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A study of tribological behaviour of W-Co and Cu electro-spark alloyed layers under lubricated sliding conditions☆

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ABSTRACT

Electro-spark-alloying was used to enhance tribological properties of carbon steel surfaces. Two different materials - copper and W-Co were used for alloying. Surfaces were compared according to topography, mechanical and tribological properties. The properties of alloyed surfaces were compared with untreated steel surface. Results show that electro-spark-alloyed surfaces have high roughness which must be reduced during grinding or polishing. The alloyed surfaces possess better tribological properties in comparison to untreated steel surface. The W-Co alloyed surface shoved the best tribological properties. The surface after the test has almost no wear and its steady state friction was about 30% smaller. Alloying with copper reduced wear more than two times, however its run-in friction is unacceptable.

1. Introduction

Electrospark alloying (ESA), also known as electrospark deposition, is a pulsed micro-welding process which uses short duration high current-low voltage electrical pulses to transfer material from the electrode (anode) to a contacting substrate (cathode). During each pulse a small amount of anode material is melted in an extremely high temperature (8000–25000 °C) of plasma arc and rapidly (10^5–10^6 °C/s) cooled down when it reaches the substrate surface. In such conditions very fine nano-sized grains or even amorphous structures of alloyed layer can be formed [1].

ESA has some inherent peculiarities which distinguish this method among the other surface treating methods. The main advantages of ESA include wear, friction and corrosion resistance improvement. Due to strong metallurgical bonding between coating and the substrate it possesses excellent adhesion. Extremely short pulse duration ensures that a very little heat is transferred to the work-piece; therefore the substrate has a small temperature increase and suffers minimal structural changes. Its simplicity, easy operation, and relatively low cost are attractive for surface engineering. Among the disadvantages high surface roughness, cracks, and porosity can be distinguished [2–4]. These limit the wider application of the method. Nonetheless there are a lot of studies suggesting methods to overcome mentioned drawbacks [2,3].

ESA alloyed layer thickness, purity, and mechanical properties are strongly related to processing conditions. Electrode and treating surface materials are mixed during ESA process, therefore purity of alloyed layer increases with processing time and number of superimposed layers [4,5]. The layer thickness follows the same route until particular surface purity is reached. At that point thickening process slows down or even opposite process - erosion can start [2]. Usually ESA layers contain three zones: alloyed surface, substrate, and transitional zone in between. These zones possess particular mechanical properties which can defer several times. A lot of studies confirm a sharp hardness variation in cross section of the layer [3–9]. The conclusion can be made that tribological properties of such layers is hardly predictable because after a few micrometres of wear the conditions can be substantially different.

ESA treated surfaces typically have relatively high roughness (Ra=2…18 μm) which limits wider application of this method in friction pair surface strengthening [6]. The alloyed surfaces contain differently shaped pits and convex asperities, their size mostly depend on the processing parameters. The pulse energy, pulse duration, treating time, and number of superimposed layers all are responsible for surface roughness [2,5]. In general, increasing pulse energy and treating time leads to higher surface roughness, however the layer thickness also increase [2]. *Ribalko and Sahin* showed that surface roughness sharply rises with pulse energy and processing time, however processing time is more important in high rather than low energy pulse [2]. The number of

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superimposed layers makes the surface layer more even. Nonetheless, during repeated processing the sparks tend to jump at the highest asperities and increase their height, consequently increasing roughness. Moreover, the repeated thermal shocks involve more tension to the surface which can lead to crack formation [5]. Besides the processing parameters, the alloying environment is important too. *Chang-bin* et al. observed that nitrogen gas and silicon oil environments can improve surface roughness and allow getting crack-less dense layer [3]. However the surfaces still are not smooth enough to be used in lubricated friction conditions.

A lot of studies show dramatic improvement in wear and friction after ESA treatment [3–6,10]. Graphite alloyed titanium surface become 10–29 times more wear resistance then the substrate [3]. WC-Co alloyed steel surface was 11 times more wear resistant, while hardness between alloyed surface and the substrate defers only four times [6]. Both wear and friction depend on ESA treated surface microstructure [10]. Recently performed investigations of ESA layers mostly are limited to dry friction conditions. Therefore the aim of current study is to investigate tribological properties of ESA layers under lubricated contact conditions.

2. Materials and methods

2.1. Electro-spark-alloying and surface preparation

Two different materials were used to alloy surfaces. One was cooper (Cu 99.9%, Alfa Aesar) and another - tungsten-cobalt carbide (W-Co) (W-15%, Co-6%, WC-79%) hard alloy stick (Plant Industrial Tools, Ukraine). First few layers were coated with vibratory electrode (device MPI- 702ER): frequency of oscillation was 30 Hz, working average current – 3 A, working average voltage – 63 V, diameter of anode 1.3 mm. Last few layers were made with rotating electrode (device MPD-103): frequency of oscillation was 100 Hz, working current – 2 A, working voltage – 30 V, diameter of anode 3 mm. Travel speed in both cases was 50…60 mm/min. To avoid extensive oxidation of heated metals, alloying was performed in argon gas atmosphere (10 l/min flow rate). After alloying surfaces were grinded with 500 grits sandpaper. Surface composition was analysed with EDS Bruker XFlash 6/10 in conjunction with SEM Hitachi S-3400N.

