Reducing the erosive wear rate of Cr$_2$AlC MAX phase ceramic by oxidative healing of local impact damage

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A B S T R A C T

The present work describes a model study to explore the possibility to heal early stage erosion damage in Cr$_2$AlC MAX phase when exposed to high air temperatures and erosive conditions. Such a healing reaction should lead to a reduction of the wear rate of this promising material for application in jet turbine engines. To this aim Cr$_2$AlC ceramic disks were subjected to room temperature erosion for 60 min using glass microbeads accelerated to 110 m/s and impinging perpendicular to the sample surface. After the usual incubation time, the erosion rate reaches a constant rate, which is associated with the formation of network of small cracks underneath the surface. Next, the material was annealed at 1200 °C for 10 min in air resulting in filling of the network of small cracks due to the formation of well-adhering Al$_2$O$_3$. The subsequent erosion rate of the healed Cr$_2$AlC ceramic at room temperature is drastically reduced. Once the healed zone is removed by erosion the erosion rate attained its original value. Clearly, exposure to high temperature oxidative conditions extends the lifetime of Cr$_2$AlC MAX phase components subjected to erosive conditions.

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1. Introduction

Cr$_2$AlC belongs to the family of MAX phase metallo-ceramics, which are tough and therefore damage tolerant compared with many other common engineering ceramics. This MAX phase is stable up to high temperatures and corrosion resistant. Its combination of high strength, high toughness up to very high temperatures and high thermal conductivity makes this ceramic very resistant to thermal shock [1–11]. Therefore this material is very attractive for high temperature applications, where the material is exposed to steep thermal cycles, high mechanical loading and oxidation. Moreover, Cr$_2$AlC has a large coefficient of thermal expansion comparable to that of Ni alloys and is hot corrosion resistant (i.e. resistant against attack by sulfur containing species) and hence would be a potential candidate coating material for application in the hot sections of turbine engines [12–15].

Erosion damage of components located along the path of the air flowing through an aero turbo engine (i.e. starting at the inlet of the compressor via the combustion chamber into the turbine) due to high velocity impact of solid particles is of major concern since it affects fuel efficiency, reduces their lifetime and ultimately impairs flight safety. The particles in the air could be fine dust particles forming regular air pollution, desert sand or volcanic ashes etc. [16,17]. To recall: the volcanic outburst in 2010 of the Eyjafjallajökull on Island shut down all air traffic in major parts of Europe for up to four days [18].

The impact of hard particles (projectiles) on a material surface (target) can lead to local plastic deformation and fracture of the target material, while the hard particles deform elastically and seldom fracture [19]. It is well known that serious abrasion only occurs at velocities above a certain threshold velocity [20,21]. The erosion rate at velocities above the threshold is largely dependent on the ratio of the hardness of the target material H_t with respect to the impact particle H_p. For $H_t/H_p < 1$ the erosive wear is caused primarily by fracture and the erosion rate increases with increasing hardness of the impact particle.

Erosion of ductile material mainly results from plastic deformation (cutting) which is manifested as indents (craters) with a peripheral rim on its surface. Whereas materials loss for brittle materials mainly happens via crack formation due to a (local) dynamic elastic–plastic stress field generated upon impact [22]. Two types of cracks can be distinguished [23]: radial or circumferential cracks perpendicular to the surface formed during impact (Fig. 1a), and lateral cracks parallel to the surface upon unloading (Fig. 1b). The latter result from a residual elastic–plastic stress field. Erosion of the target material is related to the formation and growth of the lateral cracks, ultimately leading to a
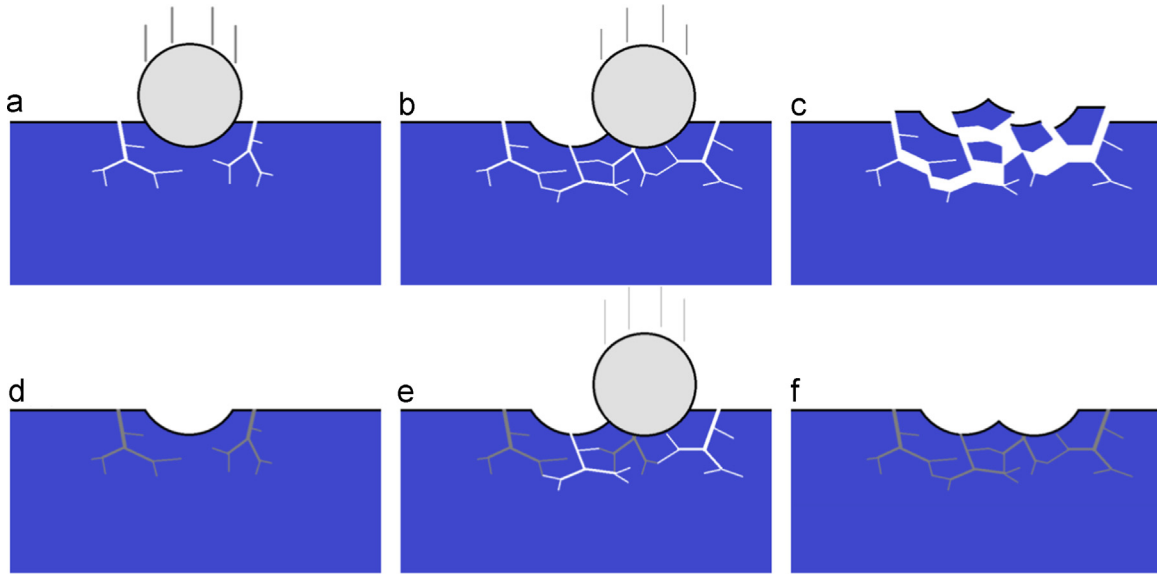
Fig. 1. Schematic drawing of erosion and healing behavior of MAX phase ceramics. (a) First impact with crack development; (b) second impact causes crack network; (c) spallation of fragments; (d) first healing due to crack closing by oxidation; (e) further impact causes cracks at new positions due to the high strength of the interface and the oxide; (f) second healing.

