] assuming constant pressure and enthalpy. Using the GRI-Mech 3.0 reaction mechanism [40] and an initial temperature of 295 K the adiabatic flame temperature at these operating conditions is estimated to be about 1581 K. Under the above mentioned assumptions of adiabatic, isobaric conditions and assuming that the reacting mixture has already reached the equilibrium state, the oxygen mole fraction at the sample holder location is computed to be about 0.0876. Assuming a mixture of ideal gases, the volume fraction of oxygen then becomes 8.76% vol.

The 6 samples (3 sets of 2) were mounted in an Inconel 800 holder suspended midway in the combustor; see figure 3. Samples are arranged back to back so that both samples of one material are exposed to the same conditions; see figure 3(b). After exposure to the chamber conditions for 4.5 h, the samples were removed after switching off the fuel supply and allowing the chamber to cool down in approximately 45 min. The temperature at the sample holder was approx. 1000 °C. Temperature fluctuations during the course of the experiment were of the order of ±2 °C.

After exposure and subsequent cooling down the samples were examined using SEM and XMA. Both the surface and cross-sections prepared by cutting with a diamond blade were investigated regarding the oxides formed and crack gap volume filled.

3. Results

3.1. Materials characterisation

All sintered materials were found to have a density above 95%; see table 3. The ceramic composite samples (Al2O3/ TiC) showed traces of WC, an impurity of the TiC powder. Impurities in the MAX phase ceramics stem from incomplete reactions during synthesis. Cr2AlC was prepared with a fine and course grained microstructure resulting in a different hardness, viz. 6.0 and 3.2 GPa, respectively. The average grain sizes are reported in table 3.

3.2. Oxidation of TiC, Ti2AlC and Cr2AlC in air and combustion environments

Differential thermal analysis of the powdered healing agents TiC, Ti2AlC and Cr2AlC determined oxidation reaction peaks for all materials below 1300 °C. In figure 4 the reaction rates are plotted as a function of the inverse temperature for the three powders investigated. Taking the values of −15 and −13 for the natural logarithm of the reaction rate as the lower and upper value for optimal healing [31] (see section 2.2), we find the following optimal annealing temperatures, 600 °C–660 °C for the formation of TiO2 from TiC. For Ti2AlC the temperature range is 556 °C–580 °C and 826 °C–885 °C for the formation to TiO2 and Al2O3 respectively. And for Cr2AlC it is 929 °C–963 °C and 1170 °C–1257 °C for the formation of Al2O3, and Cr2O3 respectively.

After exposure in the combustion chamber for 4 h where the temperature at sample location was measured to be between 940 °C and 1110 °C the colour of the Al2O3/TiC samples had changed from very dark grey to light grey, indicating full oxidation. Observations at higher resolution in the SEM showed that islands of TiO2 formed all over the surface on top of the TiC particles. The activation energy of the complete transformation of TiC to rutile amounts to 242 ± 11 kJ mol⁻¹ according to DTA. After removing the surface oxides by diamond polishing complete filling of the cracks with oxide was observed; see figures 5(c) and (d). Even, after removing a layer of about 10 μm by diamond polishing, the indentation induced cracks appeared to be fully filled with oxides. This suggests that the cracks running from the surface inside the composite are healed. Moreover, it seems that the oxides grew laterally from the TiC particles along the crack gap, while the oxides on the surface grew locally.

Observation of the tested Ti2AlC samples showed dark discoloration on the surface exposed to the combustion environment. Both Ti2AlC samples showed significant oxide growth after being exposed to the combustion environment for 4 h. Grains of less than 5 μm cover the complete surface and all cracks smaller than 10 μm in width within the indents; see figure 6. The outer layer of the oxide was identified as TiO2 by SEM–XMA and XRD. A uniform and dense mixed oxide layer with a thickness of about 13 μm developed on the high purity Ti2AlC material. According to DTA analysis
small amounts of TiO$_2$ are expected to form around 570 °C while full rutile transformation is achieved at 700 °C, followed by Al$_2$O$_3$ formation around 800 °C.

