A gap-active electrical discharge machining (GA-EDM) to rectify the textural defects of the processed surface

Shirsendu Das a,*, Swarup Paul a, Biswanath Doli b

a National Institute of Technology Agartala, Tripura, 799046, India
b Jadavpur University Kolkata, 700032, India

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ABSTRACT

Gap-active electrical discharge machining (GA-EDM) is a novel approach which provides a gap-sensible and auto-adjustable electrode-retraction system. This mechanism is conceptualized from the principle of ‘parallel-plate capacitor having two dielectric mediums’ where the inter-electrode surfaces are acted as the parallel plates. The kerosene is used as a fundamental dielectric substance, and a relatively denser and viscous layer of bio-oil is treated as secondary dielectric material. Besides this, a servo-controlled tool arrangement is employed, which is auto-sensible and synchronized with the flushing system. This multi-dielectric enhances the equivalent capacitance of the plasma-column and can dissipate huge energy during the discharging phase. The extensive heat melts most of the solidification defects and reforms the entire texture, which is far better than the surface developed with normal EDM. Moreover, the viscous layer of the secondary fluid (above the workpiece) provides an adhesive grip and slow heat dissipation procedure, which can check the formation of micro-cracks, develop due to residual effect of rapid quenching. Besides these, the flushing sensible electrode retraction system ensures an adequate passage for flushing, which helps in proper debris-expelling and controlled heat dissipations. Therefore, the adopted gap-active (GA) mechanism can facilitate better textual features with negligible indentation, solidified-agglomerates, and cracks. It is observed that the secondary dielectric enriches the carbon containments in the texture and forms a 10–14 % harder surface than the normal-EDM.

1. Introduction

The integrity of the surface processed through EDM can be improved by the addition of a few dusts of conductive or semi-conductive materials, which provide a suitable discharge ambiance and self-lubrications to the surface. Mohanty et al. [1] proposed a surface modification technique by employing tungsten disulfide (concentration: 6–12 g/L) particles and noticed an impressive deposition rate, surface feature, recast layer, and micro-hardness for various duty-factors and particle concentrations. Singh et al. [2] noticed an improved hardness and a reduction in crater depth and white layer with tungsten powder during the machining of AA606 composite. The selection of additives should not be randomized, because each additive imposes a few specific features on the surface. So, the issues like discharge condition, tool-workpiece combination, electrode polarity, and the desired outcome can be prioritized while selecting a suitable additive, as claimed by Das et al. [3] and Zang et al. [4]. Bio-active powders of hydroxyapatite are useful additive to develop bio-medical and orthopedic instruments so that the presence of chemically active particles can be eliminated. Ou et al. [5] reported that the suspension of these bio-active agents provides a smooth surface finish with a thin recast zone.

The carbon nano-particles can provide a stable machining ambiance and improve the tensile strength of the surface. Shabgard et al. [6] observed a reduction in the breakdown strength of the dielectric while carbon nano-particles were involved, which can maintain better textural integrity and stable MRR. An explosive discharge and better stabilities are noticed by Wang et al. [7] using graphite powders, which provides ten times higher MRR and 70 % lesser roughness. Han et al. [8] achieved better surface finish, lesser breakdown strength, 10 % less discharge energy with graphite during the EDM operation of borosilicate glass. Singh et al. [9] assessed the influences of graphite on the surface features of Co605 super alloy and noticed lesser breakdown strength and excellent textural features. Kumar et al. [10] used tungsten carbide to modify the surface of the die steel and noticed a reduction in dielectric breakdown with the tungsten carbide concentration.

* Corresponding author.
E-mail address: shirsendu.nita@gmail.com (S. Das).

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 Silicon or SiC-based additives control the spreading and exhibit better surface features with less penetrating crates, as noticed by Das et al. [11]. Another similar attempt where Kansal et al. [12] achieved an impressive machining rate for D2 steel with 4 g/L concentration of Si. Pecas et al. [13] observed reduced roughness, recast thickness, and revised crater shape with 2 g/L concentration of SiC. Besides these, a harder sub-surface can also be developed on Ti6Al4V with SiC, where the pulse on-time, current, and concentration played the influencing role, as investigated by Opoz et al. [14]. Tripathy et al. [15] claimed that better gap flashing and topographically improved surfaces can be achieved with 6 g/L concentration of SiC. Abdudeen et al. [16] also noticed similar kinds of responses, where the MRR improves powder concentration, but simultaneously produces a rougher surface. Besides these, the range of the process parameter, operating condition and grain size has notable influences on the responses. Some of the recent research explained the potentiality of EDM-process to machine fragile material like ceramics, which are difficult to process through conventional machining [17]. Zhou et al. [18] demonstrated an innovative approach to improve the EDM-performances, using a ‘gap servo-voltage’ arrangement, which ensured a faster removal rate with three times more machining depth.