network of connected cracks and spontaneous material removal via spallation (Fig. 1c). Various models based on fracture mechanics have been developed to relate the erosion rate V of brittle materials to its standard mechanical properties [19,21,24–28]. According to Evans et al. [29] for impact of incompressible particles perpendicular to the target surface it holds that:

$$V = \nu_p^{19/6} R_p^{11/3} \rho_p^{1/4} / K_{c,t}^{4/3} H_t^{1/4} \tag{1}$$

where ν_p is the impact velocity, R_p is the radius and ρ_p is the density of the particles, respectively. $K_{c,t}$ and H_t is the fracture toughness and hardness of the target material, respectively. The erosion rate is defined as the eroded mass of the target material relative to that of impact particles. On the one hand, the erosion rate depends on the erodent, such as particle hardness, size and shape, mass, velocity and impact angle [30–36]. On the other hand, the erosion rate depends on the strength and toughness of the material. The difference between the erosion behavior of ductile and brittle materials is also reflected in the angle of maximal erosion rate [36]. For a brittle material the maximum erosion rate occurs a at an impact angle of about 90°, while for a ductile material a maximum is observed at an impact angle of 20–30° [37].

The relatively high toughness [38] the moderate hardness [7] and the ability to undergo relatively large plastic deformation due to its layered structure make Cr_2AlC a potentially attractive erosion resistant ceramic. Recently, it has been demonstrated that crack damage in alumina forming MAX phases, like Ti_3AlC_2 and Ti_2AlC as well as Cr_2AlC, can be healed by selective oxidation of the A element [39–42]. Thus, the MAX phase is part of the healing reaction and the healing product is formed by consuming oxygen from the gas atmosphere. The filling of the crack gap with well-adhering alumina and other reaction products restores the material integrity.

Following the above concept, it is proposed that the erosion rate of MAX phase metallo-ceramics will be reduced when the surface is continuously or periodically exposed to high temperature oxygen containing environments, via a process shown schematically in Fig. 1d–f. The present model study looks at the room temperature erosion and erosion rate of Cr_2AlC and the change thereof after annealing at a high temperature in an oxidizing environment. The erosive damage healing capability of Cr_2AlC is demonstrated convincingly. From the above analysis it is clear that a reduction of the abrasion rate can be envisaged in case of a

healing reaction leading to the healing/sealing of the network of small cracks before there is full 3D local connectivity of the cracks leading to spallation.

2. Materials and methods

2.1. Synthesis of Cr_2AlC

The chromium (average particle size of about 100 µm, purity > 99.2%, TLS Technik GmbH & Co., Germany), aluminum (average particle size of about 45 µm, purity > 99.8%, TLS Technik GmbH & Co., Germany) and graphite (average particle size of 6 µm, purity > 99.5%, Graphit Kropfmühl AG, Germany) powders having a molar ratio of 2:1.15:1, respectively, were mixed for 24 h using a Turbula T2C mixer (Willy A. Bachofen, Switzerland) also filled with ZrO_2 balls. Then, the powder mixture was cold pressed into tablets with a diameter of 25 mm and a thickness of about 5 mm with a Carver press (Model 3853-0, USA). These tablets were pressure-less sintered in a flow of 500 sccm Argon (purity > 5 N) for 1 h at 1400 °C in a horizontal alumina tube furnace (Lenton Furnaces, PTF 16/75/610, UK) with an inner tube diameter of 80 mm. The tablets were placed on graphite boats and the furnace was heated with 5 °C/min. Next, the PLS samples were pulverized (using a Fritsch Pulverisette, Germany) and ball milled with 10 mm WC balls and WC jar (250 ml) for 1 h effectively, i.e. cycles of 10 min. milling at a speed of 300 rpm and 20 min. at hold using a PM100 ball grinder (Retsch GmbH, Germany). The Cr_2AlC powder obtained had an particle size around 4 µm and was phase pure according to X-ray diffraction.

The Cr_2AlC powder was densified with SPS (HP D 25, FCT Systeme GmbH, Frankenblick, Germany) at a pressure of 50 MPa with a heating rate of 50 °C/min. The powder was put into a graphite mold with an inner diameter of 20 mm applying graphite paper and BN spray (Henze, HeBoCoat® 21E, Germany), to separate the powder from the mold. After the SPS treatment the thickness of the sample was about 7 mm.

The density of the samples was measured with the Archimedes method using an analytical balance (Mettler Toledo AG-204, Switzerland) according to ASTM B 311-93 [43].