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Operational Properties of Heterogeneous Surfaces

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Abstract. The paper is concerned with testing Cu-Mo coatings deposited over carbon steel C45, which were then eroded with a laser beam. A combination of electro-spark deposition (ESD) process and laser treatment has been developed, and tested, and improvement of certain surface properties has been demonstrated. The analysis involved measuring the macrogeometry, microhardness roughness and corrosion resistance of selected areas after laser treatment. The coatings were deposited by means of the ELFA-541 and they were laser treated with the Nd:YAG, the laser parameters being variable. The properties of heterogeneous surfaces, based on laser treated ESD, are largely dependent upon material combination systems, manipulating methods, ESD and laser parameters as well as process control.

Introduction

There is an ever-increasing requirement for low-cost coatings with high quality tribological properties of its surfaces for wider applications with combined requirements. Examples are machine elements subjected to sever conditions, such as friction and wear, corrosion, or exposure to high temperature. For example, coatings of shafts of rotating machinery have combined requirements. There is a need to increase the hardness of the surfaces rotating inside the bearings to resist wear, and increase the load capacity of the surface, while the core of the shaft must retain its original plasticity, in order to prevent failure due to brittle cracking under the impact forces in operating machinery. In addition, the coating must have good bonding to the substrate material of the machine element in order to avoid undesired peeling (delamination). It has been already realized that heterogeneous surfaces, are advantageous for such combined requirements. They are designed to have the desired distribution of composition and gradients of various properties, such as microhardness, along the thin width of the coating.

There are many methods for surface coatings such as electroplating or plasma spraying. Very thin layers can be deposited by vapor deposition. Various surface treatment techniques have been developed to improve the desired properties of the deposited layers, based on the substrate material. One important low-cost method is the electro-spark deposition (ESD), which has been recognized and widely applied as an economically effective surface coating [1-4]. It is already widely used process for its expedient way of achieving the desired properties of surfaces. ESD has been known by several other terms such as *spark hardening, electric spark toughening*, and *electro-spark alloying*. Electro-spark deposited coatings have also some disadvantages but these can be easily eliminated by laser beam machining (LBM), which can be used for polishing the surface, sealing and modifying its topography, and chemical homogenization of coatings [5, 6]. This paper reports on the effects of laser treatment on microstructure, microhardness, roughness and corrosion resistance of electro-spark Cu-Mo coatings.

The technique presented in this study involves the use of lasers to modify the surface morphology, thereby impacting heat transfer. This approach has broader implications beyond the specific case studied, as it can be applied to other laser processing scenarios where surface morphology plays a critical role [7-9]. Altering the characteristics of the surface layer is a commonly employed solution in various fields [10-12], and image analysis serves as a valuable diagnostic tool in this process [13-15]. These modifications are not only relevant to the energy sector [16], but also to hydraulic power systems [17,18] and the broader field of material engineering [19-21] and corrosion protection [22,23]. By modifying the surface layer morphology, significant advancements can be made in reducing wear and tear on machine parts [24-26]. Additionally, this technique has the potential to enhance the quality of products in the automotive industry [27,28] and railway sector [29,30], which, in turn, can inspire the development of new quality control methods [31-33] implemented in both the automotive [34,35] and metal industries [36,37]. Implementing these quality enhancements has a significant impact on minimizing potential failure scenarios and their associated consequences [38-40], allowing for the effective implementation of lean manufacturing principles [41-43]. By employing these techniques, manufacturers can streamline their processes, reduce waste, and improve overall efficiency.

Methodology and Results

The testing process consisted of two stages: first, Cu-Mo coatings were electro-spark deposited on standard steel samples (C45 steel); then, they were modified with a laser beam. The electro-spark deposition of Cu-Mo wires with a diameter of 1 mm was performed by means of an ELFA-541, a modernized device made by a Bulgarian manufacturer. The subsequent laser treatment was performed with the aid of a BLS 720 laser system employing the Nd:YAG type laser operating in the pulse mode.

The parameters of the electro-spark deposition, established during the experiment, include: current intensity I = 16 A (for Cu I = 8A); table shift rate v = 0.5 mm/s; rotational speed of the head with electrode n = 4200 rev/min; number of coating passes L = 2 (for Cu L = 1); capacity of the condenser system C = 0.47 μF; pulse duration T_i = 8 μs; interpulse period T_p = 32 μs; frequency f = 25 kHz.

