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# Surface alloying of stainless steel parts with tungsten during electrical discharge machining for increased hardness

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**Abstract**

Surface alloying is a technique used to modify surface properties of a material by creating a new alloy layer on its surface. Various techniques can be employed such as laser surface alloying, plasma treatment, and electron beam treatment. However, they are solely used for producing the alloy layer. Additional processing steps and manufacturing methods are required for shaping and structuring the components, e.g., wear- and corrosion-resistant parts made of stainless steel utilized as cutting blades in food industry or industrial cutting equipment.
In this study, electrical discharge machining (EDM) using hydrocarbon based dielectric fluid will be used for ablating the workpiece surface and concurrently alloying its surface layer. Tool electrodes with diameter of 2.4 mm made from WC6Co material are used for machining stainless steel workpieces by applying a negative tool polarity. Machining parameters are chosen in with the scope to adjust roughness levels based on the VDI 3400 standard with VDI 36 and VDI 18 classes. To increase tungsten content in the modified layer, a re-modification strategy was utilized. The modified layer generated by applying VDI 36 was re-modified using VDI 18 over 30 s and 40 s of machining time. Results show that the modified layer with thicknesses from 4 µm to 25 µm contain tungsten with an amount up to 26.5 wt. %. Considering maximum removal rates higher than 0.05 mm³/min, the EDM process is a potential technique to shape components, and concurrently to alloy their surface layers, e.g., to increase wear and corrosion resistance.

Keywords: EDM, surface alloying, composition, layer thickness

## 1. Introduction

Surface alloying is a technique used to modify the surface properties of a material by creating an alloyed layer on its surface. This is achieved by introducing alloying elements into the substrate material, typically through melting and diffusion. Various methods can be employed, such as laser surface alloying [1], plasma treatment [2], and electron beam treatment [3]. A laser process was used to generate an alloyed layer on AZ91D magnesium alloy surface by adding Zr powder during the melting process. Results showed that the hardness of alloying layer was 6-7 times higher than that of the substrate, which is due to formation of re-phases of Zr, $ZrO_2$, and $Al_3Zr$. Additionally, wear and corrosion resistance of the surface was significantly improved [1]. A Cu-Ni alloyed layer on titanium was obtained by using a plasma surface alloying technique to improve mechanical properties and antibacterial activity. The formation of Cu-containing phases such as $TiNi_{0.8}Cu_{0.2}$, $Cu_{0.81}Ni_{0.19}$, $Cu_2Ti_4O$ and $Ti_2Cu$ resulted in the improvement of wear resistance. The hardness of the alloyed layer was approx. 445 HV, while only 210 HV was measured on the substrate [2]. A high-current pulsed electron beam was studied to create an alloyed layer on Ti6Al4V with Cr powder assistance. A significant improvement was reported for surface hardness, the coefficient of friction, wear and corrosion resistance of the Cr-enriched surface [3].

It is well known that the content of deposited material influences the mechanical properties of the alloyed surface layer [4]. NiCrSiBC-WC powders with varying percentage of WC (40 %, 50 % and 60 %) were laser-cladded on the same medium carbon steel substrates. No visible crack was found in the top surface and cross-section after coating with 40 % WC composite. In contrast, for 50 % WC and 60 % WC composite coatings, obvious cracks occurred on their top surfaces. The high WC content had a positive effect on the hardness, whereas residual stress was negatively effected [6]. However, an increased wear resistance by at least a factor 3 compared to the layer alloyed without WC was reported. In addition, the increase of WC content significantly improved the wear coefficient [7].

An investigation of electrical discharge machining (EDM) for alloying a tool steel surface by tungsten copper tool electrodes, which contain W contents from 5 % to 15 %, was performed. Results showed that the hardness of the workpiece surface increased with increasing W content of the tool electrode [8]. In another study, W powder was mixed into the dielectric fluid when using W-Cu, brass, and graphite electrodes to alloy different tool steel materials. The highest hardness was achieved with the W-Cu tool electrode [9].

From literature, it can be realized that various techniques, such as laser surface alloying and plasma treatment, are applicable to achieve significant improvements of the mechanical properties through alloying of their surfaces. Since most of these techniques are solely used to create alloyed layers, additional techniques are required for shaping and structuring the components.

EDM has shown its potential to deposit material from tool electrodes to the workpiece surface. However, influences of discharge parameters on the deposited tungsten content, which is not yet sufficiently investigated, need to be analyzed. Consequently, within the scope of this study, WC6Co tool electrodes are used to modify the surface of stainless steel EN 1.4404. Different parameters of the EDM process based on VDI 36 and VDI 18 classes and the re-modification strategy are utilized. It concentrates on the tungsten deposition on the workpiece surface as well as morphology of the modified layer under the effects of the VDI class and the re-modification.

