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Correlation Analysis of the Topography and Wettability of SEDM Surfaces

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Abstract

Sink electrical discharge machining (SEDM) is widely employed for manufacturing molds and components with intricate geometries and high surface quality. Despite its versatility, the conventional characterization of EDM surfaces using the arithmetical mean roughness (Ra) fails to capture the detailed topographical variations that impact functional properties. This study investigates the influence of EDM discharge parameters on surface topography, particularly the mean groove width (RSm), and its correlation with surface wettability.

Experiments were conducted on steel samples using two state of the art EDM machines with copper and graphite electrodes. Samples were fabricated with different roughnesses using standard and specialized EDM technologies designed to vary RSm independently of Ra. Surface characterization was performed through tactile and optical measurements, and wettability was assessed via drop shape analysis. The results reveal that RSm can be adjusted independently from Ra under specific conditions, offering greater control over surface functionality. A higher RSm value corresponded to a lower contact angle, indicating reduced wettability.

Keywords: EDM, Surface Topography, Surface Wettability, Function-oriented manufacturing

1. Introduction

Surface topography plays a critical role in manufacturing processes, especially in applications such as injection molding. The characteristics of a mold's surface significantly influence the flow behavior of molten polymers during injection and the quality of the final product. For example, smoother surfaces can reduce friction and improve flow uniformity, while rougher surfaces can increase resistance, potentially leading to defects or uneven material distribution. Additionally, rougher surfaces may trap air pockets, reducing thermal conductivity, which can affect the mechanical properties of the final part. As such, controlling surface characteristics is essential to ensure high-quality production and efficient material use [1–3]. The surface characteristic is commonly quantified using the arithmetical mean roughness (Ra), which provides a simple average of the deviations from the mean surface plane [4]. While Ra is widely adopted due to its ease of measurement and comparison, it does not account for the detailed features of a surface, such as the shape or spacing of irregularities. This limitation means that surfaces with the same Ra value may exhibit different functional properties, complicating efforts to optimize manufacturing processes (see Fig. 1).

Sink electrical discharge machining (SEDM) is a common process used to manufacture molds. It offers unique capabilities in creating precise and complex geometries,

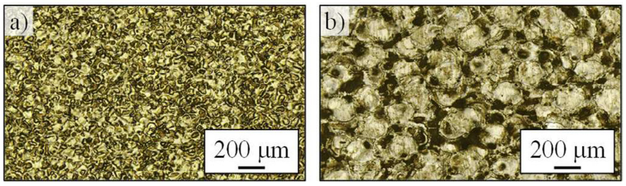

Fig. 1. Two EDM surfaces with the same roughness Ra = 1.3 µm. Surface (a) has significantly smaller craters than (b), despite being in the same VDI class.

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regardless of material hardness. EDM operates by generating controlled electrical discharges between a tool and a workpiece submerged in a dielectric fluid. These discharges locally melt and vaporize material, allowing for the creation of intricate shapes and surfaces that are difficult to achieve with conventional machining techniques [5].

The EDM process is highly complex, influenced by numerous parameters such as discharge current, pulse duration, and electrode material. Each discharge event creates a small crater on the workpiece surface, and the final surface texture is formed by the overlapping and accumulation of these craters [6]. Factors like the energy of individual discharges, the frequency of the pulses, and the dielectric fluid properties determine the size, shape, and distribution of these craters, which eventually shape the surface topography. *Koshy* et al. have shown, for example, that the wettability of aluminium can be greatly reduced by varying the discharge parameters [7].

