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Morphology and wear behaviour of single and multi-layer electrical discharge coatings

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Abstract

Electrical discharge coating (EDC) is a version of electrical discharge machining (EDM) which can produce a coating of material from a tool or from a powder suspended in the oil, onto a workpiece. Since spark temperatures are high, a large range of materials, such as hard ceramics, can be melted and deposited in the coating. These material properties, combined with the rapid quenching of the EDC layer, result in coatings which are typically very hard. Since EDC is an adaptation of EDM, coatings can be produced on components with conformal surfaces. In this study, hard ceramic materials tungsten carbide and powder-sintered titanium carbide are used as negative polarity tool electrodes, from which material is donated to produce hard coatings. The workpiece material is 304 stainless steel. Mechanical properties of the single and multi-layer coatings are assessed by dry sliding wear testing using the ball-on-flat method. Morphology and composition both on the surface and in cross-section are also analysed using SEM and EDX. The TiC single layer coating produced the best wear results for the conditions of the experiment, with the lowest and most constant coefficient of friction of approximately 0.2-0.3 despite cracking remaining in this layer. The TiC + Si double coating, despite better morphology including eliminated surface cracks, produced worse friction characteristics compared to TiC.

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Keywords: EDM; EDC; coating; multi-layer; TiC

1. Introduction

Electrical discharge coating (EDC) is an adaptation of electrical discharge machining (EDM), which is able to produce a coating of material on a workpiece, from a tool electrode or a powder suspended in the dielectric oil. The high spark temperatures associated with EDM are exploited in order to deposit useful materials such as ceramics which possess high melting points and hard wearing properties. Deposition of hard ceramics, such as titanium carbide, combined with rapid quenching of the EDC layer, result in coatings which are typically very hard [1, 2]. Combined with the ability to deposit materials with high melting points, EDC can be used to coat complicated shapes and sunken cavities, as is the case in normal EDM, making the process particularly suited to machining tools and mould tools. The application of EDC is limited by the poor integrity of the surface. The surface, much like normal EDM, is often characterised by cracking, porosity and high roughness, factors which limit the tribological properties of the coating. it has been shown that the presence of porosity worsens the delamination wear behaviour on plain iron via stress concentration as well as collection sites for wear debris [3]. Previous work on EDC has produced coatings exhibiting porosity and cracking, for example, Hwang et al. [4] produced coatings of TiC from titanium + graphite sandwiched electrodes, which exhibited poor surface quality, including porosity, cracking and high roughness. These factors are exacerbated when the coating material possesses very different thermal properties to the substrate material.

The aim of this study is compare the dry sliding wear behavior of single and multi-layer coatings via the ball-on-flat testing method. The study also aims to investigate the morphological characteristics and composition of coatings

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produced using TiC, Si and Cu electrodes. More specifically the study aims to determine if improved surface properties including reduced crack and pore density can improve the wear performance of ED coatings. A comparison will also be made with a simple EDM surface to evaluate the impact of the EDM process alone on tribological behavior.

2. Experimental

A Mitsubishi EA12V EDM machine was used for all coatings. 304 stainless steel was used as the substrate for all coating, and all substrates were polished to a mirror finish with 1 µm grit before coating. Experimental parameters used for the coatings are shown in Table 1.

Table 1. EDC parameters

Electrode material	TiC, Si, Cu
Workpiece material	304 stainless steel
Oil	Shell Paraol 250
Tool polarity	Negative
Current (A)	10 (TiC, Cu), 5.5 (Si)
On-time (µs)	8
Off-time (µs)	256 (TiC, Cu), 64 (Si)
Gap voltage (V)	320 (TiC, Cu), 260 (Si)

