Effect of different currents and compositions of Cu, MoS$_2$ and HBN on the coating thickness of mild steel substrate using electric discharge coating

Rakesh Kumar Patel$^\circledast$ and Mohan Kumar Pradhan$^\circledast$

Mechanical Engineering Department, Maulana Azad National Institute of Technology, Bhopal (M.P.), India

E-mail: rakesh1993patel@gmail.com

Keywords: electrical discharge coating (EDC), powder mixing ratio, hexagonal boron nitride (HBN), molybdenum disulfide (MoS$_2$), surface coating

Abstract

The substrate deposited on the workpiece is used by surface coating for the achievement of various properties in terms of hardness, smoothness, tear or wear etc. But various methods such as electro-plating, conversion coating or several, are less effective because of costly machine involvement, complexity during operation, complexity during work-surface installation, specific (high/low) temperatures and thick coating. To achieve better coating among all, a layer of the modified composite coated surface using Copper (Cu), Molybdenum disulfide (MoS$_2$) and Hexagonal Boron Nitride (HBN) with the help of an Electrical Discharge Machine (EDM) with reverse polarity is formed. In this process, the effect of two variable parameters current and composition (powder mixing ratio) of Cu, MoS$_2$ and HBN with a 50% duty factor on the thickness of the deposited layer is observed. During the deposition process, each green compact electrode is formed by mixing the powdered material in a mortar for approximately 2.5 h and after processing in a hot press moulding machine. The deposited layer of the coating has also been analyzed using FESEM, XRD and tribological properties, where the highest deposition or thickness of the coating has been achieved at a powder mixing ratio of 20/40/40 to Cu/HBN/MoS$_2$ with a current of 10 A at the same duty factor. Overall, better coating with controllable thickness can be achieved by using EDC, which can be helpful in automobiles or other industries where metal-to-metal friction causes performance loss.

1. Introduction

A surface coating is a covering of a substrate applied to change the behaviour of the surface without changing its bulk properties as ablation [1, 2] to protect from environmental deterioration, for low coefficient of friction and high hardness [3, 4]. By using it, various accents can be made in the surface specifications of the substrate, such as hardness, anti-friction properties, tear and wear resistance, less friction, scour resistance, corrosion and oxidation resistance [5]. This specification can be achieved by various known methods like Electroless plating [6], Electro-Plating, conversion coating [7], hot-dipping [8], chemical vapour deposition method, Roll-to-Roll coating process, thermal spraying, etc. But many of them are not as effective due to costly machine involvement, complexity during operation, complexity during work-surface installation, specific (high/low) temperatures and thick coating [9]. It requires certain work environments, such as passive environments or spaces that somehow hinder access for certain specific uses and conditions. In addition, electrical discharge coating (EDC) as a reverse method of electrical discharge machining, has several advantages over others such as not requiring these specific environments such as vacuum or inert [10]. While it only needed mixing of material powder [11] via reverse polarity [5] for surface coating. Therefore, electric discharge coating is possible and a perfect choice for industrial and research perspectives. Mostly Hexagonal boron nitride (HBN), graphite, molybdenum disulfide etc. are used for surface modifications where lubrication effect is required [12, 13]. Molybdenum
disulfide (MoS₂) is a well-known solid lubricant used in industries such as lubricating industries to reduce friction between die and forged material. MoS₂ is similar to graphite which is heavily used in industrial lubricating oils to enhance the tribological properties of lubricating oil. MoS₂ can be used in oxidizing environments up to 350 °C and in reducing environments up to 1100 °C. HBN, also known as white graphite, shows a crystal structure similar to molybdenum disulfide and graphite. However, HBN has superior properties to graphite, such as low coefficient of friction, high thermal stability than graphite, high vacuum performance, high thermal conductance, low wet ability, chemical inertness and low thermal expansion. HBN is also used as an additive in lubricating oils, paints, etc to enhance tribological performance. Therefore, both are suitable materials to choose as coating materials [14].

For example, some research has been done in the same as EDC on mild steel surface was carried out in a Die sinking EDM machine with the help of Ti-Fe cermets, in which the hardness of the coated surface was 4–8 times higher than that of the substrate surface [1]. In the mixed proportion of 75:25, W-Cu powder was prepared as a green compact electrode for mild steel surface coating by using an EDM machine [15]. Generally, the main input parameter is selected to current (A), compact load (Tons) so that green compact electrode and pulse can be made.