Currently, EDM surfaces are described by classifying them according to the internationally acknowledged VDI3400. The surfaces are classified according to equation (1), which only includes the Ra value as a variable [8]:

$$\mathrm{VDI} = 20 \cdot \log_{10}\left(10 \cdot \frac{\mathrm{Ra}}{\mu\mathrm{m}}\right) \quad (1)$$

As the Ra value is determined by the integral determination of the roughness profile, it alone is not sufficient to describe the surface. Previous work has examined a variety of different surface-describing parameters in addition to the Ra value in order to be able to describe EDM surfaces in a function-oriented manner. It has been shown that the RSm value varies significantly within regimes where surfaces exhibit similar Ra but differing topographies. Furthermore, the results demonstrate that surface wettability is significantly influenced by the RSm parameter. Specifically, an increase in RSm corresponds to a decrease in the contact angle, signifying reduced surface wettability. It was also observed that for lower surface roughness, RSm and Ra exhibit weaker correlation, indicating that RSm can be independently adjusted from Ra in this range [9].

This paper explores the influence of EDM discharge parameters on surface roughness and wettability. The focus here is on different topographies, not on the underlying EDM parameters. Samples were produced using varying EDM settings to achieve surfaces with similar Ra values but different RSm topographies. The surfaces were characterized through tactile and optical measurements, and their wettability was evaluated using drop shape analysis. The results were analysed to identify correlations between discharge parameters, roughness values, and surface functionality.

2. Experimental Setup

To systematically study the influence of EDM discharge parameters on surface topography and wettability, a series of experiments were conducted using two different state-of-the-art EDM machines: GFMS Form 2000 VHP and Makino EDAF 2. The hydrocarbon-based Ionoplus IME-MH from oelheld was used as the dielectric on both machines. The workpieces were prepared from X37CrMoV5-1 hot work tool steel. Copper and graphite electrodes, each with a machining area of 15x15 mm, were used. Three primary EDM technologies were employed in this study, each designed to achieve specific surface characteristics. On the GFMS Form 2000 VHP machine, the standard technologies for graphite and copper electrodes are referred to as *technology A*. Additionally, the *3DS technology*, which is exclusively compatible with graphite electrodes, was applied to create surfaces with a higher RSm value and more widely distributed craters while maintaining a constant Ra value. This is achieved by reducing the susceptibility to the accumulation of deposits on the surface during machining. On the Makino EDAF 2 machine, the *IC Mold technology*, which is exclusively compatible with copper electrodes, was used. This technology produces a “flower pattern” on the surface, characterized by a variable RSm value at the same Ra level. Both specialized technologies – “3DS” and “IC Mold” – are referred to as *technology B* and *technology C*, respectively. Finally, the standard technologies for both electrode materials on the Makino EDAF 2 are referred to as *technology D*. Table 1 shows the experimental pairings used in this work.

Table 1. Label of the technology-material pairings.

	GFMS Form 2000 VHP		**Makino EDAF 2**	
	Standard (A)	3DS (B)	IC Mold (C)	Standard (D)
Graphite (G)	AG	BG	-	DG
Copper (C)	AC	-	CC	DC

Preliminary experiments indicated that the correlation between Ra and RSm decreases for lower Ra roughness values [8]. This study focuses on the production of surfaces with different Ra values on a larger scale and with the addition of different tool materials and specialized technologies. However, some technologies were not able to consistently produce certain surfaces, which is why these were removed from the study. Specifically, BG1, BG2, CC1, CC6, and DG1 could not be manufactured. In the naming convention, the number following the technology reflects the machine settings used for surface generation. For statistical reliability, each sample was produced six times, resulting in a total sample size of 150.

To achieve a certain roughness, the technologies on the EDM machines have a roughing sequence and, depending on the set roughness, a varying number of finishing sequences with ever decreasing discharge power. A dressed electrode was used for each test, but it was not changed during a machining cycle.

The arithmetic mean roughness (Ra) and the mean groove width (RSm) were measured tactilely using a profilometer. Four measurements were carried out for each sample. The drop shape analysis (DSA) method was employed to determine the surface energy and wettability of EDM-produced surfaces. This technique evaluates the shape of a liquid drop on a solid surface, analysing its contour and contact area to infer surface interactions. For this study, the analysis followed the "sessile drop" method per DIN 55660-2, using distilled water as the test liquid. The measurements were conducted using the Krüss DSA100 Drop Shape Analyzer. For each technology-material pairing and roughness range, five measurements were carried out, with three images being used for each droplet for statistical reasons.

