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Alumina coatings obtained by thermal spraying and plasma anodising — A comparison

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ABSTRACT

Thermally sprayed alumina coatings are widely used in a range of industrial applications to improve wear and erosion resistance, corrosion protection and thermal insulation of metallic surfaces. These properties are required for many components to be used for production processes in the paper and printing industry.
Another appropriate method to produce ceramic coatings is the plasma electrolytic oxidation (PEO). However PEO can only be applied on self-passivating metals like aluminium, titanium, magnesium and their alloys. The present paper concerns a combination of cost-efficient arc spraying and flame spraying of Al coatings (Al99.5, AlCu4Mg1) on steel substrates and post-treatment by plasma-electrolytic oxidation (PEO). The microstructure and phase composition of generated oxide coatings are examined and discussed. The created Al_2O_3 layers show outstanding hardness up to 1600 HV0.1, good bonding strength and excellent abrasion resistance compared to atmospheric plasma-sprayed Al_2O_3-coatings. The results show the superior performance of PEO-coatings and demonstrate their applicability for technical components in extreme operating conditions.

1. Introduction

Wear-resistant Al_2O_3 coatings are often applied via atmospheric plasma spraying (APS). Mechanical and other properties of plasma-sprayed Al_2O_3 coatings are primarily determined by phase composition and porosity [1–3]. Low porosity indicates high melting rates of the corundum spray particles. Quick solidification of the molten alumina particles leads to the formation of meta-stable γ-Al_2O_3 and amorphous Al_2O_3, which show lower hardness compared to corundum (α-Al_2O_3). On the other hand, lower melting rates result in higher porosity, lower coating cohesion and decreased wear resistance.

Plasma-electrolytic oxidation (PEO), also called microarc oxidation (MAO) or spark discharge anodising, is a method to produce ceramic coatings on self-passivating metals such as aluminium, magnesium, titanium, zirconium and their alloys [4,5]. PEO-treated aluminium parts show highly improved wear and corrosion resistance. The process is based on oxide film formation under plasma conditions in low-concentrated alkaline electrolytes [6,7]. This method is an alternative to electrochemical anodising, in particular with regard to the very high hardness of the PEO layers of up to 2000 HV [8]. Hence the PEO process can also be applied as a post-treatment of thermally sprayed aluminium coatings on steel and other materials to improve their functional properties, especially for lightweight construction and high-performance applications. Due to low thermal load even polymeric and polymeric composite materials can get aluminium coated and PEO-treated. The variability of PEO process parameters (electrolyte composition and temperature, treatment time, current density, alternating or direct current, voltage) allows the adjustment of microstructure and properties of the alumina coatings according to the requirements.

The paper compares the microstructure and the properties of APS-Al_2O_3 coatings and of oxide coatings obtained by PEO post-treatment of arc- and flame-sprayed aluminium coatings applied on steel substrates. The influence of the chemical composition of the sprayed aluminium alloy on the microstructure of obtained PEO coatings is

Table 1
Spray parameters for arc, flame and atmospheric plasma spraying.

Spraying parameters	Value			Unit
	Arc spraying	Flame spraying	APS	
Power	–	–	45	kW
Voltage	27	–	–	V
Current	80–100	–	580	A
Powder feed rate	–	20	30	g min^{-1}
Wire feed rate	2×75	–	–	mm s^{-1}
O_2/C_2H_2 pressure	–	0.03/0.07	–	MPa
Ar/H flow	–	–	41/12	l min^{-1}
Spray air pressure	0.2	0.3	–	MPa
Spraying distance	150	250	110	mm

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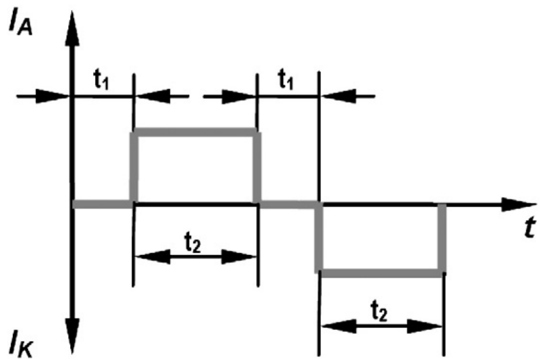

Fig. 1. Rectangular current shape of PEO treatment with $t_1 = 5$ ms and $t_2 = 10$ ms.

examined. The abrasive wear resistance, the bonding and fatigue strength of alumina coatings are characterised and discussed. The results show the high performance of alumina coatings produced by plasma-electrolytic oxidation of flame- and arc-sprayed aluminium coatings in comparison to conventional atmospheric plasma-sprayed alumina coatings.

2. Experiments

2.1. Flame and arc spraying

To increase the mechanical bond strength of spray coatings, all steel substrates (S355JR) were pre-treated by grid-blasting. The aluminium alloys Al99.5 (EN AW-1050) and AlCu4Mg1 (EN AW-2024) were thermally sprayed on the steel substrates using an OSU arc-spraying equipment (Sulzer, Switzerland) and a CastoDyn 8000 flame spray system (Castolin Eutectic, Switzerland) under spraying parameters given in Table 1. With both methods, a coating with a thickness of 250 to 300 μm was sprayed.