## 2. Methodology

The experiments were performed on a ZK genius 700 sinking EDM machine from Zimmer & Kreim GmbH (*Brensbach, Germany*) using hydrocarbon-based dielectric fluid of the type Ionoplus IME-MH made by Oelheld GmbH (*Stuttgart, Germany*). In the EDM die sinking experiments, tool electrodes made of WC6Co with diameter of 2.4 mm were used. Workpieces made of stainless steel EN 1.4404 were machined by applying a negative tool polarity. The applied EDM parameters based on the VDI 3400 standard are given in Table 1.

**Table 1** EDM processing parameters

| VDI class | *U* [V] | $t_{on}$ [µs] | $t_{off}$ [µs] | *I* [A] |
|---|---|---|---|---|
| 36 | 260 | 125 | 65 | 1 |
| 18 | 260 | 5 | 10 | 1.5 |

In the first step, three experiments were repeated with each VDI class to machine workpiece with a constant depth of 150 µm without tool rotation. After each experiment, an ethanol filled ultrasonic bath was utilized to clean the sample for 10 minutes at room temperature, and then it was dried in air. The modified surfaces were scanned by a Keyence VK9700 3D laser-scanning confocal-microscope. MountainsMap 7.4 software was utilized to analyze their roughness and topography. The elemental composition of the modified surfaces was analysed by energy dispersive X-ray spectroscopy (EDS), whereby a spectrum of approx. (1.5 x 1.5) $mm^2$ was analysed in the center of each surface. Scanning electron microscopy (SEM) was used to analyse the surface topography. For analyses of the modified layer in the cross section, the samples were cut, then ground and polished by a wet abrasive paper. Afterwards, they were chemically etched by a V2A pickling solution. The cross-sectional layer was analysed by SEM images. To analyse the layer thickness, the cross section was scanned with the Keyence microscope. A Keyence VK Analyser software was used to analyse fifty positions on each sample thus allowing for a calculation of an average thickness and standard deviation. Analyzed results are basic for calculating durations of the re-modification.

Related to an investigation of material removal rate (MRR) and tool wear rate (TWR), a depth of 500 µm was machined by the EDM process with each VDI class. The Keyence microscope was used to scan the machined surfaces, after which the removed material volume (*V*) was analyzed with the MountainsMap software. MRR, TWR and wear ratio were calculated by Eqs. (1), (2) and (3):

$$\text{MRR} = V / t \quad (1)$$

$$\text{TWR} = \pi r^2 h / t \quad (2)$$

$$\text{Wear ratio} = \text{TWR} / \text{MRR} \quad (3)$$

Here, *h* is the height of the frontal tool wear, *r* is the tool diameter, and *t* is the machining time.

In the second step, a re-modification strategy was investigated. To do that, the EDM process applying VDI 36 in the first step with a machining depth of 150 µm was repeated to create a thick modified layer. Right afterwards, the EDM process using VDI 18 was performed to re-modify the modified layer without changing the tool electrode and without tool rotation. The re-modification processes with a duration of 30 s was named VDI 36-$18_{30s}$, and with a duration of 40 s VDI 36-$18_{40s}$, respectively. The durations were determined from the results of the first step and preliminary experiments, whereby the modified layer was re-modified on its whole surface without removing it. The relative position between tool and workpiece was kept, since it remained un-changed as no tool rotation was used. Hence, uniform machining of a thin layer over the whole workpiece surface was assured in the re-modification step. Three repetition experiments were performed for statistical analyses. The cleaning process and analyses were done similarly to the first step.

## 3. Results and discussions

In this section, the content of deposited tungsten, thickness and roughness of the modified layer, as well as MRR and TWR are presented and discussed.

### *3.1. Average content of deposited tungsten*

Figure 1 shows the content of deposited tungsten depending on the VDI class and strategy of the modification and re-modification process.

