

Development of High Strength, High Thermal Conductivity Cold Sprayed Coatings to Improve Thermal Management in Hybrid Motorcycles

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ABSTRACT

The deposition of thick, pore-free, high-performance copper alloy matrix composite coatings is a topic of interest for several industrial applications, including friction materials, high-strength electrical contacts, and welding electrodes, among others. This study investigates the use of cold spray to deposit CuCrZr/Al₂O₃ cermet coatings on aluminum alloy 6060. The objective is to integrate copper-based materials with aluminum-based materials, ensuring a high degree of mechanical and thermal contact, using a low temperature process that does not adversely affect the properties of the base materials. This technique can be used to produce integral coolers and aluminum-based bearings for automotive and motorcycle applications. Fused and crushed alumina and gas-atomized CuCrZr powder blends have been used as initial feedstocks, with compositional weight ratios of 65/35 and 80/20 (ceramic/metal). The coatings have been characterized in terms of microstructure and morphology, coating microindentation hardness, cohesion strength, and adhesion strength to the aluminum alloy substrate. Microindentation hardness greater than 200 Vickers, adhesion strength greater than 50 MPa, and cohesion strength up to 250 MPa have been obtained. Thermal conductivity up to 110 W/mK has been obtained for both as-deposited and thermally-annealed coatings.

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INTRODUCTION

Since ancient times, copper and copper alloys have been extensively employed in friction and wear applications, due to their combination of abrasion resistance in lubricated conditions, ductile behavior under high bearing loads, and high thermal conductivity [1]. In past decades, Cu-Be alloys satisfied the most important needs for mechanical applications, providing a combination of hardness, mechanical strength, and thermal conductivity [2, 3]. However, due to the toxicity of Be, there is demand for Be-free copper alloys [2].

Copper-based cermet composites can meet this demand by providing improved mechanical properties compared to pure copper, while preserving its excellent thermal and electrical

properties. These composite materials could find different industrial applications in various areas like electrical contacts, lead wires and conductors in high-temperature electrical applications [4, 5], spot and seam welding electrodes [6], high thermal conductivity and corrosion-resistant components, rocket thrusters and components in aircraft engines [7]. Currently, there is a significant amount of research on innovative and high-performance copper-based materials, both in the form of bulk materials, but in particular as thin and thick coatings.

Many authors have reported the successful use of gas dynamic cold spray technology for the deposition of different copper-based materials. This technique avoids coating oxidation and preserves the properties of the base material by means of low

temperature deposition. For example, Borchers et al showed that pure copper coatings deposited by cold spray exhibit high microstructure compactness with low porosity and oxide content, leading to electrical resistivity values very close to that of cold rolled copper [8]. Similarly, Schmidt et al deposited copper coatings demonstrating properties close to highly deformed bulk material [9]. Raj et al used cold spray to deposit a CuCrAl coating, which proved to be effective in preventing the cyclic oxidation of GRCop-84 substrates for space launch vehicles up to 1075K [10].

The use of cold spray technology to deposit of copper and copper alloy matrix cermet coatings has also been extensively reported in the literature. For example, Sundarshan et al used cold spray to deposit nanocrystalline Cu/Al₂O₃ composites on copper substrates, revealing the role of alumina in inhibiting grain growth and in strengthening of the copper matrix [6]. Rech et al studied the influence of alumina content on microstructure, microhardness and coefficient of friction in cold sprayed Cu/Al₂O₃ coatings obtained by using powder blends as an initial feedstock [11]. Koivuluoto et al showed that the addition of Al₂O₃ particles to Cu powders in the low pressure cold spray process improves coating quality by densifying the coating structure [12].

The aim of this work was to explore the possibility of obtain high-strength composite copper-based coatings by cold spray deposition of a blend of CuCrZr alloy and alumina powder. CuCrZr alloy has been selected because of its wide use in several industrial applications, for example as overhead contact wires for electric railways, electrodes and holders for welding, electrical components working under mechanical stress and spark, lead frame for integrated circuit, molds and dies for continuous casting of metals, and heat sinks for nuclear power reactors [13, 14]. It is characterized by high conductivity and mechanical strength [15]. Strengthening the copper matrix with alloying elements such as Cr and Zr helps to further improve the mechanical and tribological properties of the composites, through the combined effects of age hardening and composite strengthening [14]. On the other side, Al₂O₃ has been widely employed as ceramic filler [16, 17, 18] due to its hardness, mechanical strength, and thermal resistance, as well as its market availability, and ease of obtaining stable and highly processable blends by cold spray.