The thermally induced crack in pure Ti$_2$AlC was fully filled with TiO$_2$ and Al$_2$O$_3$ up to a depth of 1.2 mm; see figure 6. Beyond this depth, oxides were formed at the opposing fracture surfaces, however not fully bridging the crack gap. The Ti$_2$AlC material containing impurities of TiC, Ti$_3$AlC, and Ti$_3$Al formed a 15 μm thick mixed oxide scale with an outer layer of TiO$_2$ of approx. 3 μm thickness. The crack, having a jagged path and a width of only 1 μm was fully filled up to its crack tip at a depth of 0.5 mm. The oxide within the crack gap is Al$_2$O$_3$. Given that oxidation still occurs at oxygen potentials lower than in atmospheric air (0.088 versus 0.2 atm), the fact that cracks 1.2 mm below the surface were not fully closed was attributed to regions of the crack being sealed by surrounding oxide bridges or to the lower rate of oxidation.

The oxidation of Cr$_2$AlC requires higher temperatures and is slower compared to Ti$_2$AlC. Formation of Al$_2$O$_3$ begins

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Table 3. Properties of sintered materials and impurities as detected by x-ray diffraction.

| Sample                | Impurities          | Average grain size (μm) | Density (%) | Hardness (GPa) |
|-----------------------|---------------------|-------------------------|-------------|----------------|
| Al$_2$O$_3$/TiC_01    | WC                  | 4.5                     | 95%         | 18.7           |
| Al$_2$O$_3$/TiC_02    | WC                  | 4.5                     | 99%         | 19.3           |
| Ti$_2$AlC-P           | none                | 15–40                   | 95.8%       | 3.9            |
| Ti$_2$AlC-LP          | TiC, Ti$_3$AlC$_2$, TiAl | 15–40               | 95.1%       | 3.5            |
| Cr$_2$AlC_FG          | Cr                  | 2                       | 99.1%       | 6.0            |
| Cr$_2$AlC_CG          | Cr$_2$C$_3$         | 20–30                   | 98.7%       | 3.2            |
around 900 °C to 1000 °C. A second peak in the heat flow signal of the DTA analysis at 1170°–1275° corresponds to the formation of an Al2O3 and (Cr, Al)2O3 solid solution according to XRD. The oxide grown on the surface after 4 h of oxidation in the combustion chamber was about 0.24 μm and 0.19 μm thick on the fine and coarse gained sample, respectively. These oxide layers are thinner than the oxide layers formed in synthetic air for corresponding temperature and time, namely: 0.6 μm and 0.5 μm, respectively. Apparently the lower oxygen partial pressure in the combustion ambient as compared with that of air resulted in low oxide nucleation density (i.e. larger oxide grain size) and consequently slower oxidation kinetics. Hence, cracks with a width of less than 0.5 μm were fully healed with oxide and those with larger crack opening were only partially healed; see figure 7.

The significant difference in oxygen partial pressure from standard self-healing investigations performed in synthetic or atmospheric air (0.2 atm) to the conditions found in the combustion setup (0.088 atm) show no significant impairment of the healing ability in the case of the three tested materials. The lower pO2 resulted in thinner oxide scales for Cr2AlC than those found in thermal gravimetric analysis, 0.2–0.5 μm for fine grained Cr2AlC. Healing in Ti2AlC and Al2O3/TiC was not affected by the reduced oxygen partial pressure. Surprisingly other compositional changes to the atmosphere due to combustions, e.g. higher NOx content, showed no effect on sample composition.

4. Conclusions

Three high temperature ceramic systems, Al2O3/TiC, Ti2AlC and Cr2AlC were investigated concerning their fracture, oxidation and self-healing behaviour under real combustion conditions. All tested materials showed full crack-gap filling for 0.5 to more than 10 μm wide cracks of up to 20 mm length, after exposure to the high velocity exhaust gas mixture at approx. 1000 °C for 4 h. Although the oxygen partial pressure...
pressure in the combustion chamber is much lower than in air (0.088 versus 0.2 atm), the conditions are sufficient to realise full healing of crack damage. The high gas flow rate (16 m s⁻¹) and thermal load did not impair the healing process.

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Figure 7. (a) Crack damage in fine grained Cr₃AlC generated by Vickers indentation; (b) crack healed by Al₂O₃ formed in combustion environment for 4 h.
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