The existing literature reviles that most of the surface modifications techniques (of EDM) are primarily focused on the involvement of different additives of various grain sizes and concentrations. However, the handling of these additives is a quite challenging issue due to the settling issues, which creates a lot of troubles in flushing. Besides this, following unavoidable issues are related with the powder mixed EDM (PMEDM) process: (a) Precise sparking is not possible for throughout the process, (b) damages the pump, pipelines, and flushing arrangement, (c) very tough to segregate the powder additives from debris particles, (d) to prohibit the deposition and sedimentation, a bulky experimental setup is unavoidable issues are related with the powder mixed EDM (PMEDM) technique, which creates a lot of troubles in flashing. Besides this, following unavoidable issues are related with the powder mixed EDM (PMEDM) process: (a) Precise sparking is not possible for throughout the process, (b) damages the pump, pipelines, and flushing arrangement, (c) very tough to segregate the powder additives from debris particles, (d) to prohibit the deposition and sedimentation, a bulky experimental setup is required, (e) maintaining a precise powder concentration is not possible, (f) expensive experimental setup and machining cost is high, (g) creates internal abrasions in the flushing arrangement.

Therefore, the present work intends to avoid these kinds of attempts of surface modifications and introduced a gap active machining ambiance. Here, instead of mixing additives in dust form, a slightly denser of surface modifications and introduced a gap active machining ambiance, which is investigated by Opoz et al. [14]. Tripathy et al. [15] claimed that better gap flashing and topographically improved surfaces can be achieved with 6 g/L concentration of SiC. Abdudeen et al. [16] also noticed similar kinds of responses, where the MRR improves powder concentration, but simultaneously produces a rougher surface. Besides these, the range of the process parameter, operating condition and grain size has notable influences on the responses. Some of the recent research explained the potentiality of EDM-process to machine fragile material like ceramics, which are difficult to process through conventional machining [17]. Zhou et al. [18] demonstrated an innovative approach to improve the EDM-performances, using a ‘gap servo-voltage’ arrangement, which ensured a faster removal rate with three times more machining depth.

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Therefore, the present work intends to avoid these kinds of attempts of surface modifications and introduced a gap active machining ambiance. Here, instead of mixing additives in dust form, a slightly denser secondary dielectric (0.94 g/cm³) is mixed with the primary medium (0.84 g/cm³) in a 4:1 ratio (primary: secondary). A small rotary stirrer is used in the dielectric chamber to prohibit the settle down of the denser fluid. The process of settling is very slow because of the small density differences between these two fluids. During the machining, the secondary medium occupies the lower position and occupies a place just above the workpiece. So, two different layers of the dielectrics are formed in-between the electrodes, which is analogous to a parallel plate capacitor with two dielectric slabs (shown in Fig. 2). Therefore, the equivalent capacitance is improved, which provides huge discharge energy with enlarged inter-electrode spaces. This proposed methodology can ensure similar kinds of machining ambiances, which could be achieved with PMEDM and can rectify the textural defects without creating any adverse effect on the equipment. So, the detailed principle, theory, experimental techniques, and obtained results are discussed in the following sections of this article.

2. Materials and methods

This subsection includes the principle of parallel plate capacitor, gap active machining, preparation of dielectric, experimental setup, and adopted methodologies, which are included in the successive subsections.

2.1. Principle of parallel plate capacitor

Here, the basic principle of a capacitor influenced by multiple dielectric mediums is explained, which has much relevance with this carried work. Consider two dielectrics of relative partitivities K1 and K2 are used in a capacitor whose plates are ‘d’ distance apart and having plate area ‘A’. Fig. 1 represents a schematic diagram of this type of capacitor. The entire inter-plate space (d) is occupied by these two dielectrics sharing t1 and t2 distances (i.e., d = t1 + t2).