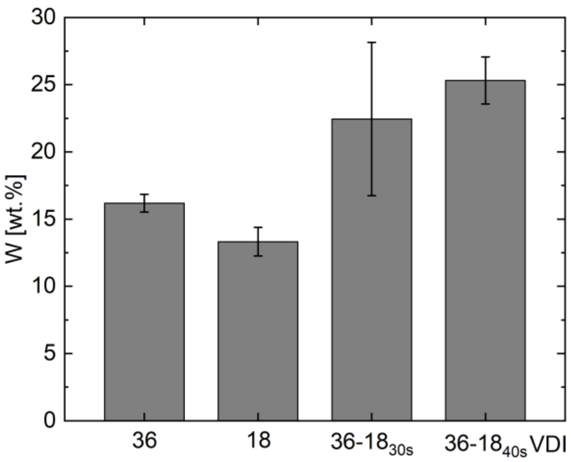


**Figure 1.** The content of deposited tungsten in the modified layer

Results show that the modified layer contains approx. 17 % W when applying VDI 36 with a high energy, whereas the deposited tungsten content only amounts to approx. 13 % when using VDI 18 with a low energy. A reduction of the applied energy leads to a decrease of the deposition efficiency. A significant reduction of spattered materials, which contains a large amount of material deposited from the tool electrode [10], is the main reason for lower amount of tungsten when applying VDI 18.

The new strategy of re-modification increases the deposited content significantly with both process durations of 30 s and 40 s. Surfaces containing tungsten contents up to approx. 26.5 % were achieved. This is due to a containment of tungsten in the modified layer formed by applying VDI 36, which combines with tungsten deposited from tool electrode during the re-modification with VDI 18. The increased tungsten content can improve the hardness of the surface according to [8,9].

As can be seen from Figure 2, backscattered electron images of the surfaces modified by the EDM process applying VDI 36 and VDI 18 classes are presented. Spattered materials were formed in both cases, however it is much less with VDI 18 compared to VDI 36. The spattered materials need to be avoided due to their low adhesive strength on the substrate surface. Additionally, by applying the VDI 18 class, the formation of micro-cracks is remarkably lower. Very few cracks were observed on the modified surface.

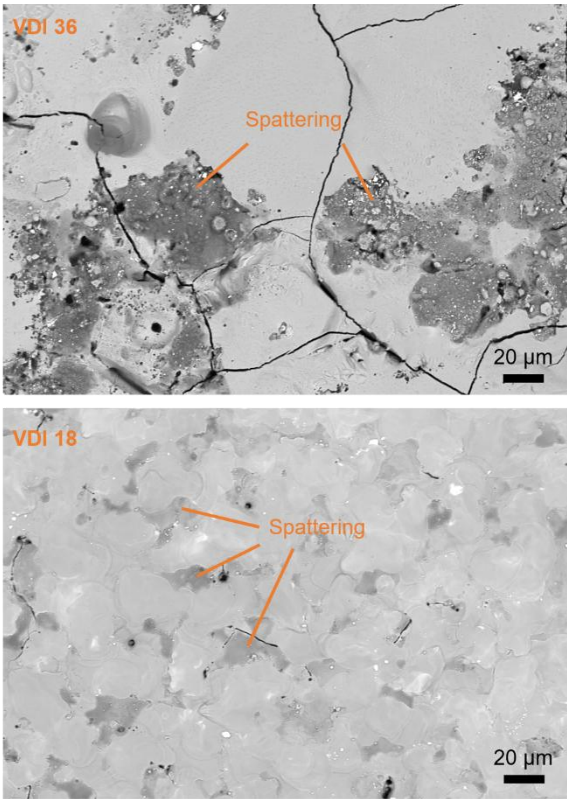


**Figure 2.** Backscattered electron images of the surfaces modified by the EDM process using VDI 36 and VDI 18 classes.

### *3.2. Analysis of the modified layers*

The modified layers formed by the EDM process with each VDI class and modification strategy are presented in Figure 3. A modified layer with thickness of approx. 25 µm is generated by using VDI 36, whereby it is approx. 4 µm by VDI 18 due to applying a much lower discharge energy. However, with a high energy of the VDI 36 class, micro-cracks with a width up to approx. 1 µm are observed. Additionally, a porosity is formed, especially in case of VDI 36 with a thick layer. With VDI 18, a much faster solidification process occurred due to a much thinner modified layer, which leads to have insufficient time to nucleate and grow of gas bubbles [11]. Therefore, the pore's size is significantly smaller.

With the re-modification strategy, the thicknesses of the modified layer are approx. 15 µm and 10 µm when the re-modification process with VDI 18 is performed in 30 s and 40 s, respectively. A double-layer is cognizable after re-modification, which consist of a lower layer formed at high discharge energy using VDI 36 and an upper layer formed at lower discharge energy applying VDI 18. The lower layer has a thickness of approx. 11 µm after re-modification over 30 s duration, whereas it only amounts to approx. 6 µm after 40 s. The depth of large micro-cracks, which were generated by the step of applying VDI 36, was reduced with an increase of the re-modification duration. However, additionally formed micro-cracks were detected after re-modification, hence, the total amount of micro-cracks is increased, which is the case for both re-modification durations.

