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Determination of elastic modulus and residual stress of plasma-sprayed tungsten coating on steel substrate

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Abstract

Plasma-sprayed tungsten, which is a candidate material for the first wall armour, shows a porous, heterogeneous microstructure. Due to its characteristic morphology, the properties are significantly different from those of its dense bulk material. Measurements of the elastic modulus of this coating have not been reported in the literature. In this work Young's modulus of highly porous plasma-sprayed tungsten coatings deposited on steel (F82H) substrates was measured. For the fabrication of the coating system the vacuum plasma-spray process was applied. Measurements were performed by means of three-point and four-point bending tests. The obtained modulus values ranged from 53 to 57 GPa. These values could be confirmed by the test result of a detached coating strip, which was 54 GPa. The applied methods produced consistent results regardless of testing configurations and specimen sizes. The errors were less than 1%. Residual stress of the coating was also estimated.

1. Introduction

Tungsten is one of the candidate materials for plasma-facing armour of the first wall components in a fusion reactor. Plasma-sprayed coatings usually show a porous, heterogeneous microstructure. Their typical porosity amounts to 20%. The pores have fairly irregular shapes and a wide size distribution often exhibiting conjoining neighbouring pores. Due to such characteristic morphology, properties of the plasma-sprayed coatings are significantly different from those of the dense bulk counterparts.

In general, component design and structural analysis are based on a macroscopic length scale. It means that the stress computation of the porous tungsten coating deposited on a large component requires materials data of homogenised (i.e., volume-averaged) properties which are also based on a macroscopic length scale. To author's knowledge, measurements of the homogenised elastic modulus of plasma-sprayed tungsten coating have not yet been reported in the literature. A rigorous analytical estimation, e.g., Eshelby–Mori–Tanaka method, is in general not viable whereas the finite element method may be applied to simulate the elastic deformation of such coatings from which the

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homogenised elastic modulus could be deduced. In this case, three-dimensional mapping of the microstructure into a mesh model will be the major technical difficulty.

The aim of this work is to measure Young's modulus of a plasma-sprayed thick porous tungsten coating deposited on a steel (F82H) substrate. There are various non-destructive test methods by which Young's modulus could be measured. These are for example vibrating reed, inverted torsion pendulum, ultrasonic pulse-echo and bending test, etc. [1]. In this work, the bending test method was applied which provides a possibility to perform a series of various mechanical characterisations consecutively without substantial modification of the test configuration.

The measured size of the pores in the tungsten coating ranged between 10 and 100 μm. Due to the presence of such relatively large pores, the specimen should not be so much down sized that the homogenisation assumption loses its validity. The dimension of a specimen (for example, thickness) should be sufficiently larger than the characteristic length scale of the pores so that the local morphology does not affect the measurement. In this work, bending experiments were performed for three different specimen sizes to explore the possible effect of specimen size.

Thermal spraying usually generates residual stress in the coating system. If the magnitude of residual stress is considerably large, the elastic limit of the materials can be readily exceeded even during processing or during subsequent testing. Hence, it is important to ensure that bending tests for elastic modulus measurements are conducted without any plastic yield. To this end, information on the stress state in the coating system is needed to control the maximum stress. The estimation of residual stress is another topic treated in this work. It was assumed that the presence of residual stress itself would not affect the system stiffness within the elastic regime.

2. Testing scheme and model systems

The tungsten coating/steel (F82H) substrate system used for the experiments was originally developed as an actively cooled first wall panel of a fusion reactor. F82H is a reduced-activation martensitic steel (Fe–8Cr–2W–0.2V–0.04Ta–0.1C). Tungsten coating was deposited using the vacuum plasma-spray (VPS) technique (Fig. 1) by the PLANSEE company. The fabricated component had a flat, rectangular shape with two material layers. The tungsten coating thickness, which was not ideally uniform along the width, ranged between 1.65 and 1.80 mm. The component showed actually no residual curvature due to the stiffness of thick substrate (7.35 mm). A rectangular cooling channel made of a stainless steel with a cross-section of $52 \times 6\ \mathrm{mm}^2$ was welded to the substrate bottom before the spray process. This component panel was actively cooled also during the thermal spray process in order to reduce the residual stress. Cooling water with a temperature of 20 °C and flow rate of 10 l/min was used [2]. The basic physical properties and heat flux fatigue test of this coating system were reported in the literature [3].

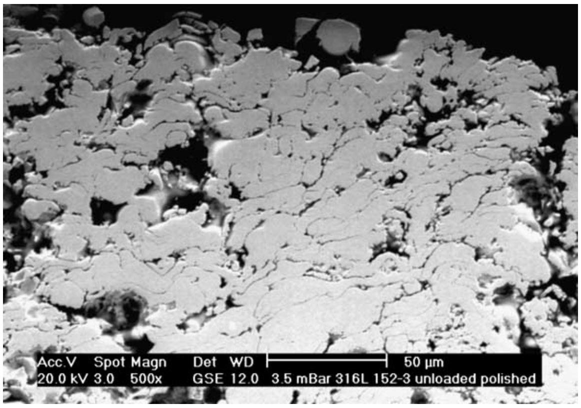

Fig. 1. Porous microstructure of a plasma-sprayed tungsten coating (SEM image).

After the thermal deposition, the component was machined to remove the cooling channel and to reduce the substrate thickness. After thinning and fine polishing, the final substrate thickness was reduced to 1.35 mm (Fig. 2). The thinning of the substrate was necessary in order to improve the sensitivity of the coating response and to avoid transverse shear deformation. Further machining was made to trim off the rough edges. The coating surface was also precisely polished in order to obtain a uniform coating thickness throughout the specimen. The final coating thickness was 1.62 mm. The dimensional error of the thickness was less than 1%. A notable feature of the thinned specimen was the remarkable residual curvature caused by the residual stress. The measured radius of curvature was (1.70 ± 0.02) m.

In the current experiment, both three-point and four-point bending tests were made. In an ideal case, the measured modulus would be independent