One possible application of such coatings would be in the integration of fin-shaped coolers used to cool power electronics in hybrid or pure-electric motorcycles. Such coatings could be used to minimize the interface thermal resistance between the hot parts and the cooling fin.

EXPERIMENTAL PROCEDURE

Feedstock Materials

The powder feedstock of CuCrZr was produced by gas atomization (TLS Technik GmbH & Co. Spezialpulver, Cu18150). The particle size was of $-45+20\text{ }\mu\text{m}$. The chemical

composition of the alloy was Cu-1wt%Cr-0.1wt%Zr. The alumina powder used in this experiment was a commercial powder (H.C. Starck Amperit 740.000, fused) with a particle size of $-22+5\text{ }\mu\text{m}$. Two different CuCrZr/Al₂O₃ powder blends, with alumina contents of 65% and 80% respectively by weight, were mixed for 60 min in a mechanical shaker (GlenMills Turbula T2F). The morphology of the powders was examined using scanning electron microscopy. A SEM micrograph of the CuCrZr/65% Al₂O₃ blend is shown in Figure 1. It can be seen that the powder mix consists of spherical CuCrZr and sharpened alumina particles.

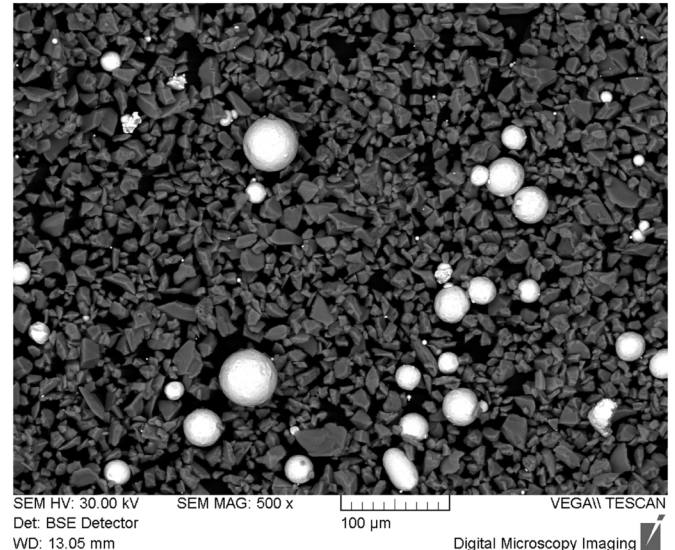


Figure 1. SEM image of the CuCrZr/65% Al₂O₃ blend.

Production Process

The deposition of both composite coatings (65% and 80% wt. alumina content, respectively) and pure CuCrZr coatings were carried out on aluminum alloy 6060 plates using a Sulzer Kinetik 4000 Cold Spray System equipped with a WC/Co Type 24 nozzle. In order to evaluate the temperature effect, the process gas temperature was varied in the range of 200-750°C and a set of deposited coatings was obtained as listed in Table 1. Other deposition parameters, such as processing gas (N₂), gas pressure (30 bar), nozzle standoff distance (20 mm), number of passes (1) and scan spacing (1 mm), were kept constant, in order to emphasize the role of gas temperature on coating microstructure and properties. The CuCrZr/80% Al₂O₃ coatings were deposited at not more than 550°C. Higher process gas temperatures are difficult to employ with highly ceramic-rich powder blends, since severe erosion of the internal walls of the nozzle occurs, which induces a rapid decay of the system's performance.

The deposition procedure was adjusted in order to deposit adhesion and cohesion specimens for ASTM-C633 and TCT characterization, respectively. Adhesion specimens were deposited with 65% and 80% Al₂O₃ powder mix at 450°C on

cast A357 aluminum substrates with a hardness of 126 HV_{0.5}. Two sets of TCT specimens were deposited with 65% Al₂O₃ powder mix at 450°C and 750°C on AISI 430 steel.