2.2. Surface morphology and mechanical properties investigation

ESA treated surface morphology was analysed using optical microscopy Nikon Eclipse - MA 100 and SEM Hitachi S-3400N. Surface roughness and topography measurements were made using stylus profilometer Mahr GD 25, (Mahr GmbH, Germany). The stylus tip radius – 2 µm, roughness measurement length 5.6 mm. Surface arithmetic mean roughness (Ra), root mean square roughness (Rq), mean roughness depth (Rz), maximum roughness depth (Rmax), mean profile valley depth (Rv), mean profile peak height (Rp), kurtoses (R Ku), and skewness (R Sk) were evaluated.

Indentation hardness, Martens hardness, indentation creep, and elastic part of indentation work were measured with a MicroCombiTester (CSM Instruments, Switzerland) using Berkovich indenter at a load of 100 mN.

2.3. Tribological properties investigation

An assessment of tribological properties was performed in the ball-on-plate reciprocating rig on a TRM-500 tribometer (Dr.-Ing. Georg Wazau Mess- + Prüfsysteme GmbH, Germany). In order to measure the evolution of wear rate at several points throughout the testing, the tests were conducted as stripe tests [10]. For the initial 10 cycles, the track length was 15 mm, the following 100 cycles, have shorter track length of 10 mm, resulting in the second stripe. The stripe was further shortened to 6 mm for the next 900 cycles and then to 4 mm for the final 10000 cycles. The resulting wear track contained four stripes, making distinct sections for analysis. The lubricating medium was low viscosity synthetic base oil PAO 4. The low sliding velocity of 0.005 m/s was chosen to ensure boundary lubricating conditions and was maintained constant for all the stripes. The 8 mm diameter bearing steel (DIN 100Cr6) ball, having a hardness of 64-65 HRC and surface roughness of Ra = 0.018 µm was used as counter-face. The applied loaded of 25 N, generated an initial average Hertzian contact stress of 670 MPa. The test temperature was 25 °C.

The reference plate was made of quenched and tempered carbon steel C45 having surface roughness of Ra = 0.064 µm, Rz = 0.622 µm, and Rmax = 0.896 µm, hardness - (30 HRC). Wear surfaces were analysed using optical microscopy Nikon Eclipse - MA 100 and SEM Hitachi S-3400N.

At least three repeats were performed for each specimen. Before each test, the balls and plates as well as all equipment in contact with the oil were cleaned with heptane and dried.

3. Results and discussions

3.1. Surface characterisation

ESA treated surfaces undergo substantial changes in mechanical properties caused by changed chemical composition and local thermal treatment. W-Co alloyed surface has more than two times higher hardness and elasticity in comparison to uncoated C45 steel surface (Table 1). Copper alloyed surface is the softest, least elastic and has the highest indentation creep. It is generally known that increased hardness improves surface wear resistance, moreover it was confirmed that ESA improved surface hardness leads to great wear resistance [2]. The thicknesses of ESA treater layers were 45 and 35 µm for copper and W-Co respectively.

EDS analysis show that copper alloyed surfaces contain iron mixed with copper, while W-Co alloyed surface contain iron mixed with tungsten and cobalt (Fig. 1). It is well known from previews studies that these materials are metallurgically bonded and mixed uniformly throughout the surface [1,3]. In case of copper alloyed surfaces the ferrous bronze is expected Cu+Fe. In W-Co alloyed layer the systems of Co+Fe, Fe+FeC+WC, Fe+W+C and WC could form. The copper alloyed surface consists of 80% copper, 15% iron. The rest is carbon from steel and various oxides. W-Co alloyed surface consist of 23% tungsten, 5% cobalt, 50% iron, and the rest is carbon and oxides as it was the case in cooper alloyed surface.

Copper and W-Co alloyed surfaces contain irregular texture, consisting of various depth valleys and sharp spikes. The texture formation is random process and cannot be easily predicted. It depends on treating regime, substrate, and alloying material as well as environment. Nonetheless based on our experience it can

Table 1
Mechanical properties of reference and ESA treated surfaces.

Parameters	Uncoated C45 surface	Copper alloyed surface	W-Co alloyed surface
Vickers hardness	400	290	840
Martens hardness, MPa	3400	2700	6300
Indentation creep, %	1.4	1.6	0.9
Elastic part of indentation work, %	16	14	37

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