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Study of high velocity solid particle erosion behaviour of Ti_2AlC MAX phase coatings

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ABSTRACT

This research work provides information about the influence of Ti_2AlC MAX phase coatings on the erosion resistance of Ti6242 alloy. Flat specimens were coated with a 20 μm Ti_2AlC film using an industrial size magnetron sputtering coater and annealed at 800 °C for 1 h in vacuum for the formation of the MAX phase. The erosion resistance of the specimens was tested using high-velocity particles at room temperature. The results indicate that the erosion resistance of Ti6242 has been significantly enhanced by the employment of MAX-phase coatings. This demonstrates the capability of using MAX phase coatings as erosion protective medium for engine components exposed to similar damage conditions. Additionally, the results show that uncoated Ti6242 samples with duplex microstructure have a better durability against erosion attack compared to uncoated samples with globular microstructure.

1. Introduction

In the aerospace industry, titanium alloys like Ti-6242 (6Al–2Sn–4Zr–2Mn) are considered good candidates for rotational parts of aero engines such as compressor blades due to their high specific strength [1,2]. Typical atmospheric conditions like sand storms, volcano ashes and ice particles can induce erosion damage on aero engines. Studies have demonstrated that abrasive wear caused by erosion can lead to a significant damage of the compressor components [3]. Dust ingested by turbines induces an erosion damage of its components, especially at the first-stage compressor blades, resulting in low performance, reduced mean-time between overhauls and an increase in costs and required logistic support [4]. The damage of compressor blades induces an increase in tip clearance and in surface roughness in the pressure side. Blunting of the leading edge, reduction in the chord, sharpening of the trailing edge, and shortening of the trailing edge are some of the effects of component erosion. Kline and Simpson [5] reported on the loss in efficiency of an aero engine up to 25% after a sand ingestion test. Ghenaiet et al. [6] reported that the main contributors to the efficiency loss of the turbomachine under erosion damage are a blunting of the leading edge and the chord reduction of the compressor blades.

It has been observed that the impacts of high velocity particles on a substrate can induce local damage like scratching, extruding, melting and crack formation as well as propagation. These damage conditions depend on several parameters like substrate and erodent material, impacting angle, erosion time, particle velocity, temperature and atmosphere among others [7]. Some authors report on the influence of additional mechanical properties besides the hardness on the erosion resistance of alloyed materials [8–11] such as the fracture toughness and compressive strength of the material [12]. Other factors also influencing the erosion damage are erodent hardness [13], erodent size [14–16], erodent shape [13,17], erodent velocity [18–22], impact angle [18,23,24], and testing conditions like temperature [23] and relative humidity [25].

Based on current state-of-the -art knowledge, ceramic coatings are regarded as a strong barrier against the degradation caused by the impact of particles at high temperature [26–28]. Recent studies demonstrate that the use of TiN, TiAlN, and TiC coatings, deposited via PVD and CVD, lead to an improvement in the erosion behaviour of coated metallic alloys [3,29–31]. Further positive effects could be determined for the use of diamond coatings on Ti-64 alloy [32] and multilayer coatings like $NiCr/TiB_2$ or W/TiB_2 on Ti-6246 alloys [33].

The present study is based on the investigation of the erosion behaviour of MAX-phase coatings. $M_{n+1}AX_n$ (MAX) phase is a new class of solids with hexagonal layered (space group P63/mmc) structures where $n=1, 2, 3,\ldots$, M is an early transition metal, A is one of the elements in groups 13–16 and X corresponds to C and/or N. These materials gained popularity due to their combined metallic and ceramic properties because of the metallic bonds between M–A and ceramic bonding between M–X in the material [34–36]. Moreover, MAX-phase coatings exhibit low density,

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relatively high stiffness, damage tolerance and high thermal shock and high temperature oxidation resistance [37,38].

Ti_2AlC has been chosen for the present study as it is considered one of the MAX Phases known for its high thermal stability at 1350 °C [39], its high thermal conductivity and good elastic properties [40,41]. This research work focuses on the potential of erosion resistance of Ti_2AlC coatings in comparison to uncoated Ti6242 substrates. Mass loss and erosion rate curves have been analysed, a correlation between erosion rates and plasticity index have been described and the experiments have been supported by a scanning electron microscopy (SEM) as well as EDX analysis.

2. Material and methods

Erosion samples of 35 mmx35 mm were cut from a 2 mm thick near-α titanium alloy Ti6242 were heat treated at a temperature just below the β-transformation zone (985 °C for 1 h, and annealed at 590 °C for 8 h) to produce a duplex microstructure. Prior to coating deposition, the substrates were wet polished to a mirror finish and then cleaned in acetone. A Ti_2AlC composite target (50% Ti, 25% Al and 25%C) manufactured by PLANSEE GmbH has been used for the deposition of coatings. A 20 μm Ti_2AlC coating was deposited on the samples with duplex microstructure using an industrial size CemeCon CC800/9 HPPMS magnetron sputtering coater. Argon etching was performed in order to clean the substrate surface before the coating deposition. The coating parameters used for the coating deposition process are available from Table 1.