Correlation analysis was then used to evaluate relationships between roughness and wettability.

3. Results and Discussion

This section presents the analysis of EDM surface characteristics based on the collected data.

3.1. Analysis of roughness and discharge parameters

Table 2 presents the measured average values for Ra and RSm across all manufactured EDM technologies, along with the corresponding tool polarity. The technologies are sorted in ascending order of increasing Ra value and marked accordingly with a number. A clear trend emerges in the relationship between tool polarity and roughness. Productive machining is carried out with positive polarity, whereas negative polarity is used for higher surface quality. This aligns with the known advantages of negative polarity in achieving finer surface finishes, but at the cost of reduced material removal rates [10].

The choice of electrode material also influenced the roughness results. Across both EDM machines – GFMS FORM 2000 VHP and Makino EDAF 2 – graphite electrodes generally achieved lower average roughness values compared to copper electrodes. This suggests that graphite tools are more effective for producing finer surface finishes under similar machining conditions.

While Ra exhibited a consistent increase within the same technologies, RSm did not follow a linear trend. In particular, for Technology A, the lowest RSm values were observed at AG3 rather than at the lowest roughness levels. This non-linear behavior suggests that additional factors, such as crater formation dynamics or overlapping discharge effects, play a role in determining groove width.

It is also noticeable that the 3DS technology on the FORM 2000 VHP produced surfaces with higher RSm at the same Ra compared to the standard process, especially for BG3 vs. AG3 and BG4 vs. AG4. On the Makino EDAF 2, IC Mold technology also achieved this effect in the low roughness range, as can be seen with CC2 vs. DC2. In addition, IC Mold produced surfaces with similar RSm but different Ra on CC4 and DC30, further demonstrating the influence of the technology on the surface structure. Microscopic analysis confirmed that specific technologies produced significantly different surface textures despite comparable Ra values. The B and C samples exhibited larger discharge craters, resulting in a higher RSm value, while surfaces with similar RSm values but different Ra values showed significant differences in crater depth and peak height. In particular, DC4 showed a rougher, less uniform structure with deeper craters and more pronounced peaks than CC4.

Figure 2 shows optical microscope images of selected surfaces. The comparison of AG3 and BG3 makes the visual difference between two eroded surfaces, which have a very similar Ra value of about 1.6 µm but a different RSm value, even clearer. The use of 3DS Technology (BG3) creates significantly larger but smoother crater structures, which increases the RSm. Something similar can be seen in the comparison of CC2 to DC2. The IC Mold technology (CC2) produces clearly recognizable “crater flowers”, which are larger than the sponge-like craters of the standard technology. The images BG4 and CC4 show the surfaces created by using different electrode materials. The RSm value is more similar here than the Ra value.

To identify possibilities where Ra and RSm can be set independently of each other, the correlation is examined. Figure 3 presents the correlation between Ra and RSm across all tested specimens. A strong overall correlation ($r = 0.871$) is observed, indicating that as Ra increases, RSm generally follows the same trend. This suggests that, in most cases, rougher surfaces also exhibit larger groove widths. However, despite the clear correlation, the distribution of data points reveals distinct groupings, implying that underlying factors

Table 2. Average roughness (Ra & RSm) and tool polarity for all manufactured technologies.