If ‘V’ is the voltage developed between two plates, and E1 and E2 are the developed field between these two mediums, then the ‘V’ can be written as,

\[ V = E_1t_1 + E_2t_2 \]  \tag{1}

\[ K_1 = \frac{E_0}{E_1} \quad \text{and} \quad K_2 = \frac{E_0}{E_2} \]  \tag{2}

Now, using eq. (1) and eq. (2),

\[ V = \frac{E_0}{K_1}t_1 + \frac{E_0}{K_2}t_2 = E_0\left(\frac{t_1}{K_1} + \frac{t_2}{K_2}\right) \]  \tag{3}

The capacitance ‘C’ of the capacitor, can be explained,

\[ C = \frac{Q}{V} = \frac{Q}{E_0\left(\frac{t_1}{K_1} + \frac{t_2}{K_2}\right)} \]  \tag{4}

Here, ‘Q’ and ‘E0’ are the charge and absolute field develop between two plates of a capacitor, using air as a dielectric medium. If ‘ε’ is the permittivity of the air, then the ‘E0’ can be explained in following way,

\[ E_0 = \frac{Q}{\varepsilon A} \]  \tag{5}

Now, from eq. 4 and eq. 5, the final expression of the capacitance can be obtained, which is presented below;

\[ C = \frac{\varepsilon A}{\frac{t_1}{K_1} + \frac{t_2}{K_2}} \]  \tag{6}

The eq. (6) represents the final expression of the capacitance in terms of few constants (ε, A, K1 and K2) and measurable parameters (t1 and t2). On the other hand, if a single dielectric is used then the entire gap (d) will be occupied by the used dielectric medium and the capacitance will be;

\[ C' = \frac{\varepsilon A}{d} \]  \tag{7}

Hence, from eq. (6) and eq. (7) it is clear that the capacitance of the capacitor increases with the involvement of multiple dielectric mediums. This increment will be higher if the dielectric constant of the secondary medium is higher than the primary one, and it is allowed for less space compare to the primary medium. The higher capacitance increases the discharge energy (\( U = \frac{1}{2}CV^2 \)) for the same value of gap voltage.

![Fig. 1. Schematic of a parallel plate capacitor.](image-url)
2.2. Concept of gap active EDM

The concept of the gap active EDM is borrowed from the principle of a parallel plate capacitor, which is discussed in the previous subsection. Here, the tool and workpiece are acting as the parallel plates, and the inter-electrode space is treated as the plate gap. The kerosene ($K_1 = 2.1$) and bio-oil ($K_2 = 3.2$) are used as the primary and secondary dielectric mediums. Fig. 2 represents the schematic of the said arrangement. The secondary dielectric (density: $0.92 \text{ g/cm}^3$) is mixed with the primary medium ($0.84 \text{ g/cm}^3$) in 1:4 proportion (secondary: primary) and a stirring arrangement is assigned to develop a continuous vortex in the fluid tank so that the settlement of the denser fluid can be checked inside the dielectric tank. Another small chamber (chamber-2), which contains the secondary medium, is engaged to provide an adequate supply of the bio-oil at the spark-gap. An in-depth analysis of the normal EDM process explains about the formations of the vapor-bubbles after every spark [19]. These bubbles expand and collapse the inter-electrode gap. Bubbles receive heat from the workpiece surface and finally escape from the surface or expand (when the internal vapor pressure is more than surface tension), which creates a pressure drop at the point of detachment [20]. The secondary dielectric (from chamber-2) responds to this pressure drop and occupies the low-pressure point. In this way, a thin layer of secondary fluid is developed above the workpiece surface, which is displayed in Fig. 3.

Fig. 3 (a) presents a schematic view of the flashing and molecular movement of the dielectrics. The flashing jet contains both the dielectrics in 4:1 proportion, having the velocity and pressure of 12 m/s and 18 kg/cm$^2$. The molecules of the denser dielectric tend to occupy the lower position, and the relatively lighter molecules are positioned above the heavier particles. The velocity of the flashing jet is remarkably higher, so it is impossible to maintain an accurate proportion of the secondary fluid above the workpiece. Therefore, a small feeder chamber is assigned to contribute a sufficient amount of bio-oil through the ‘additional supply vent’. The feeder system supplies the oil based on the pressure drop created due to the ‘expansion and detachment’ of the vapor bubble. The final occupancies of both the dielectrics are presented in Fig. 3 (b). So, the presence of both the dielectrics creates a closer analogy to a ‘parallel plat capacitor’ (with multiple dielectric mediums), which has higher capacitance than a single dielectric system and can dissipate more energy (already discussed in the previous section). Apart from these, the presence of the secondary dielectric retracts the tool in an upward direction, which ensures a relatively larger passage for flashing and better debris expelling. The schematic of the entire experimental setup is shown in Fig. 4. Here, the secondary dielectric is slightly denser and three time viscous than the primary dielectric (shown in Table 2), which helps to occupy different layers inside the inter-electrode gap. So, this wide variation in viscosity does not entertain the mixing of these two fluids inside the discharge gap. If both the fluids are mixed (partially) due to the high turbulences of the flushing (during the spark off-time), then also the feeder tank (shown in Fig. 4) is assigned to ensure a direct supply of the secondary dielectric (through the additional vent) at the discharge gap, so that two different layers of the dielectrics can be maintained.