Figure 1. (a) Schematic diagram of sparking process, (b) material deposition after sparking.

Figure 2. Duty factor cycles for a period at peak amplitude.
on and off-time (micro-second). Apart from this, as output parameters, the content transfer rate \( (\text{mg min}^{-1}) \) and surface roughness are measured, after which the presence of Cu, W, WC and W\(_2\)C is confirmed by XRD of the coated surface. With the help of W-Cu in the ratio of mixing powder 75:25, as the effect of EDC on mild steel surface, it received a collective transfer rate of the coated layer thickness of 281 mg min\(^{-1}\) and 1262.90 μm with 5–6 times rigid compared to the surface of the substrate [16].

This coating technique is practically swapped for EDM, while only one difference can be used with the reverse polarity to coat equally to the straight polarity used in electrical discharge machining. Basically, as a better approach to coating through the substrate, it can be connected to the positive terminal of the machine setup and the electrode used can be connected to the negative terminal, which is the exact opposite of the machining process [15–17]. The processing approach for this study is shown in figure 1 for better understanding. This
immerses the entire setup in the dielectric medium so that sparks ignite under the dielectric (inert medium) medium for the die-sinking effect and the EDM machine is started to reverse the polarity and set the required process parameters from the control console. After which the appropriate voltage, a voltage gap is generated between the substrate and the electrode. This voltage difference created a dielectric breakdown and, because of this spark, it was generated between the electrode surface and the part closest to the substrate surface, which generates heat and it melts the loosely compacted electrode surface particles. After melting, the molten particles move towards the substrate because of the electromotive force generated and the applied voltage, and these particles get settled down in the substrate surface and make uniform coating layer by layer if suitable process parameters are used. Overall, this process takes place periodically and continuously for a specified amount of time and this leads to a layer-by-layer coating process and its thickness depends on the time of the coating process and other parameters. The coating thickness depends on various parameters, such as the chemical composition of substrate material and electrode material, electrical conductivity of the material, green compact electrode bond strength, current, voltage, duty factor, peak current amplitude. A term duty factor can be elaborated as the amount of time that current flows through the set-up throughout one cycle as shown in figure 2. Its equation is also mentioned below where \( T_{\text{high}} = \) Time for which current flows with its peak amplitude, \( T_{\text{period}} = \) Period of one cycle.

\[
\text{Duty Factor} = \frac{T_{\text{high}}}{T_{\text{period}}} \times 100
\]

Based on many studies, it has been observed that the coating of the mild steel surface can be performed accurately with the help of EDC using different materials and their subsequent process properties. However, according to the variable parameters such as mixing ratio, process parameters, current, the Cu/HBN/MoS\(_2\) material has not been given much attention. The reason for the selection as a combination of MoS\(_2\) and HBN is that both possess hexagonal structure and stability to each other. In addition, the reason for the selection of Cu is to increase the bond-ability and electrical conductivity of the electrode because the electrical conductivity of MoS\(_2\) and HBN is very low. Overall, for mild steel substrates, Cu, HBN and MoS\(_2\) can be used as coating materials with the help of input parameters such as powder mixing ratio and current. Whereas an output parameter, the mass deposition rate on the substrate surface, the coating layer thickness with powder mixing ratio, the FESEM analysis to detect the uniformity and pores and the kinetic coefficient of friction of the coated surface can be analyzed.

The main objective of this study is to analyze the effect of various process parameters such as powder mixing proportions of MoS\(_2\), HBN and Cu, current, on the surface coating process of mild steel as a substrate depending on its thickness with the help of EDC (using reverse polarity on EDM). For evaluation of surface coating thickness obtained on substrate, the morphology of coated surface, mass deposition rate on substrate surface and tool wear rate about current and powder mixing ratio have been observed.