Technology	Avg. Ra	Avg. RSm	Tool Polarity
AG1	0.98	119.92	-
AG2	1.13	103.41	-
AG3	1.62	96.36	-
AG4	3.04	132.87	+
AG5	5.02	199.79	+
AC1	1.28	259.03	-
AC2	1.77	192.00	-
AC3	2.29	124.61	-
AC4	4.46	160.55	+
AC5	6.77	212.45	+
BG3	1.55	147.40	+
BG4	2.97	165.73	+
BG5	6.70	258.08	+
CC2	0.81	76.48	-
CC3	1.39	95.59	-
CC4	2.20	158.26	-
DG2	0.63	43.75	+
DG3	1.10	63.21	+
DG4	2.67	122.26	+
DG5	6.23	296.26	+
DC1	0.70	61.58	-
DC2	0.73	54.64	-
DC3	1.38	63.85	+
DC4	3.43	150.23	+
DC5	6.63	227.54	+

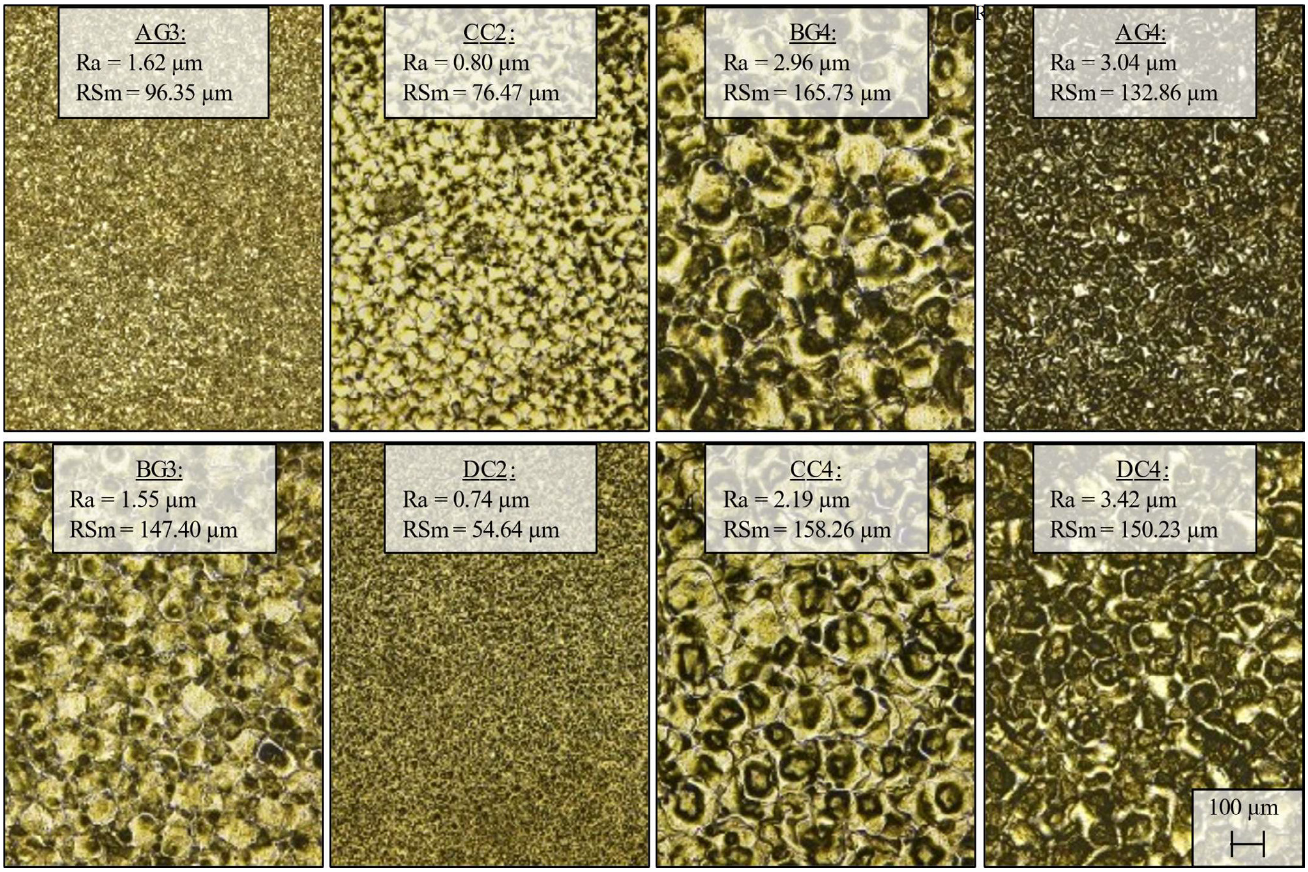

Fig. 2. Microscopic examination and comparison of surfaces produced by different EDM technologies.