2.3. Tool, workpiece, and dielectric

The locally available kerosene and ester of bio-oil are treated as the primary and secondary mediums. Since the last few decades, the kerosene is using as a reliable fluid for EDM due to its excellent dielectric features, availability, low cost, and machining responses. Dzulkiﬁ et al. [21], Das et al. [22], and other researchers explained about the potentiality of the bio-oils as a dielectric for EDM. In terms of the responses, these oils can provide better MRR, lesser roughness, and decent integrity than conventional fluids, as reported by Khan et al. [23] and Singaravel et al. [24]. Therefore, based on these observations, bio-oil can be considered as a secondary dielectric for this study.

Titanium alloy (Ti6Al4V) and copper are used as a workpiece and tool for this study. The mentioned alloy has extensive applications in automotive, medical, aviation, and other relevant sectors, as claimed by Ahmed et al. [25] and others. So, the imperfect and defected texture of this alloy (after EDM) can reduce the life-span of the manufactured goods. This is the prime reason behind the selection of this alloy as a workpiece metal. Besides this, the study will capture more attention of the industries due to the involvement of this alloy. Ahmed et al. [26] experimented about the influences of different tool materials on the responses of Ti6Al4V and obtained impressive machining characteristics with copper, irrespective of the polarity. So, the copper is chosen as an electrode material for this work. The experiments are performed at three different discharge conditions to evaluate the feasibility of ‘gap active EDM’ properly. The justifications behind the selected levels of process parameters are discussed in Table 1.
2.4. Experimental procedure

The experiments are carried out with 50 L of dielectric (kerosene: 40 L and bio-oil: 10 L) and the obtained responses are compared with standard kerosene (without bio-oil). All the useful properties of the dielectrics are presented in Table 2. An electric stirrer is assigned with the main tank to maintain a proper mixture of these two fluids. The feeder chamber contains only bio-oil (1 L) to ensure the proper supply of the secondary dielectric inside the discharge gap. A saline bottle including its vent and flow controller (except the needle) is considered as a feeder chamber. The insertion of the saline fluid is happened due to the pressure gradient creates at the discharge zone due to the continuous pumping of the human heart. A similar kind of pressure gradient creates by the continuous pumping of the human heart. A similar kind of pressure gradient creates at the discharge zone due to the ‘collapse and detachment’ of the bubbles [20]. The outlet of the additional vent is kept a little bit closer to the discharge zone so that, it can respond to the pressure gradient. Moreover, a peripheral contact is maintained between the outlet of the vent and the workpiece surface, to ensure a minimum mean free path (i.e., the path that each bio-oil droplet requires to travel before reaching to the workpiece surface). A flow controller is assigned with the separate pump to regulate the pressure and velocity of the flushing. The various components of the flow-control unit are displayed in Fig. 5. The controller is synchronized with the tool-retraction arrangement to provide a required gap for flushing. The amount of the retraction is displayed in the digital axis monitor given in the machine. The used machine is manufactured by Sparkonix India Ltd, which is RC-type and MOSFET controlled. After the experiment, the samples are sent for the textural, elemental, and hardness (micro) analysis to observe the influences of the gap-active process on the mentioned responses. The textural analysis is performed with a scanning electron microscope, manufactured by Carl Zeiss, which is assisted with an EDX-analyzer. Textural features like crater shape, size, overlapping, cracks, extended solidified zone, recast layer, etc. are primarily emphasized in this work. Apart from the texture and elemental analysis, the micro-hardness analysis of the recast, heat affected, and base metal zones are also performed to inspect the influences of ‘gap-active EDM’ on the zone-wise micro-hardness. A digital hardness analyzer (HV), model: FM-7 is used for this purpose.

3. Results and discussions

This section mainly contains the influences of the ‘gap-active EDM’ (GA-EDM) on the crater shape, crater overlapping, cracks, indentation, and other textural aspects of the surface. However, before discussing the influences of the ‘GA-EDM’ on surface modification, the assessment of the primary responses is required. Therefore, the comparison of the MRR for both the GA-EDM and normal-EDM is presented in Fig. 6.