2. Experimental setup and procedure

2.1. Material’s specification

The coating process, a workpiece of mild steel plate (material composition Fe – 96.8%, C – 0.29%, P – 0.04%, Cu – 0.30% and Mg – 1.04%), is selected with the dimension of 15 mm × 15 mm × 5 mm. It has also been cleaned/crushing using 900 μm particle size sandpaper. MoS\(_2\), HBN and copper (Cu) powder have been taken to create green compact cathode electrodes comprising HBN particles of size 60 nm, Cu particles of size 10 μm.
and MoS₂ nanoparticles of size 5 μm. In addition, the density of MoS₂, HBN and Cu was 5.07 g cm⁻³, 2.26 g cm⁻³ and 8.97 g cm⁻³, respectively. The evaluation of the powder used in this study has tested it for particle size and purity. On a different scale, for MoS₂, Cu and HBN can be seen in figure 3, where the average particle size of both was 3–5 μm as carried out with the assistance of microstructure on FESEM with EDS.

2.2. Experimental setup
EDM is used for coating as shown in figure 4(a), whose coating process for the arrangement of electrodes and workpiece holder inside the EDM machine is shown in figure 4(b). In this figure, the workpiece is held in the magnetic vice with the help of clamps and the magnetic vice is affixed to the machine base to avoid any movement because of magnetic action. The electrode is clamped vertically upward to the work-piece arrangement on the machine head. Attention is also paid to the parallel arrangement of the upper surface of the electrode and the substrate to allow it to have a uniform gap between the two surfaces during operation. After that, by adjusting the machine head, the electrode is set just above the substrate so that the upper surface of the substrate is completely covered by the electrode for direct projection. This is then closed the side gate of the machine and the pump is started which fills the arrangement space with dielectric fluid. Thereby ensuring that the fluid is continuously flowing through the work area to remove the debris particles and proceed with the die sinking process. It is then reversed the polarity of the process as it is used in the EDM process and sets the current, duty-factor and voltage parameters from the machine’s controlling console. During use, it can observe the fluctuations of voltage and current with the help of a controlling console and oscilloscope.

2.3. Preparation of green compact electrode
Initially, the MoS₂, HBN and Cu powders used have different common molecule sizes of 5 μm, 60 nm and 10 μm which were continuously mixed in mortar for 2.5 h. The mixing time of the powders taken by the test experiments is 2.5 h because the mixing time of 60 min gives a rough coating. After all, due to improper mixing, it becomes almost difficult to achieve uniform distribution of material on the surface of the substrate [23]. Then the hot mounting press green compact electrode was prepared by pouring the mixed powder into the machine by applying proper pressure which also plays an important role [24, 25]. The pressure gauge continuously shows the current pressure applied to the mixture, which gradually decreases all the time because of condensation, making it maintain the proper pressure manually at all times. The proper pressure potentially indicates the required average pressure that was used as 160 KPa where it was seen to be between 120 and 200 KPa. Thereafter, cooling was done for 20 min, while the first 10 min of cooling was done by normal cooling and the next 10 min of cooling by running water outside the hot mould. It has been powdered in appropriate quantity to produce
green compact electrodes of 5 mm thickness and 15 mm diameter. Since the coating process involves current, all components of the process must be conductive, so the Cu bar and green compact electrode were glued together using silver paste [26], which is highly conductive in nature. The complete preparation of the green compact electrode is also shown in figure 5.

Since the current is involved in the EDC process, these materials have been used as highly conductive to allow current to pass through easily and efficiently. HBN and MoS$_2$ are not superior conductors of electricity, so Cu is mixed with them to increase the conductivity of the green compact electrode. In addition, Cu increases the

---

**Table 1.** Process parameters used for making green compacted electrodes using EDC.

| Parameters       | Values                        |
|------------------|-------------------------------|
| Composition      | Cu/HBN/MoS$_2$                |
| Pressure         | 250 kg cm$^{-2}$              |
| Temperature      | 150 °C                        |
| Time             | 20 min (10 + 10)              |

**Table 2.** Process parameters used in EDC machine.

| Parameters       | Values                        |
|------------------|-------------------------------|
| Pulse on time    | 30 µs                         |
| Applied Gap voltage | 40 V                        |
| Duty Factor      | 50%                           |
| Coating Time     | 4 min                         |
| Polarity         | Tool Electrode (Negative) Work piece (Positive) |

---

Figure 6. FESEM images of coating for powder mixing ratio (Cu/HBN/MoS$_2$), (a) 20:40:40, (b) 30:35:35, (c) 40:30:30, (d) Plots of average coating layer thickness at duty factor of 50% and 5A current.
viscosity between HBN and MoS₂ and helps to form a stronger electrode structure, while Cu helps to generate a good spark. During spark, heat is generated and, since Cu has a lower melting temperature, it melts earlier than HBN and MoS₂ and allows the process to distribute the coating evenly over the substrate surface.