influence this relationship beyond a simple linear trend. These clusters suggest that different EDM process conditions, such as discharge parameters or electrode materials, affect surface formation in unique ways. The presence of such variations means that while Ra and RSm appear strongly linked when considering all specimens together, this correlation may not hold consistently across specific subsets.

To isolate conditions where RSm can be adjusted independently of Ra, the data is further divided into distinct Ra ranges. Therefore, seven roughness classes are formed with approximately the same number of samples. The Ra ranges include Ra < 0.7 µm, 0.7 - 1 µm, 1 - 1.5 µm, 1.5 – 2 µm, 2 - 3 µm, 3 - 6 µm and Ra > 6 µm. Within these seven subgroups, the correlation between Ra and RSm is calculated again (see Fig. 4). While there is a positive correlation in some areas, the negative sign indicates that a higher roughness may be associated with a smaller average groove width. In lower Ra ranges, the values for RSm tend to fluctuate more strongly. As Ra increases up to around 1 µm, RSm generally rises in tandem, indicating a positive correlation. There is no clear relationship between 1 and 1.5

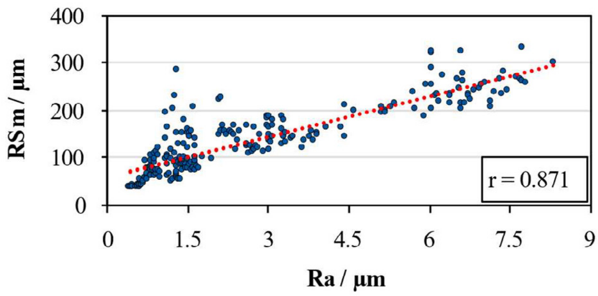

Fig. 3. Correlation between RSm and Ra across all roughnesses.

µm, which allows the roughness parameters to be set more independently. From 1.5 – 3 µm, the correlation even appears negative, which implies that higher Ra values might occur alongside smaller average groove spacings. Beyond 3 µm, a more pronounced linear relationship becomes evident once again. In general, it can be seen that there is only a weak correlation between Ra and RSm in the Ra range 0.7 – 3.0 µm, while it is stronger in the other ranges (Ra < 0.7 µm & Ra 3.0 – 6.0 µm).

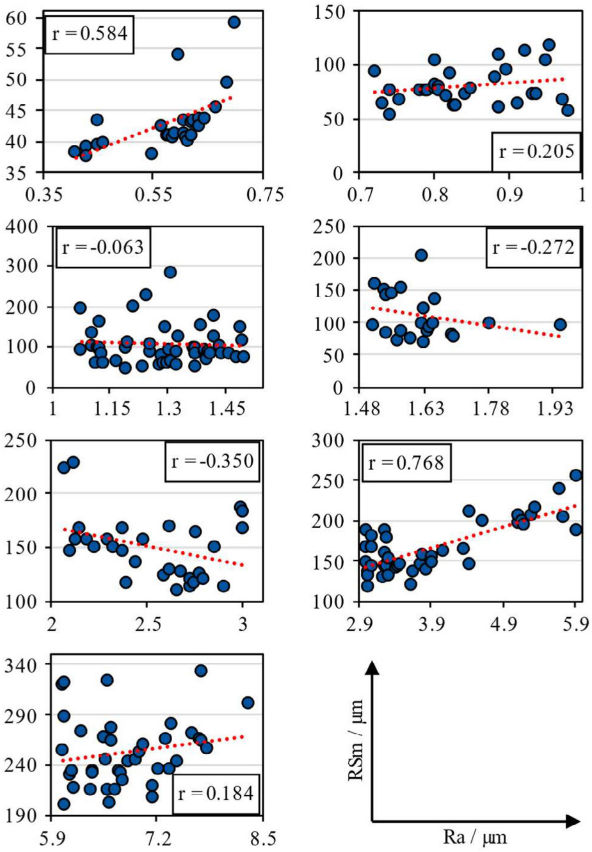

Fig. 4. Correlation between Ra and RSm, divided into different Ra ranges.

