Modification of the surface layer of magnesium with 1050A aluminum alloy using electrospark deposition

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Abstract. This paper discusses the results of the preliminary investigations into the use of electrospark deposition (ESD) for the surface enrichment of magnesium with 1050A aluminum alloy. The experiments focused on the effects of the capacitor’s value on the surface layer microstructure. Four capacitances were considered. The modified material was analyzed at the macro and micro scales, using optical and electron scanning microscopy. The microhardness of the modified layer was also determined.

1. Introduction
Over the recent years, much attention has been paid to surface modification of soft and reactive materials in order to improve their surface properties, for example, their resistance to corrosion and abrasive wear. Surface modification is particularly important when the production of machine components needs to be cost-effective.

Although electrodischarge machining (EDM) [1-4] is generally classified as a removal process, it can be used to surface treat materials whose properties are unsatisfactory. In such cases, the technique is called electrospark deposition (ESD) [5-8] or electrical discharge alloying (EDA), and various materials can be used as electrodes. The method is also employed to precision repair expensive components [9-13]. The ESD process consists in depositing the material from the electrode in the molten state onto the surface of the solid substrate. The layer produced by electric discharges is generally metallurgically bonded after solidification. The main parameters of the ESD process are voltage, capacitance and discharge frequency. To select optimal parameters requires analyzing the properties of the electrode material, including its melting temperature, thermal conductivity and density. This study focused on the effects of the capacitor’s value on the surface layer formation.

The use of thermally sensitive materials such as aluminum as an electrode in ESD to be deposited onto magnesium for protective purposes have not been investigated so far. Researchers dealing with the subject have applied other techniques to improve the surface properties of magnesium, for example, metal inert gas (MIG) welding [14], laser welding [15, 16], electron beam welding (EBW) [17], friction stir welding [18], diffusion bonding [19, 20], hot rolling [21, 22], explosive cladding [23], twin-roll casting [24], and other casting techniques [25, 26].

ESD involves rapid solidification of the deposited material. Research in this area has been done for superalloys, used as the electrode [27, 28], and Fe-based alloys and magnesium alloys [29, 30], employed as the substrate. However, the ESD process has rarely been applied to produce Al or Al alloy coatings that improve the microstructure and the cavitation erosion behavior of the magnesium substrate.

Magnesium is a highly reactive material, which makes it susceptible to corrosion attack. Numerous
solutions are being looked into to protect magnesium in mechanical components from the interaction with other chemicals found in the environment, e.g. chloride in sea water. Some applications of Mg require plating it with Al, which is justified when large surface areas are to be protected. When parts complex in shape are involved, it is impossible or too costly to use this method of protection. ESD could be an alternative solution as the method is relatively inexpensive and does not require complicated equipment.

This paper presents the results of the preliminary research into the use of ESD to produce thick surface layers of 1050A aluminum alloy on the magnesium substrate. Different capacitances were analyzed. The macro- and microstructure of the surface layers was characterized and their hardness was measured.

2. Experiment

2.1. Surface layer fabrication

The experiments involved enriching the Mg surface with 1050A aluminum alloy using the electrospark deposition technique. The aluminum alloy in the form of wire (2 x 3 mm) was used as the anode, while the Mg substrate (40 mm x 20 mm x 5 mm plates) acted as the cathode. The chemical composition of the aluminum alloy is shown in Table 1.

Table 1. Chemical composition of 1050A aluminum alloy (according to EN 573-1).

| Mg [%] | Mn [%] | Fe [%] | Si [%] | Cu [%] | Zn [%] | Ti [%] | other, each [%] | Al [%] |
|--------|--------|--------|--------|--------|--------|--------|----------------|--------|
| <0.05  | <0.05  | <0.40  | <0.25  | <0.05  | <0.07  | <0.05  | <0.03          | ≥99.50 |

A specially designed ESD system was used for the experiments. The parameters assumed to be optimal for this surface modification process were selected on the basis of the authors’earlier studies, and they were as follows: voltage \( U = 600 \text{ V} \), capacitance \( C = 50 \mu\text{F} - 250 \mu\text{F} \), and discharge frequency \( f = 50 \text{ Hz} \). The four values of the capacitance tested were: 50 \( \mu\text{F} \), 150 \( \mu\text{F} \), 200 \( \mu\text{F} \) and 250 \( \mu\text{F} \). The electrospark deposition was carried out at room temperature using a hand-held gun.

2.2. Microstructure and hardness analysis

The surface-modified specimens were sectioned and placed in acrylic cold setting resin (VariDur 10). Metallographic polishing was then performed using a STRUERS machine, with the final polishing suspension being the Microdiamant 0.05 \( \mu\text{m} \) Al\(_2\)O\(_3\) suspension. The specimen preparation for the microstructural analysis did not include etching. The examinations involved optical microscopy (OM) using a Nikon Eclipse 200 with NIS Elements AR imaging software and scanning electron microscopy (SEM) applying a JEOL JSM-7100F coupled with an Oxford Instruments X-MAX energy dispersive spectrometry (EDS) detector. The Vickers microhardness of the material tested was measured at a load of 0.1961 N applied for 15 s. an INNOVATEST Nexus 4504 was used for this purpose. The indentations were made at regular intervals across the specimen cross-section to compare the hardness of the surface layer with that of the bulk.