The produced heterogeneous coatings were eroded by laser beam after the electro-spark deposition. The laser surface treatment was performed by an Nd:YAG laser (impulse mode), model BLS 720, and operating in the pulse mode under the following conditions: laser spot diameter, d = 0.462-0.739 mm; laser power, P = 10-150 W; beam shift rate, v = 1200 mm/min; nozzle-sample distance, h = 1 mm; pulse duration, t_i = 0.8 ms, 1.2 ms, 1.48 ms, 1.8 ms, 5.5 ms, 8 ms; frequency, f = 8 Hz.

A typical methodology used for surface analysis was established by using optical image analyzer, Vickers microhardness tester, and computer controlled surfoanalyzer with computer data acquisition. This equipment was used to measure the surface finishing as well as other mechanical properties of the applied coating on the outer surface and properties distribution inside the coating. All metallographic examinations were carried out on samples polished and etched by Nital**.**

The Vickers microhardness tests, along the depth cross section of all zones (as shown in Fig. 3) used 40 G load, while for crater cavity cross section, 100 G load was applied (Fig. 4).

Materials Research Proceedings 34 (2023) 161-168 https://doi.org/10.21741/9781644902691-20

Results and Disscussion

Surface topography of produced by ESD and followed by laser spot treatment specimens is shown on Fig.1. Coated substrate by ESD has a matt appearance, with "small craters", due to local roughening by individual sparks. Noticeable features are pores and erosion pits on the surface, in particular for EDS treated surface at 0.5 mm/sec EDS applicator speed, as shown in Fig. 1a. Surface roughness was measured by using a group of parameters: Ra, Rz, Rq, Ry, Rsk and tp. Some parameters, such as Ra and Rz, have been increased by the ESD over 10 times in comparison with the original surface. Surface roughness results for various ESD treatments are summarized in Table1.

Table 1. *Surface roughness parameters (Ra = roughness average; Rz = average maximum height of the profile; Rq = root mean square roughness; Ry = maximum height of the profile; Rsk = skewness)*

Specimens	Ra, μm	Rq, μm	Rz, μm	Ry, μm	Rsk
Original as machined surface - curve A	0.36	0.45	2.28	1.25	-0.58
ESD treated surface, Fig1a, Sample 1 - curve B	3.01	4.07	23.84	23.99	-0.61
ESD treated surface, Sample 2 - curve C	3.90	4.92	30.35	30.88	-0.54

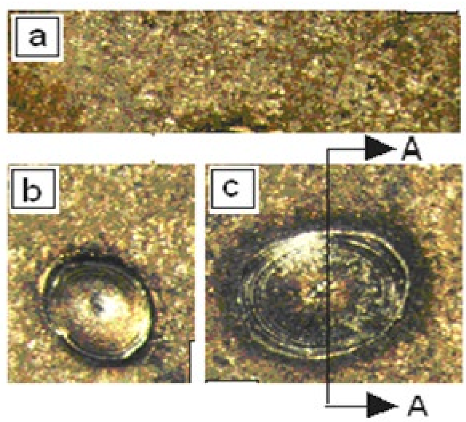

Fig. 1. *Surface topography produced by ESD and laser treatment (x50): a-EDS treated surface at 0.5mm/sec applicator speed (Sample 1), b & c-laser treated surface with craters of Sample 1:*
(b)- 20W; (c) - 100W.

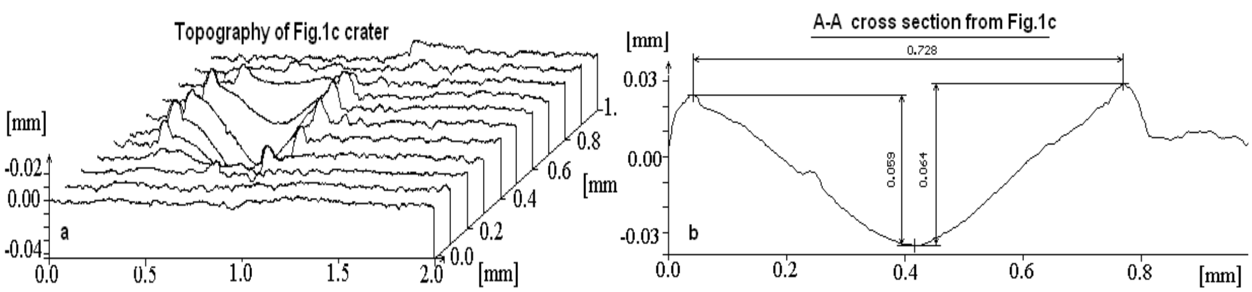

Fig. 2. *Macrogeometry and cross section of the crater formed under the influence of laser: a-3D crater topography; b-A-A cross section on Fig.1c.*

Materials Research Proceedings 34 (2023) 161-168 https://doi.org/10.21741/9781644902691-20

A 3D macrogeometry of the developed heterogeneous surface, eroded by the laser craters, for the used specimens with build in 2-D crater cross section A-A (Fig. 1c) is shown on Fig. 2a, b.