These variations indicate that the correlation between Ra and RSm depends on the roughness range, which may be linked to different mechanical and physical processes occurring during EDM. At higher discharge energies, larger craters form on the workpiece surface, leading to increased Ra values [11]. However, the distribution of crater sizes can influence the strength of the correlation between Ra and RSm. In high roughness ranges, RSm may not increase proportionally with Ra, as the peak spacing remains relatively constant while Ra continues to rise. Additionally, inefficient flushing could leave debris on the surface, introducing irregularities that affect Ra and RSm differently. Another factor influencing these results could be electrode wear. Since each machining process was performed using a single electrode, its gradual degradation over time likely impacted both roughness values. Initially, when the electrode surface was smooth, discharges were more stable, leading to consistent crater formation. As wear progressed, discharge behavior became increasingly erratic, affecting position, intensity, and frequency. This increased variation in crater formation could lead to a significant rise in Ra due to a less uniform surface, while RSm would be influenced less predictably, as crater spacing fluctuated more irregularly.

A further breakdown of the correlations between Ra and RSm in tool electrode material and polarity is shown in Table 3. The choice of electrode material and polarity affects the correlation between Ra and RSm values. This is influenced by material properties such as thermal conductivity, which impacts energy transfer to the workpiece. Higher thermal conductivity, as seen in copper, leads to more uniform heat distribution on the electrode surface. Graphite and copper electrodes show differences in the correlation between the arithmetic mean roughness (Ra) and the mean groove width (RSm) across various roughness ranges. The correlation between Ra and RSm is 0.93 for graphite, while for copper, it is lower at 0.78. In certain Ra ranges, such as 0.7 – 1.5 µm and 2 – 3 µm, correlations differ by 0.2 – 0.3. Although these differences are not large, they indicate that the electrode material can influence Ra and RSm in distinct ways.

3.2. Analysis of surface wettability

Figure 5 shows a sample image of the drop shape analysis. The drop has a wetting angle of just under 89°. In general, surfaces with contact angles greater than 90° are considered hydrophobic, and the larger the angle, the more hydrophobic the surface. Conversely, surfaces with contact angles below 90° are considered hydrophilic, and the smaller the angle, the more hydrophilic the surface.

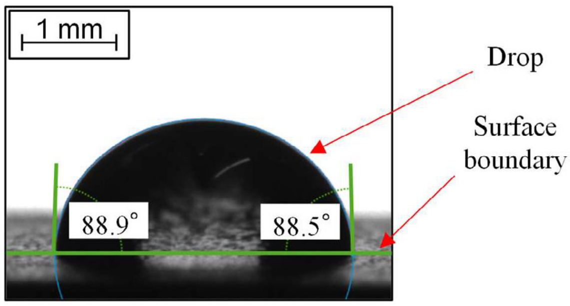

Fig. 5. Example image of the drop shape analysis.

Table 4 presents the correlation coefficients between Ra, RSm, and the measured contact angle across different roughness ranges. In most cases, Ra and RSm exhibit similar correlations with the contact angle, indicating that both parameters influence surface wettability. However, certain roughness intervals deviate from this trend, highlighting that the relationship between roughness and wettability is not uniform across all ranges.

For surfaces with Ra values between 0.7 and 1.0 µm, a

Table 3. Correlation between Ra and RSm, divided into test conditions and roughness ranges.

