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A mechanistic approach to extract the mechanical properties of individual constituents in plasma-sprayed metal matrix composite coatings

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A B S T R A C T

A mechanistic approach to determine the in-situ properties of individual constituents in a plasma sprayed metal matrix composite (MMC) coating was proposed. The approach was based on micro-indentation and inverse analysis techniques. Utilising the indentation data obtained from the micro-indentation experiments, elastic moduli of each constituent were calculated using a well-established method whereas yield strength and hardening exponent were extracted using the inverse procedure based on finite element analysis. Finite element results gave a satisfactory agreement between the numerically simulated and the measured indentation load–depth curves. Further studies using three dimensional finite element analyses of Vickers indentation on the MMC coating based on its actual microstructure also showed that the indentation behaviour of the MMC coatings is strongly dependent on its morphology, volume fraction, size and distribution of the reinforcing phase.

1. Introduction

The use of plasma sprayed metal matrix composite (MMC) coatings in engineering applications involving contact damage, high temperature and corrosion has recently been explored [1,2]. MMC coatings are seen as potential materials for coating light aluminium or titanium structures, structural engine parts, bearing cases of titanium alloys as they have properties that lie between soft and hard coatings. The principle of the plasma spray process consists of a complete or partial melting of feedstock material (typically in the form of powder) followed by the acceleration of molten particles and their subsequent impact onto a substrate, where the particles rapidly solidify and form deposits known as splats [3,4]. The high energy associated with the plasma sprayed torches, and hence the impinging particles, gives rise to a lamellar pattern. In order to quantify the overall property of the MMC coating, it is necessary to identify accurately the material properties of its constituents. Due to the micrometer size of the MMC reinforcements, it is a challenging task to experimentally measure the mechanical properties of the MMC coating constituents. The in-situ properties of the MMC coating constituents can differ significantly from their nominal, bulk properties since very high temperature is involved during plasma spraying process. For this reason, micro- or nano-indentation techniques have become the most popular method for evaluating the mechanical properties of various micro-structural materials and thin coatings [5–7]. In addition, these techniques combined with an atomic-force microscope (AFM) have also been increasingly used to probe the mechanical properties of multiphase materials in the sub-micron regime [8–10].

It has been established that the mechanical properties of materials such as Young's modulus, yield strength and strain hardening behaviour can be deduced from the indentation load versus displacement curves for loading and unloading. For example, the Young's modulus can be calculated from the initial slope of the unloading curve [11,12]. In addition, the elastic–plastic properties, such as Young's modulus, yield strength and hardening behaviour, could be uniquely identified from the measurement of the peak load, unloading slope of the indentation curve and the residual contact area of indentation [13,14]. However, the efficiency of this method is strongly dependent on accurate measurements of the measured quantities. For instance, a 5% error in the measured residual contact area may result in errors as high as 20% and 60% in the predicted yield strength and hardening exponent, respectively. In practice, the residual contact area is difficult to locate precisely. Therefore, this method may not be appropriate for small load indentations or in situations where piling-up or sinking-in effects may occur. Recently, a method based on inverse analysis and finite element (FE) techniques has been proposed for predicting the mechanical properties from the indentation data [15]. This method is seen very promising and advantageous as it only relies on a direct measurement of indentation load–depth curve.

In this study, a mechanistic approach was proposed for extracting the in-situ mechanical properties of the constituent phases of MMC coating. The approach was based on the combination of

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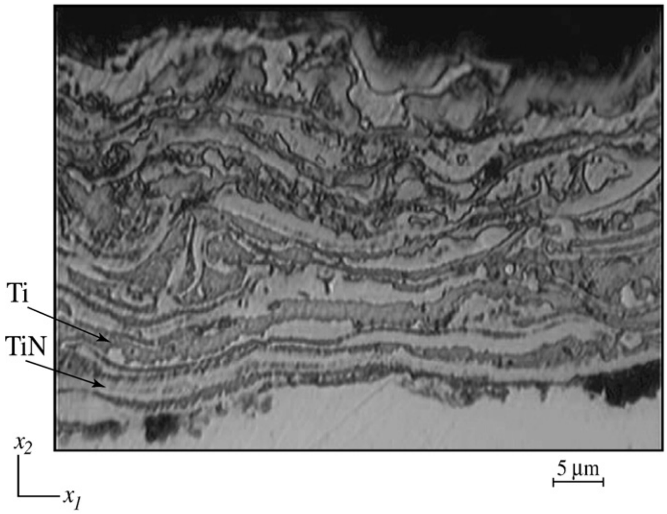

Fig. 1. A Micrograph showing a typical plasma sprayed MMC coating [2].

micro-indentation experiment, finite element and inverse analysis techniques. The studied MMC coating was composed of a lamellar arrangement of titanium nitride (TiN) reinforcement in a titanium (Ti) matrix. In addition, finite element analyses of Vickers indentation on the MMC coating using the predicted properties were performed to demonstrate the influence of MMC microstructures, such as volume fraction and particle size and distribution, on their indentation behaviour.