Figure 4 represents exemplary profiles of the modified surfaces.

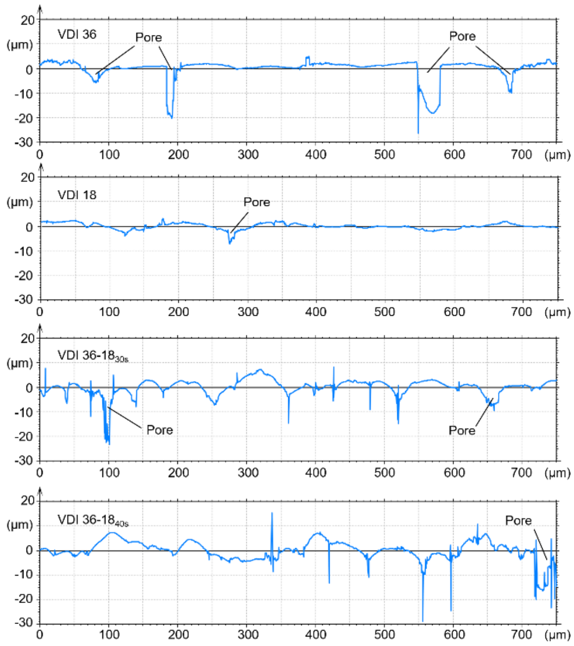


**Figure 4.** Typical profiles of surfaces modified by different VDI classes and strategies

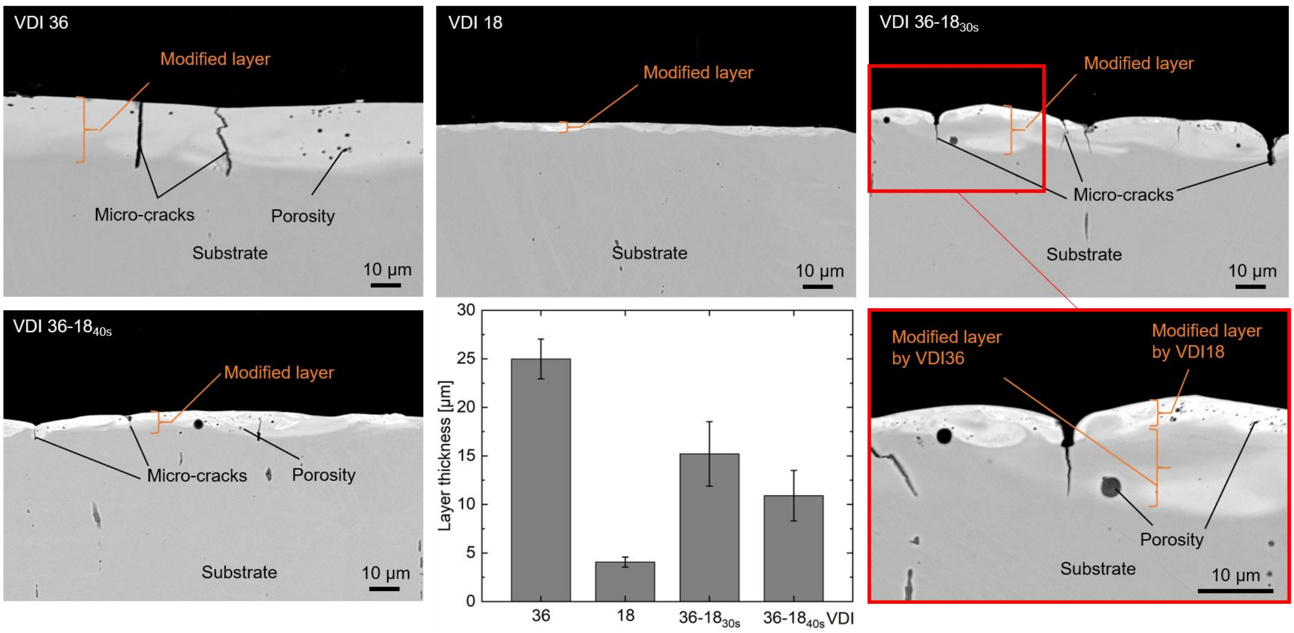


**Figure 3.** SEM images of the modified layer and effect of the VDI class and strategy of the modification process on the layer thickness

It can be realized that the surface generated by the EDM process applying VDI 36 class is quite flat. However, big and deep pores of the modified layer was formed. When using the VDI 18 class, a quite smooth surface with some small and shallow pores is achieved.