Roughness Range	Total	≤ 0.7	0.7 – 1	1 – 1.5	1.5 – 2	2 – 3	3 – 6	≥ 6
Graphite	0.930	0.702	-0.208	0.117	-0.282	0.703	0.777	0.018
Copper	0.780	0.696	0.080	-0.144	-0.229	-0.435	0.869	0.218
Negative	0.870	0.696	0.305	-0.182	-0.133	-0.435	-	-
Positive	0.92	0.702	-	0.583	-0.736	0.703	0.768	0.184

Table 4. Correlation between contact angle and Ra or RSm.

Number of Specimen	150	16	27	12	13	13	20	22
Roughness Range	Total	≤ 0.7	0.7 – 1	1 – 1.5	1.5 – 2	2 – 3	3 – 6	≥ 6
Ra	-0.350	-0.350	-0.352	0.081	0.280	0.316	0.297	0.116
RSm	-0.316	-0.316	0.362	0.095	0.014	0.223	0.282	0.048

moderate negative correlation of -0.352 is observed between Ra and the contact angle, suggesting that increasing Ra enhances wettability. In contrast, RSm in this range shows a moderate positive correlation of 0.362 with the contact angle, implying that wider groove spacing reduces wettability. This divergence indicates that Ra and RSm can have opposing effects on wettability in specific roughness ranges. In the roughness range of 1.5 – 2.0 µm, this difference becomes less pronounced. While Ra still exhibits a weak to moderate correlation with the contact angle, RSm no longer shows a significant correlation. This suggests that in this range, Ra plays a more dominant role in determining wettability, whereas RSm has little effect.

Overall, the results confirm that higher surface roughness generally improves wettability [8], as the contact angle tends to decrease with increasing Ra and RSm. This behavior aligns with the Wenzel model, where rough surfaces increase the liquid-solid contact area, promoting better wetting. In lower roughness ranges (Ra < 1 µm), the Wenzel effect dominates, as the liquid fully wets the surface and penetrates the microgrooves, leading to improved wettability with increasing roughness. However, at higher roughness levels (Ra > 1.5 µm), this trend weakens or even reverses, suggesting a shift toward the Cassie-Baxter state. In this regime, the liquid no longer fully penetrates the surface texture, instead sitting on the peaks of the roughness and trapping air pockets beneath. This results in higher contact angles and reduced wettability.

The subdivision of roughness values into different ranges reveals additional variability in the contact angle. In lower roughness ranges, the contact angle decreases with increasing roughness, consistent with the Wenzel model. However, in higher roughness ranges, the contact angle either remains constant or increases, potentially due to the transition to the Cassie-Baxter model. This transition is particularly evident in the range of Ra 1 – 2 µm, where the surface is rough but not sufficiently rough to allow complete liquid penetration. In this intermediate range, the interplay between the Wenzel and Cassie-Baxter models may occur, leading to complex wettability behavior [12].

4. Conclusion and Outlook

This study confirms that Ra alone is insufficient to characterize EDM-generated surfaces, as identical Ra values can correspond to different topographies. Including RSm as an additional parameter allows for a more precise differentiation of surface structures.

While Ra and RSm show an overall correlation of 0.871, their relationship varies across roughness ranges, electrode materials, and polarity conditions. For instance, in the Ra range of 2 – 3 µm, graphite electrodes exhibit a strong positive correlation (0.703), whereas copper shows a negative correlation (-0.435). Additionally, negative tool polarity weakens the Ra-RSm correlation, suggesting that other factors influence groove width (RSm) under these conditions.

The contact angle is influenced by Ra and RSm. Ra generally has a stronger influence than RSm. In the range of Ra 0.7 – 1 µm, the correlation difference is largest at 0.714. At low roughness, wettability increases with roughness, while at higher roughness, wettability decreases and the contact angle increases.

Future work will focus on investigating the influence of electrical parameters to achieve targeted variations in Ra and RSm.

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