Overall, it has attempted to make a suitable mixing ratio for efficient electrode formation for uniform deposition of mass on the substrate surface. But among the many mixing ratios of Cu, HBN and MoS₂, only a few could produce satisfactory results. The mixture ratios \((\text{Cu} / \text{HBN} / \text{MoS}_2)\) of \((20/40/40)\), \((30/35/35)\) and \((40/30/30)\) were used for further investigation.

### 2.4. Process parameters and their selection

It has implemented related process parameters through the mixing ratio, where the substrate is connected to the positive terminal and connecting the green compacted electrode to the negative terminal. The oscilloscope is connected at the terminals to check for spark occurrence, which is nothing but a suitable position for the covering process. Nine test experiments were performed for \(20/40/40, 30/35/35, 40/30/30\) using the mixing ratios of \(\text{Cu}/\text{HBN}/\text{MoS}_2\), the duty factor of 50% and peak current of 5, 7 and 10 A, which can give excellent results without arcing and can be suitable parameters. Parameters used beyond these values led to the formation of abnormal arcing before the proper coating time and caused the formation of an island-type structure on the substrate surface, which is the closest point. In addition, it performed each procedure for 4 min to prevent proceeding with the selected process parameters. The process parameters used in making the green compacted electrode and in the EDC machine are listed in table 1 and table 2, respectively.

### 3. Results and discussion

#### 3.1. Chemical composition and microstructure of selected powders

In the evaluation of coated substrates applied to mild steel, the observation table is listed in table 3 as the mass deposition rate and tool wear rate based on the input parameters. The obtained parameters tool wear rate and mass deposition rate are highest achieved in a mixture ratio of \(\text{Cu}/\text{HBN}/\text{MoS}_2\) at \(20/40/40\) at current 10 A. The phenomenon of Tool wear is an electrochemical reaction between the surface and the environment during the application of current, by which a protective surface layer is formed as a corrosive layer of the substrate [27].
3.1.1. Variation of cross-section morphology with powder mixing ratio

The microstructure of the edges of a substrate coated on mild steel is shown in figure 6 for all three power mixing compositions based on a 50% duty factor and 5 A current. Figure 6(a) shows no crack growth between the substrate and the coating, but the diffusion between them is mild with the powder mixing ratio of Cu/HBN/MoS\(_2\) of 20/40/40. Whereas figure 6(b) shows minor cracks between the coating and the substrate, which may be because of non-compatibility between the mixture and the substrate surface, as the process parameters are of importance. Moreover, the improved diffusion between the substrate and coating material in figure 6(c) resembles that of the difference in coated thickness concerning the powder mixing ratio [28]. The coating thickness decreases with the Cu content in the mixing ratio as shown in figure 6(d), which is because of the higher binding of the particles as the copper content increases. Overall, the thickness of the coated layer increases with the current amplitude but decreases during the increase in the portion of Cu, so Cu must be present in proper proportion, i.e., not too much but not too little.

3.1.2. Surface morphology of the coated surface

FESEM images of the coated surface are shown in figures 7(a)–(c) to study the surface morphology, separately with (Cu/HBN/MoS\(_2\)); (20:40:40) based on various current (A). In EDM, the peak flow probably demonstrates the ability to achieve an ideal spark temperature to transfer the anode material to the workpiece. To deposit a uniform material with high density with a higher material deposition rate on the substrate surface, a suitable higher peak current need to be taken. Some voids or pores with a non-uniform coating can form with a low current because they cannot provide enough spark energy to melt the green compact electrode. Therefore, the appropriate parameters should be the melt anode material for a uniform testimony of the molten material on the substrate surface layer.
Uniform mass deposition rate but few large pores are found as shown in figure 7(a) where the mixing ratio (20/40/40) of (Cu/HBN/MoS₂) is used, which is under additional parameters duty factor 50% and 7A peak current. While at a higher peak current (10A) with the same mixing ratio and duty factor, the coating material deposition is uniform, as well as very few large voids, are observed as also shown in figure 7(b). This may be because of the excessive energy generated through high current flow, which helps to generate a good spark, resulting in easy melting and uniform deposition of the material.