Result explains that the GA-EDM exhibits less MRR than normal-EDM, irrespective of discharge levels. Here, plots mainly present the variation with the current and duty factor. The MRR is much lesser with the gap-active arrangement at lower values of current and duty factors (i.e., at low discharge energies), however, it improves with further increments in process condition. The MRR of GA-EDM reaches closer to the MRR of normal-EDM beyond 20 A of the current 70 % of the duty factor. The presence of a relatively viscous and denser layer of secondary fluid in the inter-electrode space increases the gap-resistance and results in a weaker discharge. Besides this, the secondary dielectric increases the breakdown strength, which can’t be achieved with low discharge energies. A potential spark requires a conductive bridge, which is formed due to the polarization of the dielectric presents inside the inter-electrode gap. Multi-dielectric arrangement demands more polarization field, which can’t be developed by low current and low duty factor. Therefore, the MRR is lower at low discharge conditions, but it increases with current and duty cycle. Every dielectric has an energy storing capacity, which increases with the capacitance. The capacitance of the discharge-gap is higher for GA-EDM (than normal EDM-process), which is capable of storing the energy when it is more than the mean requirement. The most of the energy which is liberated due to the high current and high duty-factor, is stored by the dielectric and a steady supply of the energy is maintained even after the completion of the spark on-time. This small but steady supply of the energy extends the sparking duration, but the intensity of the heat is lesser than the normal EDM condition as the multi-dielectric system discharges a minimum amount of energy (remaining energy is stored and dissipated when the available energy is less than the mean requirement). Therefore, the MRR is less with the gap-active arrangement for any type of discharge condition. However, this stored energy facilitates extended sparking and heating of the surface, which melts the spikes, solidified extensions, and other textural defects.

3.1. Crater modification by GAEDM

The crater is an impression developed on the workpiece after every spark. The integrity of the processed texture is fully dominated by the shape, size, and overlapping of the craters. Das et al. (2019) noticed that...
Levels of different process parameters.

<table>
<thead>
<tr>
<th>SL. No.</th>
<th>Parameter</th>
<th>Level</th>
<th>Justifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Discharge condition</td>
<td>Low discharge: (current: up to 10 A, On-time: up to 200 μs)</td>
<td>The surface modification involves special care to the surface so that the defects like crack, molecular in-homogeneity, indentation, and solidified extensions can be minimized with decent recast properties and micro-hardness. Different discharge conditions are needed to achieve expected textural allotropy. Therefore, all the possible discharge conditions are tried to be maintained. The surface modification demands a huge amount of heat on the workpiece to melt and modify the defected texture, indentations, cracks, etc. So, the negative electrode polarity will mobilize a huge number of electrons towards the workpiece, which collides with the workpiece and dissipate an enormous amount of momentum and kinetic energy on the surface. Therefore, the straight polarity is chosen to ensure more heat flux concentration on the workpiece than the tool. Velocity less than the mentioned range is not sufficient to expel the debris effectively. However, velocity more than this range reduces the plasma-strength (discharge column) by destroying the reinforcement of the particles. The used arrangement has the lowest flashing pressure 15 kg/cm², and it can be increased up to 34 kg/cm², but the increment in pressure beyond the mentioned limit reduces the flow velocities (&lt; 10 m/s) occurs troubles in debris removal. Rich dielectric ratio (higher amount of secondary fluid) creates a pumping problem due to having two fluids of different densities. On the other hand, the lean ratio (less amount of secondary fluid) does not have any significant approach to surface modification.</td>
</tr>
<tr>
<td>2.</td>
<td>Polarity</td>
<td>Straight (-ve tool)</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Flushing velocity</td>
<td>11 – 12 m/s</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Flushing pressure</td>
<td>15 – 18 kg/cm²</td>
<td></td>
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<tr>
<td>5.</td>
<td>Dielectric proportion</td>
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Properties of primary and secondary dielectrics.

