Surface & Coatings Technology 291 (2016) 413–422

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Investigations on flexural performance and residual stresses in nanometric WC-12Co microwave clads

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ARTICLE INFO

Article history:
Received 29 December 2015
Revised 26 February 2016
Accepted in revised form 5 March 2016
Available online 7 March 2016

Keywords:
Microwave
Cladding
WC-12Co
Microstructure
Flexural strength
Residual stresses

ABSTRACT

The flexural strength and residual stresses significantly influence the mechanical, structural and tribological performance of the coatings/claddings on metallic substrates. In this study, micrometric and nanometric WC-12Co clad were developed on stainless steel substrates using microwave hybrid heating technique. The flexural strength of the WC-12Co clads was evaluated using a three-point bend test. The nanometric clads exhibited approximately 14% higher flexural strength compared to the micrometric clads. The presence of eutectics of nanocarbides in the nanometric clads restricted crack propagation in the decohered ductile metallic matrix. The residual stresses in the micrometric and nanometric clads were evaluated through the $\sin^2\psi$ technique using X-ray diffraction. The nature of residual stresses was observed to be compressive in the micrometric and nanometric clads. However, the magnitude of the stresses in the nanometric clads was observed to be ~68% higher than the micrometric clads.

1. Introduction

Modern engineering components require improved tribological and thermal properties to function in aggressive working environments. Surface engineering provides optimised solutions in producing such components. Hard coatings and cladding on metallic materials are such techniques that are popular due to their attractive mechanical, thermal and tribological attributes. The flexural strength and residual stresses are important parameters for safe design and application of the clad-substrate system. Flexural strength influences the durability of an engineered surface significantly [1,2]. Residual stresses play an important role in cracking, spalling and bonding behaviour of the engineered surfaces [3]. The performance of the coating/cladding is strongly affected by the presence of residual stresses. High residual stresses lead to cracking and spalling of the overlay deposits [3]. Both deposition process and the material may produce residual stresses if there is a large mismatch between the thermal, structural and mechanical properties of the substrate and the overlay material [3,4]. Therefore, evaluation of residual stresses of the surface deposits is an important aspect.

Cladding/coatings on metallic surfaces are popularly produced through thermal spraying (high velocity oxy fuel spraying, plasma spraying and arc spraying), welding based techniques (gas tungsten arc welding, plasma transferred arc welding) and laser cladding [5–7]. The coatings developed through the thermal spraying based techniques are usually mechanically anchored to the roughened surface and possess porosity, cracks and inhomogeneous microstructures [8,9]. On the other hand, surfaces engineered through welding are metallurgically bonded to the substrate. But excessive heat input during the process leads to the dilution of the substrate [10]. Laser cladding provides excellent control over dilution, development of fine microstructures and high quality clads. However, the presence of high residual and thermal stresses due to high temperature gradients, the presence of solidification cracks and porosity are a few concerns associated with laser cladding [11]. On the other hand, a relatively new process "microwave cladding" has demonstrated its ability to develop clads with uniform microstructures, less porosity and improved properties [12–14]. These characteristics have been attributed to the uniform and volumetric heating associated with microwave processing [15]. Furthermore, the effective conversion of microwave energy into heat depends on the loss tangent of the irradiated material. Ceramics such as WC, exhibit low loss tangent at ambient temperatures, however, their loss tangent increases significantly beyond the critical temperature [16]. Hybrid heating has been proved to be viable to process such materials [17–20]. Therefore, microwave hybrid heating (MHH) technique was used to develop the MM and NM WC-12Co clads.

In the present work, micrometric (MM) and nanometric (NM) WC-12Co clads were developed using the MHH technique. The flexural strength of the MM and NM clads was evaluated using a three-point bend test. The thermal cycle during microwave cladding results in the generation of residual stresses in the clad layer. Evaluation of residual stresses is necessary as the engineering components are used in

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http://dx.doi.org/10.1016/j.surfcoat.2016.03.009

Table 1
Elemental composition of clad powders and substrate.

Material	Elemental composition (wt.%)	Average carbide size
WC-12Co MM powder	77.3 ± 1.3 W, 12.4 ± 0.6 Co, 10.2 ± 1.2C	2–5 μm
WC-12Co NM powder	74.6 ± 1.2 W, 12.5 ± 0.5 Co, 12.8 ± 1.1C	100–200 nm
SS-304 substrate	68.2 ± 0.3 Fe, 19 ± 0.4 Cr, 9.8 ± 0.2 Ni, 2.1 ± 0.2 Mn, 0.7 Si, 0.08C	–

applications involving mechanical and thermal loading. Furthermore, the adhesion or the interfacial strength between the clad and the substrate is greatly influenced by the presence of residual stresses [21]. The presence of residual stresses leads to delamination and spalling of the clad layer. Furthermore, the presence of compressive stresses at the interface inhibits the formation of through thickness cracks, improves adhesion, tribological and fatigue life of the components [21]. Non-destructive techniques, in particular the bending radius of substrate method and the X-ray diffraction, are popular to evaluate residual stresses in thin film such as coatings/cladding [22]. Spatial resolution below 1 μm is attainable using XRD techniques [22]. Presently there is no literature available on investigation of residual stresses in microwave clads. Therefore, in the present work, residual stresses in the MM and NM microwave clads were determined using the $\sin^2\psi$ technique through XRD. The aim of the present research is to investigate the correlation between the flexural strength and residual stresses in the MM and NM WC-12Co microwave clads.

