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Laser cladding of metal matrix composites reinforced by cermet inclusions for dry friction applications at ambient and elevated temperatures

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ABSTRACT

Metal matrix (CuSn, Stellite + CuSn, stainless steel + CuSn) composite coatings reinforced by conventional or nanostructured cermet inclusions (WC–Co, WC–Co–BN) are deposited by laser cladding. A particular focus is on minimising the heating of particles-in-flight by laser radiation. Coating microstructure, composition and element distribution are analysed. Dry friction coefficient at ambient and elevated (450 °C) temperatures is measured using reciprocated plate-on-plate test. Evolution of the friction coefficient during testing and its average value over a whole series of measurements *versus* coating composition are analysed and discussed as well as an eventual influence of cermet nanostructuring. Stellite + CuSn based coatings with nanostructured cermet inclusions are found promising for dry friction conditions at ambient temperature. In particular, their high performance is evident at the initial stage of friction tests when the accumulated debris quantity is limited. Evolution of the friction coefficient for ambient and elevated temperatures has qualitatively different characters. Conventional WC–Co–Cr coating deposited by detonation spraying is used for comparison.

1. Introduction

Laser cladding (LC) is a well-known technology that is widely applied for: (a) deposition of protective coatings, (b) repairing of worn-out parts and (c) direct manufacturing of near-net shape objects [1–6]. LC technology is based on the use and optimisation of diverse complex physical phenomena at different spatial, temporal and temperature scales [7–11]. It is possible to mix various powders during their addition to the cladding area and to obtain coatings with the required composition and internal structure [12–14]. Current trends in LC are to produce multifunctional protective coatings which combine several exploitation properties, for example, wear and corrosion resistance, high electrical conductivity and abrasion resistance, thermal resistance and low friction coefficient, *etc.* [3,4,6,7,13].

A metal matrix composite (MMC) belongs to a class of composites with at least two components one of which is a metal. MMCs are applied, for example, in the automotive and aerospace industries owing to their enhanced high temperature strength, fatigue resistance, wear resistance and lightweight design [15]. The performance of MMC objects are influenced by the properties of the particulate reinforcement phase such as chemical composition, shape and size, volume fraction and spatial distribution in the matrix [16–20]. MMCs reinforced by a ceramic component are increasingly used to meet technical challenges in terms of wear resistance and friction coefficient.

The objective of the study is to apply LC to deposit MMCs reinforced by nanostructured or conventional cermet inclusions for dry friction applications at ambient and elevated temperatures.

The present research follows the baseline developed in [21,22]. The novelty of this research lies in applying a cladding head conical in shape in order to minimise the overheating of the particles in-flight. Another novel aspect is that the deposited coatings were studied through the X-ray analysis to verify if thermally sensitive powders were decomposed or not, and a thorough investigation of the evolution of the friction coefficient over a whole series of measurements at ambient and at elevated temperatures.

2. Equipment

The experimental set-up consisted of an Ytterbium-doped fibre laser, a laser beam delivery system by fibre optics, a numerically controlled work station, a powder feeding system, and an originally developed cladding head.

The laser source was a 10 kW Ytterbium fibre laser LC-10 by IPG Photonics, 1.07 μm wavelength, CW mode. The work station was a KR-60-3 by KUKA Robotics supported by a substrate rotation system. The laser source and the work station were connected by an optical fibre with a diameter of 200 μm and a length of 20 m. The powder feeder

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was a Twin 10-C Sulzer Metco, 2-channel powder delivery system with an independent feeding rate for each channel. Argon was used as the carrier gas.

The originally developed "conical" cladding nozzle was applied to limit powder–beam interaction and to avoid powder decomposition. A shielding gas (Ar) was used to transport and protect the particles-in-flight as well as protect the melting pool from oxidation. The size of the laser beam spot on the substrate, depending on beam defocusing, varied from 0.2 mm (at the focal point) up to 6 mm (for a 30 mm defocusing distance).

The following LC parameters were used: laser power 1.8 kW–2 kW, cladding head velocity relative to the substrate 1.2–3.5 m/min, powder feeding rate 4–18 g/min, and clad width ranging from 1 to 7 mm.

Detonation spraying was carried out using an industrial type installation "Ob" developed by Lavrentiev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia. The detonation barrel has a length of 1200 mm and diameter of 20 mm. A $C_2H_2 + O_2$ gas mixture was used.

The powder size distribution was determined using a Malvern Mastersizer 3000 laser diffraction particle size analyser. SEM analysis of the powder was conducted using a Carl Zeiss Auriga CrossBeam Workstation with an Oxford INCA X-MAX EDS/EDX attachment for local energy-dispersive X-ray spectroscopy.

3. Experimental procedure

Before cladding, the powder was dried in a SNOL 60/300 furnace at 80 °C, and sieved using a HAVER EML 200 digital-plus device in order to obtain the desired granulometry. The effective sieve diameter ranged from 20 to 150 μm. Particles smaller than 20 μm were not specially removed. Their trajectories followed the carrier gas stream lines and, consequently, were different from those of coarser particles. Therefore, one can suppose that finer particles were not embedded into the cladded track.