3. Results and discussion

The SEM images in figure 1 show the microstructures of the Mg specimens modified at the surface with 1050A aluminum alloy through ESD at four different capacitances. As can be seen, the microstructure and thickness of the surface layer were affected by the capacitor’s value. Melting the Mg surface with lower value capacitors (50 \( \mu\text{F} \) and 150 \( \mu\text{F} \)) led to the formation of thicker layers characterized by relatively more uniform morphology and smaller porosity (figures 1(a) and 1(b)), respectively). When higher value capacitors (200 \( \mu\text{F} \) and 250 \( \mu\text{F} \)) were used, the enriched surface layer of the Mg substrate was thinner, exhibiting more heterogeneous microstructure with larger porosity (figures 1(c) and 1(d)), respectively). At the highest capacitance, extensive cracking and delamination were observed. This was due to the fact that the pulse energy was too high, part of the deposited material evaporated, and the
stress relaxation occurred too rapidly. At lower capacitances, more thermal energy could be absorbed by the material so the cooling (stress relaxation) was slower.

Figure 1. SEM images of the Mg specimens with the surface modified through ESD at (a) 50 μF, (b) 150 μF, (c) 200 μF, (d) 250 μF (magnification x1000).

Figure 2 shows a panoramic OM image of the Mg specimen surface-modified with 1050A through ESD capacitance of 200 μF. The surface layer is not uniform in thickness; locally, there are pores differing in size and numerous precipitates.

Figure 2. Microstructure of the surface layer fabricated using a 200 μF capacitor (magnification x500).
The specimen microstructure was further analyzed using higher magnification (figure 3).

![OM images of the surface layer microstructure fabricated using a 200 μF capacitor: (a) upper zone and (b) lower zone (magnification x1000).]

Figure 3. OM images of the surface layer microstructure fabricated using a 200 μF capacitor: (a) upper zone and (b) lower zone (magnification x1000).

The OM images in figure 3 reveal a relatively uniform microstructure with numerous precipitates at the top and dendrites at the interface between the modified surface layer and the substrate.

Figures 4(a) and 4(b) present the SEM and EDS results obtained for the surface layers produced at 200 μF and 50 μF, respectively.

![SEM cross-sections and the corresponding EDS line scans obtained for the Mg specimens enriched at the surface with 1050A at (a) 200 μF and (b) 50 μF.]

Figure 4. SEM cross-sections and the corresponding EDS line scans obtained for the Mg specimens enriched at the surface with 1050A at (a) 200 μF and (b) 50 μF.
The EDS analysis indicated diffusion bonding of the two materials. As can be seen from figure 4, the aluminum alloy used to enrich the Mg surface diffused deep into the substrate, with the interface being about 30 μm in thickness. From figure 4 (b), it is clear that the composition of the material modified at 50 μF changed less rapidly.

Figure 5 provides the SEM-EDS data recorded for the surface layer produced with a 200 μF capacitor. The SEM image in figure 5 (b) shows the specimen microstructure with two characteristic zones: the thicker, lighter zone at the top and the thinner, darker zone adjacent to the Mg substrate.

![Figure 5.](image)

**Figure 5.** (a) EDS spectrum showing the elements present at point 1 and (b) SEM image showing details of the microstructure of the surface layer fabricated using a 200 μF capacitor with points of the EDS quantitative analysis.

| Point | Mg at. % | Al at. % |
|-------|----------|----------|
| 1     | 55.95    | 44.05    |
| 2     | 55.55    | 44.45    |
| 3     | 83.76    | 16.24    |
| 4     | 85.59    | 14.41    |
| 5     | 84.14    | 15.86    |
| 6     | 84.01    | 15.99    |
| 7     | 100.00   | 0.00     |
| 8     | 100.00   | 0.00     |

Table 2. EDS results at the points shown in figure 5(b).

These observations are similar to those described by other researchers for Al-enriched surface layers on Mg fabricated through welding [25, 26], with the difference that the structure of layers obtained via ESD is much finer and its characterization requires the use of relatively large magnifications. The EDS
quantitative analysis was carried out at six points, as marked in figure 5(b). The content data are given in table 2. The microstructures of the surface layers were characterized using the Mg-Al binary phase diagram. The results obtained for the material at points 1 and 2 indicate the occurrence of the intermetallic phase (Mg17Al12). The surface layer contained both Mg and Al in similar amounts. The contents of Mg at points 3,4,5, and 6 ranged from 83.76% to 85.59%, which suggests a solid solution of Al in Mg. Full identification of the phases present in the material after the ESD would be required, using the XRD technique.

In all the cases considered, the microhardness of the surface layer was higher than that of the Mg substrate. The substrate hardness was about 40 HV0.01, whereas that of the ESD-modified surface varied between 200 and 220 HV0.01.

4. Conclusions
The experimental data suggest that ESD can be used to modify the surface layer of the Mg substrate using 1050A aluminum alloy. The microstructure and thickness of the enriched layer depends on the process parameters. In this study, four different capacitances were considered. The layers produced with lower value capacitors were thicker and more uniform in structure. The surface enrichment achieved with higher value capacitors resulted in thinner layers. There were two characteristic zones: the upper zone containing similar amounts of Al and Mg (Mg17Al12 intermetallic phase), and the lower zone, i.e., the interface, with a much higher content of Mg, which suggests a solid solution of Al in Mg. The highest capacitance used (250 μF) led to the formation of a layer characterized by extensive cracking and delamination. In all the cases studied, the surface layer had much higher microhardness than the Mg substrate.

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