2. Material and methods

2.1. Materials and cladding process

Austenitic stainless steel is widely used is several engineering applications attributed to its low cost, high tensile strength and excellent corrosion resistance. Therefore, an austenitic grade stainless steel (*SS*-304) was selected as substrate. Specimens of size 50 × 12 × 5 mm^3 were prepared from *SS*-304 rolled plates. The specimens were degreased and ground to achieve an initial surface roughness (R_a) of 0.2 μm. The chemical composition of the *SS*-304 substrate was determined using an optical emission spectrometer (Metavision, 1008i). The chemical composition of the *SS*-304 substrate is presented in Table 1. Commercially available micrometric (H.C. Stark, Germany) and nanometric (Hongwu Group, Hong Kong) WC-12Co powders were used to deposit clads on the SS-304 substrate using the microwave hybrid heating (MHH) technique. Further details about the clad powders are presented in Section 3.1.

The MM and NM clad powders were heated in conventional muffle furnace for 8 h at 120 °C to remove any possible moisture. The SS-304 specimens were ultrasonicated in an ethanol bath to remove any oil or grit and were hot dried. The clad powders were manually preplaced on the substrates maintaining an approximate thickness of 1 mm. A glass slide fixed on the tip of a CNC controlled spindle was utilised to maintain uniform thickness of the preplaced clad powder layer on the substrate. A 1 mm thick alumina plate (purity 99%) was placed over the preplaced clad powder layer. This alumina plate acted a separator between the clad powder and susceptor. A fine charcoal powder was used as the susceptor. The charcoal powder was placed above the alumina separator as schematically illustrated in Fig. 1. The charcoal initiates the heating and helps to raise the temperature of the clad powder beyond its critical temperature. Once the clad powder reaches its critical temperature, it couples with incident microwave radiation and get heated and subsequently melted. The metallic substrate was selectively masked in a carbon block to avoid reflection of microwaves in the applicator cavity. This hybrid heating arrangement was then exposed to 2.45 GHz microwave radiations in an alumina wool envelop in ambient conditions (Fig. 1). The alumina wool allows the microwaves to pass through and insulates the heat generated. The cladding was accomplished in an industrial multimode applicator (Enerzi Microwave Systems, MH-1514-101-V6) equipped with an infrared pyrometer (Range: 350 °C–1800 °C). The process parameters utilised in the present study are presented in Table 2. As a fact that nanometric powder has higher surface area than the micrometric powder, microwave interaction is faster and better in the nanometric powder [23]. Therefore, less power and exposure time is sufficient to develop the NM clads. The optimisation of process parameters was done on the basis of proper metallurgical bonding between the clad layer and the substrate, physical aspects like minimal porosity and cracks through trial and error method and is reported in our earlier work [13,23,25,26]. Further details on developing of clads through MHH are available elsewhere [12,13,20, 23–26].

The clad specimens were sectioned using a low speed diamond saw. The sectioned specimens were polished using standard metallographic techniques. The microstructure of the cross-sections of the MM and NM clads was studied using a Carl Ziess Ultra Plus SEM.

2.2. Flexural strength testing

The flexural strength test was used to evaluate the interfacial strength of the clad-substrate interface. The interfacial strength of the WC-12Co MM and NM clads was evaluated through the three-point bend test on a Instron 5982 UTM as per ASTM C1161 [27]. The test was carried out at a constant crosshead speed set at 1 mm/min (Fig. 2(a)). The size of clad specimen for flexural strength test was

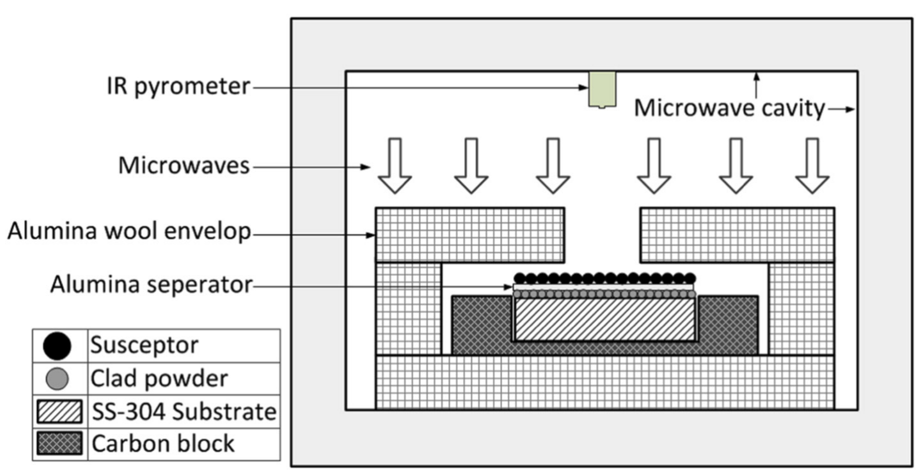

Fig. 1. Schematic representation of the MHH experimental setup used to develop the clads.