Table 1
Process parameters used during coating process.

Argon etching period	0.5 h
Chamber pressure during etching	540 mPa
Coating deposition temperature	540 °C
Substrate bias (DC)	90 V
Cathode power	2000 W
Chamber pressure during coating	600 mPa
Deposition time	18 h
No. of targets used	1
Target-substrate distance	70 mm

Coatings deposited at low temperatures between 300 °C and 800 °C show the presence of a ternary Ti_3AlC phase with a perowskit structure [42]. Coatings deposited at a temperature above 900 °C [43] or vacuum annealed at 800 °C for 1 h [44, 45] exhibit a phase change from perowskit Ti_3AlC phase to hexagonal Ti_2AlC phase. Since the above mentioned Ti_2AlC MAX phases were deposited at low temperatures, annealing was performed in a vacuum oven for 1 h at 800 °C in order to achieve the required Ti_2AlC phase.

The erosion experiments were carried out at room temperature using a house inbuilt erosion test rig equipped with a compressor, a pressure vessel, a powder feeder, an acceleration nozzle and a test chamber. The particles interact with the impulse given by the compressed air in the air-particle mixer and gain high kinetic energy along the acceleration nozzle toward the test samples. The specimen is aligned to a certain angle (30°, 90°) with respect to the acceleration nozzle. Since the size [46] and shape [47] of the erodent play an important role in determining the erosion behaviour of the coatings, this work focus on the effect of spherical friable glass beads with an average size of 40–80 μm (Fig. 1). The test parameters can be found in Table 2.

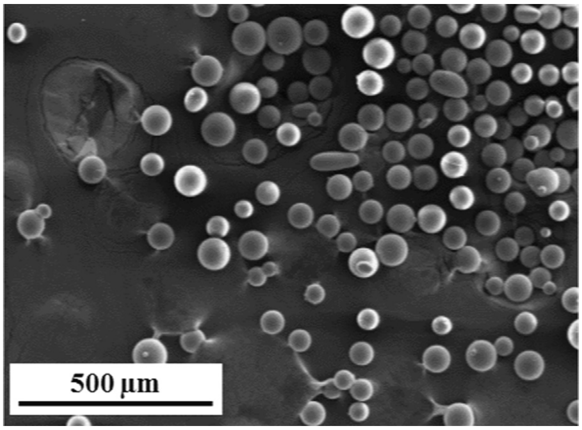

Fig. 1. SEM image of the glass microbeads used for the erosion tests.

The particle velocity is measured at a distance of 25 mm (sample position) from the acceleration nozzle via Laser Doppler Anemometer (LDA) manufactured by TSI. A set including an 800 W laser with a wavelength of 514.5 nm connected to a band pass filter of 20–80 MHz within a signal processor and a photo detector module was used for the measurements.

The mechanical properties of the substrate and the deposited Ti_2AlC coatings have been measured by means of nanoindentation. For this purpose, a nanoindenter from ASMEC GmbH was used and mechanical properties like hardness and E-Modulus have been interpreted by a load–displacement curve generated after each measurement with a constant load of 200 mN.

3. Results and discussion

The initial globular (a) and duplex (b) microstructure of Ti6242 alloy is shown in Fig. 2. A heat treatment resulting in a transformation of globular structure (approx. 80% α-phase) into a duplex microstructure (approx. 20% α-phase) was performed in order to improve the mechanical properties of the alloy.

The coatings were then deposited on the heat treated substrates and post annealing is performed in order to achieve the required Ti_2AlC phases. Fig. 3 shows a representative top view (a) and a cross-section (b) of the deposited Ti_2AlC after 1 h heat treatment at 800 °C in vacuum. The coating reveals a very dense cross-section with the formation of a nano-structured columnar and quasi-equiaxed grain zone in the bottom and top region (Fig. 3b). However, macro-defects in form of “carrots”, shown in Fig. 3a, have grown on the surface of the coating. These defects decrease the capability of PVD coatings to act as protective medium against oxidation and corrosion due to the open gaps around them.

The phases grown in the Ti_2AlC coating after annealing can be observed from Fig. 4. The coating consists of mainly Ti_2AlC MAX phase with traces of Ti_3AlC_2 and intermetallic Ti_3Al, $TiAl_3$ phases. Similar results were observed in studies of Ti_2AlC bulk material produced by sintering by Barsoum [37] where the appearance of additional two phases (Ti_3AlC_2 and TiC_{1-X}) to the main MAX phase was reported.

The results of the hardness measurements of the uncoated globular and duplex Ti6242 alloy and the Ti_2AlC coating are summarised in Table 3. A heat treatment from globular to duplex structure lead to an increase in the hardness and E-Modulus of the Ti6242 alloy. Moreover, a comparatively high hardness of deposited Ti_2AlC coating can be observed then for uncoated alloy. Increased values of H/E and H^3/E^2 can also be observed for coated alloys in comparison to uncoated ones. The significance of the above discussed factors would be discussed in the next section.