3.1.3. XRD Evaluation

The chemical composition of the coated surface or the incorporation of various particles is investigated with the help of XRD during EDC. The plot is shown in figure 8, where X’PERT programming was used to probe x-ray diffraction to get its vertices. The diffraction angle (2θ) was used between 20° to 80°, which resulted in various components, such as Fe₂B, MoS₂, BN, Cu, CuS and BC. The presence of Cu, BN and MoS₂ was found through XRD, the phases of Mo, BN and Cu-S are also shown with intermetallic compound formation, where there is a uniform distribution of compounds on the coating surface.

3.1.4. Effect of peak current amplitude on the mass deposition rate

The material deposition rate is shown in figure 9 where the graph is drawn using observation data for table 3. It is found that for the mixing ratio (Cu/HBN/MoS₂) of (20/40/40), the material deposition rate is increasing regarding the current when the other mixing ratios of the incident remain the same.

Overall, the mass deposition rate has been observed to be directly proportional to the peak current used. The rate of change in mass deposition rate is found to be higher from 5 to 7A current, which further found that the increase rate of mass deposition rate decreased from 7 to 10A. This may be because of excessive heat generation, which causes a higher mass removal rate of the substrate than the mass deposition rate on the substrate.
3.2. Coefficient of kinetic friction of the coating surface

The uncoated workpiece and the coated workpiece are shown in figures 10(a) and (b), respectively, where the microstructure of this coating is shown in figure 10(c). In addition, this coated workpiece is also analyzed for tribological behaviour, as shown in figure 10(d) where a Pin-on-disc test is performed between a Mild steel circular plate and the Coated surface sample. A mild steel disc with 120 mm and thickness 25 mm is used for the pin-on-disc test where it is carried out within a radius of 90 mm and it took the time duration to be 5 min. The load applied for the test was applied at 2 kgf (20 N), where it is found that the coefficient of friction varies over time because of the closure of the coating layers [29].

The coefficient of kinetic friction of the coated surface is got with the help of the pin-on-disc test [1], where figure 11 is shown the plot for the coefficient of friction. It is got that the mean coefficient of friction, standard deviation and variance is found to be 0.290, 0.051 and 0.003, respectively. However, the kinetic friction coefficient of mild steel ranges from 0.09 to 0.6, as can be seen from the FESEM of the wear track in figure 10(c), which starts to smooth after a certain time. As continuous measurements under the pin-on-disc bottom of the rotating disc, the major peaks and valleys began to settle beyond 240 s at an average coefficient of friction of about 0.33 as can also be seen in figure 10(d). Overall, it is found that there is no reduction in the coefficient of kinetic friction because of the presence of HBN and MoS2 because of the coating. They have a hexagonal packing structure and slide smoothly over each other layer, which helps in reducing friction.

The bonding strength between HBN and MoS2 is not sufficient, as they do not stick together firmly to coat the substrate. Therefore, Cu is used as a binder to bond the powder together, which helps in sticking all the components together. In addition, it also helps in making green compact electrodes easily and provides firmness. But HBN and MoS2 are not good conductors of electricity and electricity easily passes over it for efficient coating because of Cu as the EDC process [4]. Therefore, Cu is added specifically to enhance the green compact electrode conductivity instead of all other elements. Furthermore, Cu has a low melting temperature and melts first during heat generation, allowing HBN and MoS2 to detach from the electrode and deposit easily into the substrate.

The coating of the substrate made using a powder mixing ratio of (20/40/40), with the use of a peak current 10A and a 50% duty factor, achieving superior surface morphology with fewer voids or pores over all other samples. However, to experiment, after so many test experiments, it also achieved the binder selection with a suitable mixing ratio to enhance the better morphology of the coated surface. The material fusion between the substrate and coated surface is found better in a mixing ratio of (40/30/30) with a 50% duty factor and 5A peak.
current. The process parameters have a high impact on the mass deposition rate, which is shown as an increase with peak current amplitude, whereas the maximum rate of mass deposition rate is between 5 and 7 A.