The re-modification process in this investigation forms uneven surfaces. Although VDI 18 was utilized in the re-modification process, the reuse of the tool electrode already worn after the first modification step led to non-uniform machining results after re-modification. However, the depth of big pores is significantly decreased.

Figure 5 shows a point diagram of the roughness values *Ra* and *Rz* of the modified surfaces.

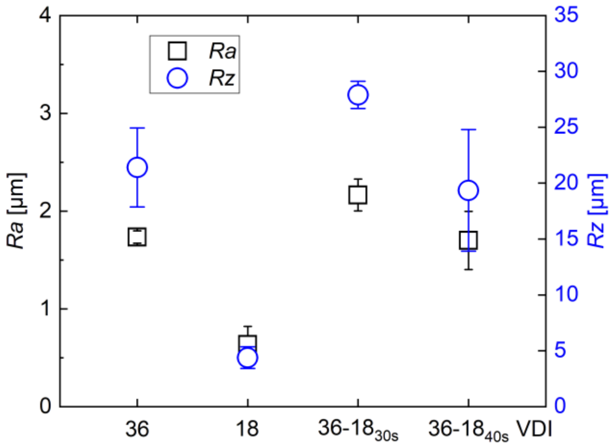


**Figure 5.** Surface roughness *Ra* and *Rz* depending on the modification process

Roughness values *Ra* achieved by applying VDI 36 and VDI 18 classes are 1.74 µm and 0.64 µm, respectively. They are much lower than *Ra* values of 6.3 µm and 0.8 µm of the VDI 3400 standard of these classes. This is due to the use of a negative tool electrode for the modification with the aim of W deposition.

The re-modification process, due to the uneven surfaces, results in a high value of roughness. In case of re-modifying in 30 s, the final surface is even rougher than the surface formed by VDI 36 with *Ra* = 2.16 µm. With re-modification duration of 40 s, the surface is flatter than after 30 s with a roughness value similar to the surface modified by using VDI 36.

### *3.3. Analysis of material removal rate and tool wear*

MRR and TWR realized in the machining processes utilizing VDI 36 and VDI 18 classes are shown in Figure 6.

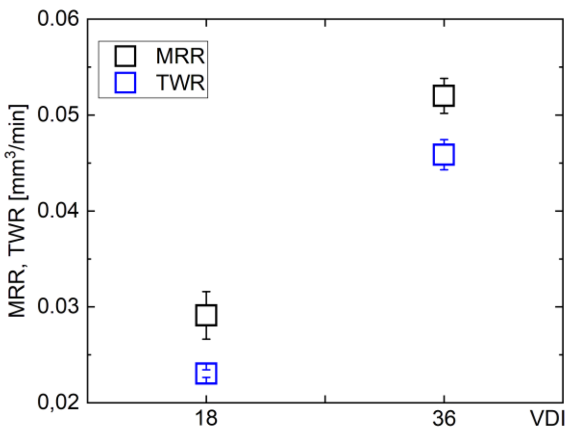


**Figure 6.** MRR and TWR as function of the VDI classes

In both cases TWR is only slightly lower than MRR. Co, which is the metallic binder material of the WC6Co tool electrode, has a melting and evaporation points of approx. 1320 °C and approx. 2700 °C, respectively, whereas they are approx. 2800 °C and approx. 6000 °C for WC. Therefore, melting and evaporation of the EDM process mainly affects Co rather than WC, and WC grains are expected to be released after melting and evaporation of Co resulting in the deposition of WC on the modified layer. A high discharge energy, such as with the VDI 36 class, results in a higher MRR compared to a lower discharge energy of VDI 18. In addition, when applying VDI 36 the wear ratio with a value of 0.88 is also higher compared to 0.79 of VDI 18. It means that more molten tool material is generated and deposited.

## 4. Conclusion

In this study, WC6Co tool electrodes were used to machine stainless steel with EDM sinking and concurrently deposit tungsten from the tool electrode to the workpiece surface. From the results, the following conclusions can be drawn:

- The deposited content of tungsten is significantly influenced by the VDI class and modification strategy. The modified surface contains a maximum tungsten content of 26.5 %.
- Re-modification with lower discharge energy significantly increases the tungsten content in the modified layer.
- Modified single layers or double layers with thicknesses from 4 µm to 25 µm can be generated.
- Generation of micro-cracks and porosity is a challenge.
- The EDM process offers a promising potential for shaping the workpieces with concurrent alloying of the surface layer, e.g., to increase wear and corrosion resistance.

## Recommendation

Further studies are recommended to characterize the modified layer in cross-section regarding the distribution of deposited material within the layer. Mechanical properties and metallurgical structures of the modified surface should be evaluated.

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