As can be concluded from these built graphs, crater edges are sharp and are advanced up to 0.03mm above an average height, just treated by ESD surface, what is within a range of tolerances for designed clearance fit. The average size of the crater, shown on Fig.1c, produced by laser power 100 W has diameter about 0.7 mm and the total depth about 0.06 mm. The crater is going below so-called “ground zero level” by down to 0.030mm. For instant, crater displayed on Fig.1b, produced by laser power 20W has diameter about 0.05mm and depth of 0.015mm. Produced crater profile (picks and valleys) and also order of craters location, depending on the required or desired surface performance, could be controlled and adjusted to acceptable level.

The microhardness test results, concerning the Cu-Mo coating before and after laser treatment, is presented in Fig. 3. After the indentation was made on metallographic specimens parallel in three zones: the coating, the remelted coating, and the heat affected zone. The original material was also tested. The electro-spark deposition process caused some changes in the material. Laser treatment had a favorable effect on the changes in the microhardness of the electro-spark deposited coatings.

In Fig. 4, a microhardness-profile is shown along the depth of obtained craters measured across the cross section shown on Fig.1c. The surface of this cross section was treated by ESD and then post finished by laser erosion. Its microhardness profile reveals distribution of properties from the fusion zone into the bulk materials. It is shown that there is a soft region in the bottom valley of the fusion zone while a big increase is achieved across a fusion line. Since the samples were deposited by a two-stage process, the softening effect can be caused by insufficient alloying and reheat affection. This saying is confirmed already by the microstructural examination which shows very limited penetration of alloy components into the bottom fused layer. The thermal cracks presence, due to rapid solidification, could increase their contributions toward the low hardness values. The microhardness profile shows gradient transition from outmost surface to the bulk materials while the variation in the outmost layer reveals the non-uniformity and the existence of micro cracks. The highest hardness value of about 800 HV achieved for the melted zone during the laser process is due to the fast-quenching effect of highly alloyed surface. By comparison, surface softening effect, near the bottom of the fusion line, is achieved due to a milder extent so that better bonding can be expected.

Moreover, the microhardness values above the fusion lines present less variation corresponding to the concentration distribution in the EDXA profiles. Therefore, the formation of compounds and effect of diffusion can be confirmed. Measured average microhardness of the crater’s tips of about 800HV, HAZ zone about 650HV and substrate of 300HV shows that the hardness of the working surface could be almost tripled by preparation of the heterogeneous surface.

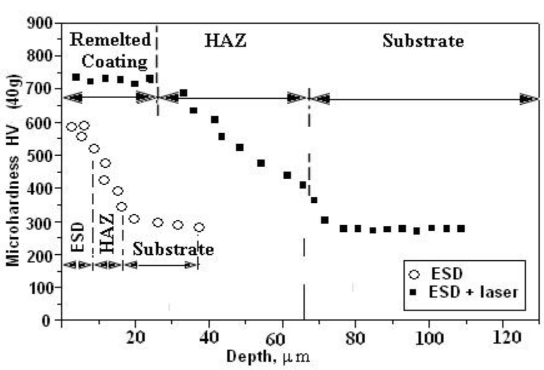

Fig. 3. *Results of microhardness tests.*

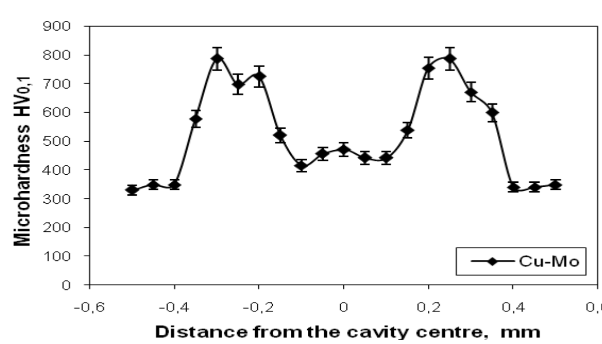

Fig. 4. *Microhardness distribution along crater cross section.*

Corrosion resistance tests were carried out by the computerized Atlas'99 electrochemical analysis system using the potentiodynamic method. The cathodic and anodic polarization curves were acquired by polarizing the tested specimens at 0.2 mV/s (within the area of ±200 mV from the corrosion potential) and 0.4 mV/s (within the area of higher potentials). Specimens with a 10 mm diameter separated area were polarized to 500 mV. In order to establish the corrosion potential, the polarization curves were acquired 24 hours after exposure to the test solution (0.5M NaCl). All tests were carried out at 21±1°C. The corrosion resistance results are shown in Fig. 5.