2.2. Plasma-electrolytic oxidation

The arc- and flame-sprayed aluminium coatings were plasma-electrolytically post-treated using a typical PEO setup. The oxide coatings were synthesised under pulsed alternating current (current density I_A and I_K: 50 A dm^{-2}) with rectangular current shape (Fig. 1). The temperature of the aqueous alkaline electrolyte (containing 3 g l^{-1} Na_2SiO_3 and 5 g l^{-1} KOH) was kept within a range from 18 to 20 °C. Due to steel is not a valve metal a complete oxidation of sprayed aluminium coatings would lead to PEO coating delamination. The process time was chosen to be 75 min to achieve only a partial oxidation of the thermally sprayed Al coatings.

2.3. Atmospheric plasma spraying

APS was carried out with an F6 plasma spray torch (GTV Verschleiss-Schutz GmbH, Germany) on the steel substrates mentioned above with spray parameters given in Table 1. Corundum powder with a defined grain fraction (−45 +20) was used to prepare Al_2O_3 coatings with a thickness of 200 μm.

2.4. Characterisation and testing

For materialographic investigations of the cross sections, the optical light microscope Olympus PMG 3 and the scanning-electron microscope LEO 1455VP were used. The composition of the coating phases was determined by X-ray diffraction (XRD, Siemens D5000) using Cu-K_α radiation (2θ between 20° and 70°, step time: 10 s, step: 0.02°). The hardness of the coatings was measured with a microhardness tester (Struers Duramin) according to the Vickers scale under a load of 100 g.

The alumina coatings were tested concerning their resistance against abrasive wear load. The rubber wheel wear test (ASTM G65, 130 N force, 71.8 m/718 m/1436 m testing distance each sample) was applied to determine the wear resistance of the PEO coatings against the non-fixed abrasive in comparison to plasma-sprayed alumina coatings. In addition, cyclic 3-point bending tests were performed to investigate the bond strength of the coatings to the substrate material. Samples of 20 × 10 × 100 mm were loaded at a stress ratio of 0.1 and a frequency of 20 Hz with a bearing distance of 80 mm. Tensile stress was applied to the coated plane. Fatigue tests of up to 2×10^6 cycles were performed and recorded in an S–N curve, comparing the coated material and the uncoated, grid-blasted reference material.

3. Results and discussion

3.1. Microstructure

The thermally sprayed Al coatings show a typical lamellar structure with interlamellar oxidation and good substrate bonding. The coatings exhibit a typical appearance for each spray method independent of the sprayed aluminium alloy. A comparison of arc- and flame-sprayed AlCu4Mg1 coatings is shown in Fig. 2. Due to the higher melting rate of the spray feedstock, the arc-sprayed coatings exhibit a more homogeneous microstructure than the flame-sprayed coatings. For both spray methods, the coating thickness averages 250 μm and the porosity is in the range of 4–6%.

The growth of PEO coatings on thermally sprayed Al coatings generally starts from the surface and propagates in the direction of the substrate [9]. The resulting coating structure can be classified into three different layers: the required mechanical properties of the

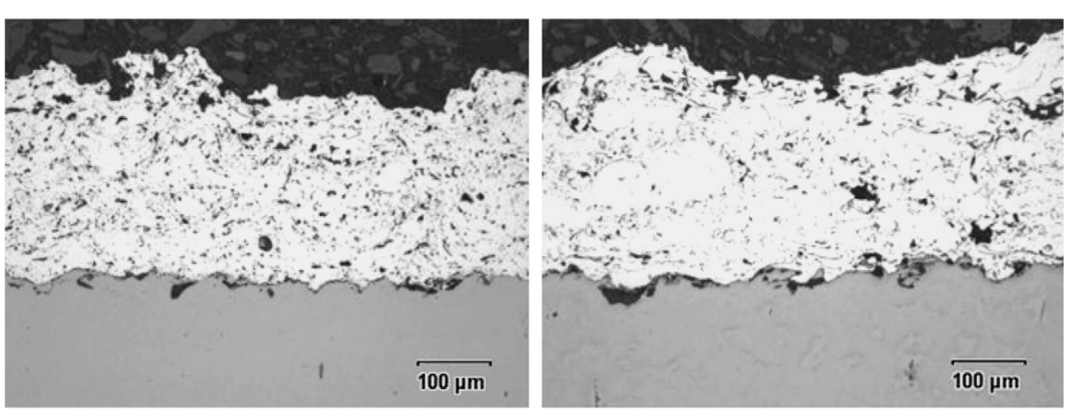

Fig. 2. Cross-sections of arc-sprayed (left) and flame-sprayed (right) AlCu4Mg1 coating with a thickness of 250 μm and a porosity of 4–6% before PEO treatment.