<table>
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<th>SL. No.</th>
<th>Property</th>
<th>Primary dielectric</th>
<th>Secondary dielectric</th>
</tr>
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<tr>
<td>1.</td>
<td>Density (g/cm³)</td>
<td>0.84</td>
<td>0.92</td>
</tr>
<tr>
<td>2.</td>
<td>Viscosity (cSt)</td>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>3.</td>
<td>Flash point (°C)</td>
<td>54</td>
<td>135</td>
</tr>
<tr>
<td>4.</td>
<td>Sp. Heat (kJ/kgK)</td>
<td>2.1</td>
<td>1.8</td>
</tr>
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</table>
3.2. Crack and other textural modification by AG-EDM

The cracks are usually formed due to two basic reasons which are closely related to the grounded theory of this machining process. The duty cycle of this process continues a periodic heating and cooling processes, which last for μs interval. The discharge process raises the temperature to 8000–10000 °C for a few fractions of seconds and then rapidly quenches by the flashing jets. This sudden discrimination of the temperature develops huge residual stress (tensile) on the solidified surface, which can create cracks on the surface if it is higher than the maximum tensile stress of the metal [28]. Besides this, molecular non-homogeneity is another crucial issue, which is developed due to the immigration of the particles from the tool and dielectrics. Therefore, the mutual interactions of these two consequences develop cracks on the EDMed surface. Mostly, three distinctive types of cracks are usually observed in EDM, followed by, surface cracks, penetrating cracks, and scattered cracks, as claimed by Ekmekci et al. [29] and Lee et al. [30]. The cracks which penetrate the recast layer and extended up to the interface (common surface between the recast and HAZ), are called surface cracks. These types of cracks are generally formed with kerosene dielectric medium when the machining is performed at low current and high pulse on-time, as observed by Khan et al. [31]. The penetrating cracks penetrate both the recast and HAZ, and extended up to the base metal. Generally, deionized water and EDM-oil based dielectrics create these types of cracks. Third categorized cracks are limited up to the recast zone and randomly present on the solidified texture. These cracks
are very thin and long, which are also called line cracks. Fig. 11 (a) and (b) present the cracks develops during the normal-EDM condition. It is noticed that the cracks are very thin and long, which may be categorized under line or surface cracks.

Fig. 11 (c) presents the solidified texture developed with normal EDM conditions at high discharge energies. The texture is affected by several defects like cavities, extended parts, and solidified chunks, which are created due to the solidification process. It is not possible to maintain a uniform field strength over the entire inter-electrode zone. The field strength depends on the particle concentration and the reinforcement strength of the column. Therefore, the entire machined surface is not facilitated with equal thermal energies, and the temperatures of the different sparking zones are different. The dielectric fluid runs through the gap during the spark off-time and withdraws the heats from the surface. The dissipations of the heat totally dominated by the temperature difference exists between the fluid and the individual spots, and thermal gradients still exist over the surface. Besides these, the dominant spark also migrates few particles of the tool into the texture, which entertains a non-homogeneous molecular configuration. So, a peripheral transformational stress exists on the texture during the solidification and re-crystallization, which shrinks the upper texture and creates cavities at low molecular contentment zone (weaker sections). Apart from these, the dissolved gases are also emerged from the surface during the solidification, which creates the small holes (Fig. 12).

Meanwhile, the GA-EDM acts as a parallel plate capacitor of two dielectric mediums, and having high equivalent capacitance than normal EDM condition. Therefore, this arrangement is capable to store and discharge the energy and control the fluctuation of the discharge. If the discharge potential is higher than effective gap strength, then the capacitor is capable to store the energy, and also can dissipate the energy when the it is less than the mean level. So, the energy distribution is uniform and more stable than normal EDM condition. The heat flux is more and the sparking time is increased, which facilitates sparks even after the completion of the on-time. Therefore, the re-solidification of the texture and overlapping of the craters are occurred, which melts extended chunks and fills the line crakes/ cavities. Generally, no textual defects like cracks, cavities, and chunks are noticed at 20 μm scale and 300–500 X zoom (the level which is maintained during the capturing of the normal-EDM samples); so, the magnification is increased up to 1.00 Kx. (The magnification more than 1.00 KX distorts the image quality). However, no such defects are detected at the higher magnification and the texture is far better than the normal-EDM condition, but the surface is dark and blackish. Actually, the presence of a viscous layer of secondary dielectric on the workpiece surface enrich the carbon percentage, which is confirmed by the EDX analysis (shown in Fig. 15c). The intense heat of the discharge burns the dielectric partially and forms oxides of carbon, which further react with the molten base metal and creates metallic carbide. Therefore, the upper-layer of the recast appears dark and black.