The Cu-Mo coating was reported to have the highest corrosion resistance. The corrosion current density of the coating was 42.9 μA/cm^2, while that of the C45 steel substrate was 112 μA/cm^2. Applying the Cu-Mo coating improved the sample corrosion resistance by approx. 162%. The fusion of the coating and the substrate resulted in a considerable heterogeneity of electrochemical potentials on the coating surface. The microcracks in the surface layer also contributed to the intensification of the corrosion processes.

There was some improvement in the corrosion resistance of the electro-spark deposited coatings after laser treatment. The healing of microcracks resulted in higher density and therefore better sealing properties. The highest corrosion resistance after laser treatment was reported for the Cu-Mo coating (I_k=30.7 μA/cm^2). For the C45 steel substrate, I_k was 6.4 μA/cm^2. Thus, the corrosion resistance increased by about 30 % after laser treatment.

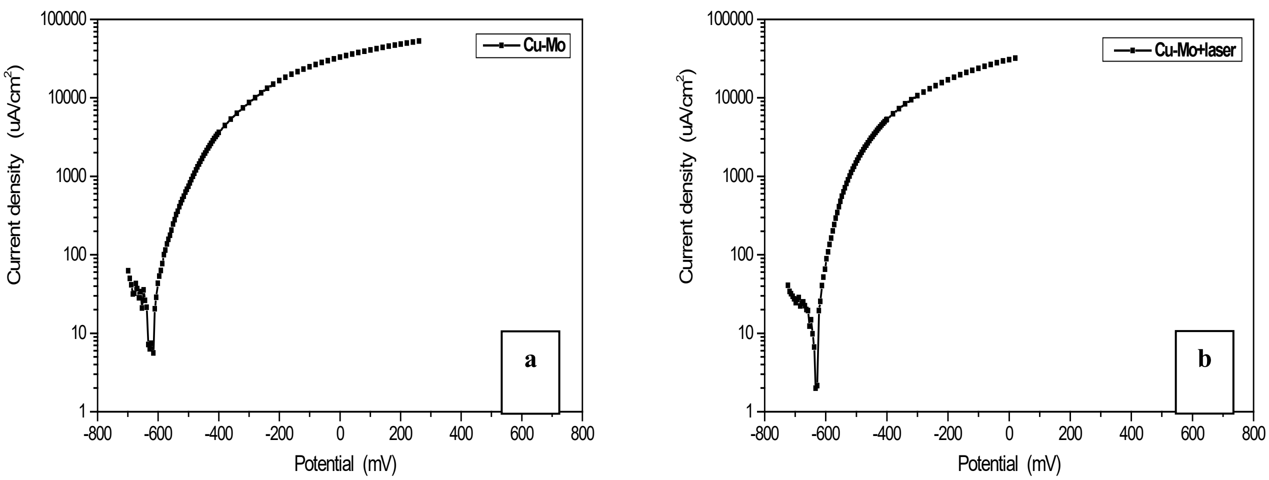

Fig. 5. *Curves of the Cu-Mo coating polarization:*
a) before laser treatment, b) after laser treatment.

Summary

1. The process of creating technological surface layers by the ESD method is associated with the transfer of mass and energy and the phenomenon of the formation of low-temperature plasma.
2. A concentrated laser beam can effectively modify the state of the surface layer, i.e. the functional properties of electro-spark coatings.
3. Laser radiation causes an improvement in the functional properties of the two-layer electro-spark deposited Cu-Mo coatings, i.e. they exhibit higher microhardness and higher resistance to corrosion.
4. Laser treatment of ESD coatings resulting in crater formation made the surface stronger and more resistant to wear.
5. The surface heterogeneity (i.e. the cavities) are desirable in sliding friction pairs. They may be used as reservoirs of lubricants as well as sources of hydrodynamic forces increasing the capacity of a sliding pair.

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