Flushing was directed at the location of coating for all samples in order to maintain stable spark conditions. Coatings investigated were titanium carbide, titanium carbide + silicon, pure silicon, and pure copper. Scanning electron microscopy (SEM) was performed using a Hitachi S2600N and a Philips XL30 SEM. Energy dispersive X-ray spectroscopy (EDX) was on the Philips SEM equipped with performed using an Oxford Instruments INCA X-ray Microanalysis system at a beam voltage of 20 kV. Large-area EDX measurement was performed over an area of 1.2 mm2. ImageJ software was used for crack length analysis, in which cracks were traced and measured manually, using 5 images for each sample each covering 0.3 mm^2. Ball-on-flat reciprocating wear tests were performed using a CETR Universal Micro-Tribometer (UMT-2) with a silicon nitride (Si_3N_4) ball, using 10 N force, 100 rpm for 10 minutes. Box plots used to represent data contain a small box for the mean value, a large box representing lower and upper quartiles and median value. Whiskers represent 5% and 95% of the data, and the cross represents the maximum value. Error bars on graphs represent the minimum and maximum of the values used to calculate the mean.

3. Results and discussion

3.1. Coating characteristics

All single layer coatings were produced using 500 µm of z-axis displacement as a benchmark. This allowed sufficient coatings to be produced and compensating for misalignment of electrode and workpiece. TiC and Si coatings were produced from sacrificial coating electrodes designed for shedding of material and deposition as a coating. A standard pure Cu electrode was also used in order to compare the coatings with a typical EDM surface. SEM images of the coating surfaces can be seen in Figure 1.

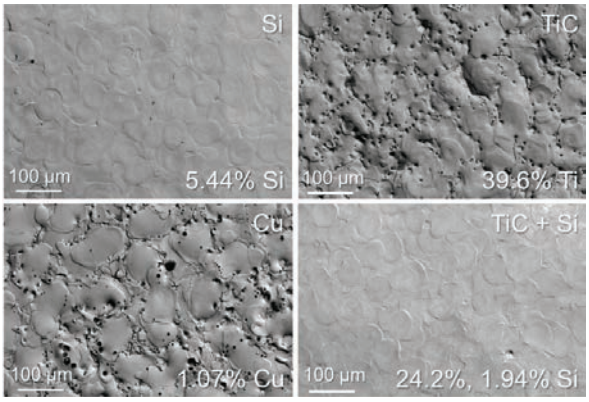

Fig. 1. Surface morphology of different ED coatings

Based on imaging of the coating surfaces, both Cu and TiC surfaces were dominated by porosity and cracking, in contrast to the Si surface characterised by smooth craters and absent of cracks and pores. All coatings possessed distinct compositions, with the TiC coating containing the highest level of deposited material with 39.6% of Ti, compared to 5.44% Si using the silicon electrode and just over 1% of Cu detected on the surface coated using the pure copper electrode. Based on this, the ability to successfully coat a surface with a sacrificial tool electrode material depends strongly on the electrode material type. Si was investigated as a second coating layer in order to introduce the improved surface properties of no porosity or cracks observed on the pure Si layer, onto the TiC layer. Crack density with different wear amount of Si was investigated, and the results are shown in Figure 2.

In terms of surface crack density, after 0.5 mm of Si wear, density was reduced by a factor of 5 compared to the TiC only surface, and after 1 mm of Si coating, cracking was virtually eliminated, being reduced by a factor of approximately 500. This was not further improved with continued addition of the Si layer, but was in fact slightly worsened. For this reason, the coating containing TiC + 1 mm of Si was used as the double layer coating in the friction tests in order to appraise the performance of these coatings.

3.2. Cross-sectional analysis

In order to confirm the composition, thickness and extent of cracking and porosity in each layer, it was necessary to perform analysis on the etched cross-sections of the coatings. Surface compositional analysis is not sufficient to describe the entire thickness of the coating layer due to the limited electron interaction volume. Box plots of the layer thickness of TiC and TiC + Si can be seen in Figure 2 (a). Cross-sections and EDX maps of TiC and the TiC + Si double coating can be seen in Figure 3. Interestingly, the addition of the Si coating reduced the average thickness of the coating from 8.0 to 7.1 µm, and the maximum thickness was reduced from 14 to 10 µm.