2. Experimental procedure

2.1. Specimen preparation

The plasma sprayed MMC coating used in this work was deposited onto a medium carbon steel (AISI 1040) using titanium (Ti) and nitride powders. The processing details and spraying conditions are described in [1,2]. A typical microstructure of the Ti/TiN MMC coating is shown in Fig. 1. It consists of a lamellar structure with Ti/TiN alternating layers parallel to the substrate material. Ti and TiN layers are shown as a dark-grey and light-grey area, respectively. Prior to the indentation experiments, surface preparation was made by standard metallographic techniques with the final polishing finished with a 1 µm diamond suspension. The final average coating thickness was 80 µm.

2.2. Micro-indentation test

The mechanical properties of the individual constituents of the MMC coating were investigated with a Vickers micro-indenter. Experiments were performed using a Fisherscope H100 tester which has a test load ranging from 0.4 mN to 1000 mN. Statistically, as many as 30 indentations were made with a maximum applied load of 1000 mN. Each indentation was separated by at least 30 µm in order to eliminate any residual effect from previous indentation. It was noting that this distance was not fixed but altered depending on the size of the previous indentation mark. It was carefully judged through a microscope that each indentation would not be affected by the previous indentation.

3. Finite element procedure

The indentation of elastic–plastic materials using a conical indenter as shown in Fig. 2(a) is considered in this study. The elastic–plastic material with Young's modulus, E, yield strength, σ_y, and hardening exponent, n, can be characterised by a power law relation which is defined as

$$\frac{\tilde{\varepsilon}}{\varepsilon_y} = \frac{\tilde{\sigma}}{\sigma_y} \quad \text{for} \quad \tilde{\sigma} \le \sigma_y \tag{1}$$

$$= \left(\frac{\tilde{\sigma}}{\sigma_y}\right)^n \quad \text{otherwise} \tag{2}$$

where $\tilde{\sigma}$ and $\tilde{\varepsilon}$ are the equivalent stress and strain, respectively and $\varepsilon_y = \sigma_y / E$, is the yield strain.

The FE computations were performed using the commercial FE code ABAQUS [16]. The conical indentation has a geometric and loading symmetry about the axis of the indenter. Hence, they can be modelled as a cylinder being indented by either rigid conical or spherical indenters. In the conical indentation, the indenter with half-angle $\theta = 70°$ was chosen since this angle gives the same contact area-to-depth ratio as the Berkovich three-sided pyramidal and Vickers four-sided pyramidal indenters (see Fig. 2(b)). The presence of the substrate material was ignored in the analyses as the indentation depth is shallow enough to regard the influence of the substrate material as negligible. A mesh sensitivity analysis was carried out to ensure a mesh independent solution and the final mesh consisted of 12,490 four-noded axisymmetric elements with reduced integration (see Fig. 3). Furthermore, a downward displacement was applied to the rigid indenter. Displacement-controlled condition is preferred to a load-controlled loading because of its stable numerical convergence in contact simulations. The equivalent reaction force is reported as the

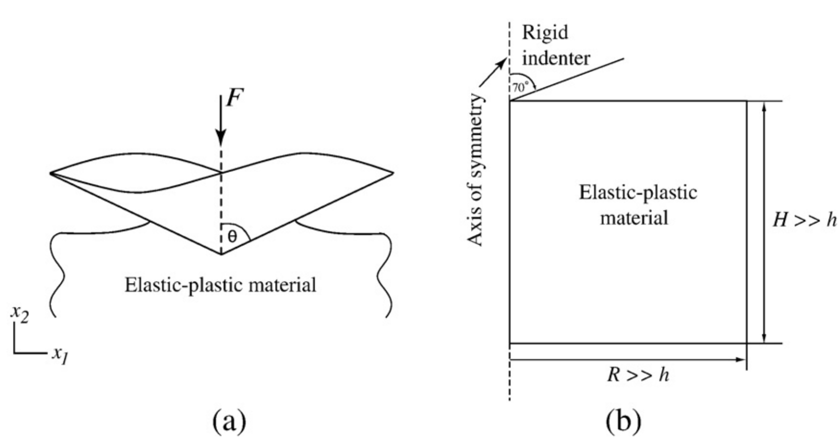

Fig. 2. (a) Illustration of an indentation test using a conical indenter and (b) geometry of indentation problem.