Table 1. Deposition parameters for coatings deposited on AA6060 plates

ID	Feedstock Al ₂ O ₃ (wt.%)	Transverse speed (mm/s)	Feeder rotation speed (RPM)	Gas temperature (°C)	Gas flow rate (m ³ /h)
ID01	0	100	4	200	94
ID02				300	85
ID03				350	83
ID04				450	78
ID06				550	73
ID07				650	67
ID08				750	63
ID11				200	93
ID12	65	20	4	300	84
ID13				350	82
ID14				450	78
ID15				550	72
ID16				650	68
ID17				750	65
ID21				350	82
ID22	80	10	6	450	78
ID23				550	72

The influence of post-deposition precipitation hardening heat treatment on coating microstructure and cohesion was also studied. Coatings were deposited on steel substrates with a gas temperature of 750°C. The thermal treatments were conducted in a vacuum furnace (TS-UHV 25/25/25 TAV). Specimens were heated to 425°C in about 30 minutes and held at temperature for 2 hours at a pressure 10⁻¹ Pa, then fan-cooling in nitrogen, with a cooling rate of about 1.5°C/s in the temperature range of 425-200°C.

Characterization Procedure

The coatings were characterized in order to determine microstructural, mechanical and thermal properties. Coating thickness was measured using a micrometer (Kennon Instruments) with a spindle diameter of 6.45 mm. Five thickness measurements were taken per coating. Microstructure observation was carried out by means of light optical microscopy (Leica DM6000M) and scanning electron microscopy (Tescan VEGA LMU). The ceramic particle content was evaluated as a function of gas temperature and initial feedstock composition by image analysis performed using ImageJ software. Each coating characteristic was obtained by

processing ten micrographs obtained with 200X magnification. Coating microhardness was measured using a Vickers microhardness tester (Leica VMHTAUTO) on cross-sectioned samples that were mechanically polished to 3 µm; 15 measurements for each sample were taken. Evaluations of the coatings' adhesion and cohesion strength were performed following the ASTM C633 standard and the tubular coating tensile test (TCT), respectively [9, 19]. The pull-off apparatus was a MTS mechanical testing machine under force control and the load was measured by a 50 kN load-cell. Averages and standard deviations of three measurements per set were calculated. In the TCT test, the coating thickness was around 1.0 - 1.5 mm. The mechanical coating strength was estimated to be 1.5 times the average von Mises stress, comparable to conventional tensile tests (MFT test) [9]. Thermal conductivity was evaluated by using a LFA 457 Microflash apparatus (NETZSCH) equipped with liquid nitrogen cooled InSb detector. The laser wavelength was 1054 nm (up to maximum energy of 15 J) and the pulse duration was set to 300 µs. The sample density was evaluated as the ratio between the sample mass and the geometrical calculation of the sample volume (Mitutoyo MDC-1"SFB), while the specific heat value was determined by employing a pure iron certified sample (supplied by Netzsch) as internal standard during the measurement. The test was performed in a pure argon atmosphere to avoid oxidation, and each measurement was repeated five times in order to have higher reliability.

RESULTS AND DISCUSSION

Coating Growth

The overall coating thickness as a function of the process gas temperature, for both the CuCrZr/65% Al₂O₃ and un-mixed CuCrZr alloy, are shown in Figure 2. As may be seen, the pure CuCrZr exhibited a noticeably larger growth rate than blend, so the transverse speed used to obtain similar overall coating thickness was 100 mm/s rather than 20 mm/s employed with the blend. This reduction of the growth rate observed with blends containing high ceramic content (approximately more than 40 % wt. [18]) may be attributed to the different flowing abilities and deposition efficiencies between metal and ceramic powders as well as to the erosion effect of the ceramic particles [20]. This behavior is in agreement with the results obtained by many authors [16, 17, 18, 21]. All the powder blends show that the higher thicknesses are obtained at higher spray temperatures. This is because increasing of the process gas temperature increases the gas velocity in the nozzle, consequently increasing the particle velocity and the deposition efficiency [19]. The CuCrZr alloy growth rate behavior shows a quite deep rise in the low-temperature region between 200°C and 400°C and then reaches a plateau at 400°C, maintaining a stable value up to 750°C. This indicates that the saturation limit of the deposition efficiency has been reached [9]. In contrast, the CuCrZr/65% Al₂O₃ growth rate exhibits a continuous rise in the whole temperature region shown in Figure 2.