3.3. Analysis of the recast layer and micro-hardness

It is not possible to have a debris-free inter-electrode passage after each discharge cycle, and a reasonable quantity of the debris always lasts inside the vicinity. The quantity of the particles increases discharge after discharge, and finally forms a thin layer on the base metal, after repeated melting and solidification. The thickness and the hardness of
this layer are fully dominated by the process conditions and significantly influenced by the current, duty cycle, flushing condition, and dielectric used. Moreover, the durability and the life-span of the manufactured goods also depends on the hardness and textural condition of the recast zone. Fig. 13 shows the recast layer forms under normal and gap-active EDM conditions (magnification of these two images are different because it was hard to capture a clear view of the GA-EDM sample at low magnification. However, capturing scale, working distance, and accelerated potentials are maintained). The thickness of the recast zone varies between 18–23 μm for normal EDM and 12–15 μm for GA-EDM. So, the recast layer is 50–53 % thicker with normal-EDM than GA-EDM. The lesser thickness (with GA-EDM) is due to better flushing facilities provided by GA-EDM. The gap-active arrangement offers an auto-retraction of the tool, which enlarges the flushing passage and contributes a better debris evacuation than normal-EDM.

Fig. 14 presents the layer-wise micro-hardness of the samples for three different discharge conditions. Basically, the changes of hardness through the recast zone, heat affected zone (HAZ), and base metal are reported here. It is observed that irrespective of discharge conditions, the harness of the recast and HAZ are higher than the base metal, and gap-active arrangement provides a harder surface than normal-EDM. The hardness of the recast and HAZ portion is highest at medium discharge condition and lowest at high discharge condition. The recast surface is 38.25 %, 44.11 %, and 35.29 % harder than the base metal at low, medium, and high discharge energies, with normal EDM conditions. On the other hand, the recast zone is 52.17 %, 59.47 %, and 47.82 % harder for low, medium, and high discharge energies, when the gap-active arrangement was used. Similarly, the HAZ is 20.58 %, 26.47 %, and 17.64 % harder than the base metal at low, medium, and high discharge energies, with the normal-EDM condition, and for gap active arrangement the percentages are 30.43 %, 33.34 %, and 27.53 % respectively. Actually, the sample undergoes both the thermal and carbonation treatment during the EDM process. So, the hardness of the surface is mainly dominated by the amount of carbonation and cooling rate (dielectric heat dissipation). Generally, the low discharge energy does not provide sufficient heat treatment to the process surface but ensures a better heat dissipation due to having more duration of flushing (low duty cycle, i.e., a higher spark off-time). On the other hand, the high discharge condition facilitates an enormous heat treatment but, provides very minimum time for heat dissipation (high duty cycle, i.e., lesser spark off-time), which is inadequate to improve the hardness. But the medium discharge condition maintains a better proportion of heating and cooling than the higher and lower discharge condition, which is the prime reason for having a higher surface hardness, irrespective of the machining arrangements. The HAZ positions bellow the recast zone so, it is partially heat-treated and not carbonized as much as the recast zone. Therefore, the hardness level of the HAZ is relatively lesser than the recast zone but much higher than the base metal.

It is observed that the hardness offers by the gap-active arrangement are much higher than normal-EDM condition, irrespective of discharge energies. The recast surface is 12.76 %, 13.40 %, and 10.86 % harder for GA-EDM than normal-EDM conditions at low, medium, and high discharge energies. Similarly, the hardness of the HAZ is 9.75 %, 11.90 %, and 9.02 % more than that of the normal-EDM for low, medium, and high discharge energies. The higher is mainly due to two reasons. (1) High carbonation: The EDX pattern shown in Fig. 15 confesses the presence of a high amount of carbon with a gap-active arrangement. The base metal (before machining) contains 6.01 % (by weight) of carbon, which increases up to 14.33 % and 50.68 % for normal and gap active EDM processes. This high carbon content facilitates huge carbonation to
process surface over a wide zone, which forms hard metallic carbides on the surface. (2) Poor heat dissipation of secondary dielectric: The GA-EDM provides a layer of secondary medium on the workpiece. This medium possesses a poor dissipation than the primary medium due to having a higher viscosity. Therefore, the secondary medium confirms a lengthy heat expelling, which provides a slow and steady cooling of the processed surface and helps to improve the micro-hardness.

The comparison of the recast and heat affected regions (displayed in Figs. 13 and 14) clearly explains that a thinner recast layer and thicker HAZ are developed with the gap-active arrangement. The enlarged flushing passage of GA-EDM provides relatively better debris expelling, which reduces the thickness of the recast zone. On the other hand, lower heat dissipation of the secondary dielectric creates a temperature gradient inside the workpiece, which flows the heat towards the low-temperature regions of the workpiece (conductive heat transfer) and offers a thermal treatment to a wider zone. This is the only reason to have a thicker HAZ with gap-active arrangement for all discharge conditions.