The selected powder blends were mixed by a Turbula T2F powder mixer during 20 min.

The deposited coatings were investigated by metallographic examination, SEM, X-ray spectroscopy, and tribological tests. Equipment used for metallographic examination was from Wirtz-Buehler GmbH facilities including a linear precision saw and an automatic mounting press. Other equipment used included an Ecomet 300 Pro polishing machine, a Polimat electrolytic polishing and etching device, an Axio Observer A1m (up to ×1000) optical microscope, a Tukon 2500 digital microhardness (HV) tester, and a Shimadzu XRD-7000 X-ray diffraction system.

The evolution of the friction coefficient was observed by an originally developed reciprocated plate-on-plate installation under the following conditions: 5 mm plate-on-plate displacement; 10 mm/s sliding speed; 1 s for 1 cycle of displacement; total duration of the test corresponding to 360 cycles, that is to 1 h; 50 DaN load with 10 MPa resulting pressure; ambient or 450 °C temperature at friction interface; and 10 mm diameter alacrite disc as counterbody. The thin upper layer of the cladded surface was removed before the friction tests for all the coatings.

3.1. Powder used in experiments

Several different powders were applied for LC of MMCs reinforced by cermet inclusions. Two experiment protocols were applied: deposition of pre-mixed powder blends and *in-situ* powder remixing. Powder compositions and size distributions are listed in Table 1 and powder photos are presented in Fig. 1.

WC–Co powder was produced by mechano-chemical alloying. Its properties are as follows: real density — 12.5 g/cm^3; apparent density — 5.6 g/cm^3; mean particle size — 56 μm; and WC crystal size — 13 nm. The properties of the nanocomposite WC–Co–BN powder produced by the same method are as follows: real density — 11.9 g/cm^3; apparent density — 5.2 g/cm^3; mean particle size — 28 μm; and WC crystal size — 13 nm.

Table 1
Powder composition and size distribution.

Powder specification	Powder composition (wt.%)	Particles size distribution (μm)
Stellite Grade 12 HMSP 2541, Osprey	C 1.35; Cr 30.5; Fe 3; Ni 3; Si 1; Mn 1; W 8.5; Co balance	−150 + 53
CuSn, Osprey	Sn 38.9; P 0.16; O 0.012; Cu balance	−106 + 10
BRONZE, BROV 10-1	Cu 89; Sn 10; P 1	−80 + 10
WC–Co–Cr Dimalloy 5849, Sulzer Metko	WC 86; Co 10; Cr 4	−45 + 11
Stainless steel 430 L, Ospray	FeC; Fe 81.79; Cr 17; Si 0.7; Mn 0.5; C 0.01–0.03	−53 + 10
Nanostructured WC–Co, MBN	WC 70; Co 30	−75 + 38
WC–Co–BN, MBN	WC 65; Co 30; BN 5	−60 + 10

Substrate material was Cr–Ni stainless steel (Cr 25%, Ni 18%, Si 1%, and Fe rem.).

3.2. Laser cladding parameters

The coatings were produced by the superposition of individual laser cladded beads with 20% overlapping. Composition of the powder mixtures and the laser cladding parameters are presented in Table 2. A plus sign (+) indicates individual components of a given powder mixture, a slash sign (/) serves to separate numbers indicating volume percentage of an individual powder in a given mixture. The compositions of the individual powders are indicated in Table 1.

Two methods of powder blend supply into the working zone were applied: one through a single channel of the powder feeder and another through two channels simultaneously. In the latter case, metals and cermets were mixed *in-situ* during the cladding process.

The criteria to choose the optimal cladding parameters were based on the observations of the cladded layer geometry and microstructure. The primary objective was to avoid cracks, porosity and poor remixing of different components of the powder blends. The conditions of powder injection were adjusted to avoid thermal decomposition of WC and BN. When the particle trajectory is quasi-parallel to the laser beam, the particle, due to a long exposure, is drastically heated and can reach its boiling point [11]. When there is a limited particle trajectory/laser beam intersection, the particle is only slightly heated. In order to minimise powder–beam interaction, the particle injection was angled at 45° relative to the laser beam (or normal to the surface). The aim was to let the particles reach the molten pool without being directly heated by laser radiation. Owing to this 45-degree injection angle, the method applied in this study could be seen more as "conical" rather than "co-axial". The schematic diagram of the laser cladding nozzle is presented in Fig. 2.

Detonation spraying was carried out using an industrial type installation "Ob" equipped with a 1200 mm detonation barrel. It was filled at 65% of its volume by a $C_2H_2 + O_2$ gas mixture, the spraying frequency was 5 Hz and the stand-off distance was 180 mm. The spraying parameters were optimised to completely melt the Co binder and to minimise thermal decomposition of WC.

4. Results and discussion

4.1. Coating microstructure

The microstructures of several MMC coatings are presented in Figs. 3–7.

The commercial cermet powder WC–Co–Cr (−45 + 11 μm) is characterised by a smaller particle size than the size of the nanostructured WC–Co (−75 + 38 μm) powder. However, it was found that nanostructured WC is much finer dispersed in the bulk of MMCs (see Fig. 1) as it had been stated previously in [22].