4. Conclusions

This work highlights the utility of multi-dielectric fluids for surface modification, which can overcome the operational constrains, segregation issues, pipe-line abrasion, and other serious issues generally associated with powder additives. The results demonstrate the potentiality of the adopted arrangement for surface modification and textural rectification. The gap-active arrangement offers three distinctive features like high capacitance, auto-gap retraction, and slow heat dissipations, which have notable impacts on the texture and integrity of the surface. So, based on the outcomes, the following issues can be claimed:

(i) The gap-active EDM provides a better surface texture than normal EDM for all energy levels by filling most of the indentations with repeated overlapping of the crates.

(ii) The relatively higher viscosity of the secondary medium exhibits poor heat dissipation and develops a few thermal spots on the surface, which do not occur with normal EDM.

(iii) The auto tool-retraction of GA-EDM provides an enlarged flushing passage and ensures an effective debris evacuation. Therefore, no agglomerated chunk (develops due to weak van der wall forces) is created on the texture with the gap active EDM process.
The low dissipation of the GA-EDM provides a slow and steady cooling of the surface, which reduces the intensity of the residual and transformational stresses. So, a crack-free texture can be achieved with gap active EDM.

Normal EDM develops deep cavities due to non-homogeneous thermal distributions and shrinkage during the recrystallization and solidifications. However, GA-EDM provides higher equivalent capacitance, which can store and discharge the energies as per the mean requirement and can hold the sparking process for an extended period, with a uniform thermal distribution. So, this type of textural defects does not develop with GA-EDM.

The tool retraction and enlarge flushing passage of GA-EDM facilitate a proper debris evacuation. Therefore, the recast layer is 50–53 % thinner than normal-EDM.

The poor convective dissipation of GA-EDM develops a conductive thermal gradient inside the workpiece, which offers a heat-treatment to a larger zone. So, 30 % wider HAZ is developed with GA-EDM.

The gap-active arrangement offers intense carbonation and slow cooling to the process surface, so, the recast zone and HAZ are 10–14 % and 9–12 % harder than that of the normal-EDM.

The involvement of multi-dielectric to ensure a few distinctive features to the discharge gap was not noticed earlier for surface modifications. The experimental findings confess that the solidification defects, textural inhomogeneity, surface cracks, and other morphological defects can be rectified with the adopted arrangement. Beside these, it has few operational advantages over the powder-mixed EDM. The working fluids can easily flush and they do not cause any abrasion in the pipeline, pump, and other flushing apparatus. There is no segregation problem, as both the working substances are fluid, and the debris particle can easily separate from the fluids. The issues like deposition and sedimentation are not associated with the adopted arrangement; moreover, it eliminates bulky experimental setup and reduces the operational cost. However, the adopted arrangement also has some shortcomings, which are experienced during the experimental run. Therefore, further research is expected to mitigate these shortcomings.
5. Limitations and future scopes

The research intends to show a technique of surface modification, which can eliminate the bulky setup, pipeline damage, and internal abrasion of the pump/flushing arrangement which occur with powder mixed EDM. However, it is a pilot run of the gap active arrangement, and has few lacunae, which can be mitigated in the near future. Therefore, the following limitations are noticed during the pilot run, where further value-addition is required to make it more feasible for industrial applications.

(I) The present work is performed with a limited volume of dielectric (50 L), to evaluate the performances of gap-active arrangement. However, a larger volumetric dielectric is used in industrial EDMs. So, further research is required in this domain.

(II) The flushing parameters are restricted within the safest limit to prohibit the chances of unwanted hazardous issues, as the machining is performed with a limited quantity of fluids. So, further research can be carried with more ranges of flushing parameters to provide an in-depth assessment of this arrangement.

(III) Further research can be carried to determine the optimum proportions of the dielectric (primary and secondary), which is corresponding to the best textural features.

(IV) More value-addition is essential to conform an adequate supply of the secondary dielectric medium from the feeder tank through the additional vent. In the present study, the discharge of the feeder system is controlled by the pressure drop at the discharge gap. However, the inclusion of minimum quantity dielectric feeder [conceptualized from minimum quantity lubrication (MQL) arrangement of conventional metal cutting] can improve the accuracy of the feeder system.

Declaration of Competing Interest

The article is solely submitted in this journal and the authors don’t have conflict of interest.
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