Peak current is the most important factor in electrical discharge coating to control coating thickness. Higher amounts of spark energy require higher amounts of peak current amplitude. This means that the spark energy is directly proportional to the peak current so that a greater amount of electrode device melts and accumulates on the substrate because of the cumulative effect of plasma and gravity. Therefore, the applied peak current is directly proportional to the thickness of the coating got. In addition, a wear test is applied to the pin-on-disc to analyze the coating surface tribological behaviour, where it was found that they reduce the coefficient of kinematic friction between the coated surface and the mild steel because of the coating.

The variation in peak current, duty factor and mixing ratio in the coating affect the quality the most. The high peak current improves spark generation, which enhances the transport of the electrode material and increases the temperature and melting for a denser coating while the low peak current generates sufficient heat that can cause pores on the coating surface. Similarly, the duty factor can be balanced in such a way that a low duty factor (less than 50%) reduces the spark orientation and density and gives a low material transfer rate with good surface quality. Whereas high duty factor (over 50%) creates rough and uneven coating, which leads to high degradation of the surface by reducing surface quality and prime material transfer rate. In addition, Cu increases the viscosity between HBN and MoS₂ and helps to form a stronger electrode structure, while Cu helps to generate a good spark. During spark, heat is generated and, since Cu has a lower melting temperature, it melts earlier than HBN and MoS₂ and allows the process to distribute the coating evenly over the substrate surface.

Overall, Cu allowed performing EDC to coat mild steel, where the required combination of powder mixing ratio with HBN and MoS₂ produces a difference with different current amplitudes, even at constant duty factor. The surface composition can always represent a control parameter because of the quality of the type of coating developed over the cross-section of the coating, which was appropriate with the use of EDC as the reverse polarity of EDM. In future work, it may vary the strength and density of the coating in the applied load to make the green compact for better quality.

4. Conclusion

This study is based on the evaluation of the effect of the surface coating of various parameters to develop advanced coating substrates on mild steel. Where three powder mixing components Cu, HBN and MoS₂ are used to make the green compact electrode with the help of a hot mounting press machine. This electrode is then used to coat onto mild steel using EDC, reverse polarity of EDM. Three different currents and powder mixing ratios were used using a constant duty factor, where varying thickened coatings have been achieved. The best coating performance has been found because of the high powder mixing ratio of Cu, HBN and MoS₂ at a thickness of 442.1 μm at 20/40/40 with a 10 A current. In addition, mass deposition and tool wear rates as high as 0.2242 g min⁻¹ and 0.34751 g min⁻¹ were also observed, where the coefficient of friction was 0.260 mean. Overall, by using a substantial combination of HBN and MoS₂ with Cu, an easy and cost-effective method for coating can be obtained via EDC, which can be useful in automobiles or many other fields.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Funding

No funds provided.

Ethical approval

Not applicable.

Conflicts of interests

No conflicts to declare.
ORCID iDs

Rakesh Kumar Patel 🌐 https://orcid.org/0000-0001-5330-3126
Mohan Kumar Pradhan 🌐 https://orcid.org/0000-0002-2718-7181

References

[1] Algodì S J, Murray J W, Brown P D and Clare A T 2018 Wear performance of TiC/Fe cermet electrical discharge coatings Wear 402 109–23
[2] Zhang S, Han K and Cheng L 2008 The effect of SiC particles added in electroless Ni-P plating solution on the properties of composite coatings Surf. Coatings Technol. 202 2807–12
[3] Sorensen P A, Kiil S, Dam-Johansen K and Weindl C E 2009 Anticorrosive coatings: a review, J. Coatings Technol. Res. 6 135–76
[4] Liew P J, Yap C Y, Wang J, Zhou T and Yan J 2020 Surface modification and functionalization by electrical discharge coating: a comprehensive review Int. J. Extrem. Manuf. 21 12004
[5] Kumar D, Mittal K, Kataria S, Kadiyan S and Sharma S 2013 Experimental investigation on surface modification of Wc–Co by electrical discharge coating process using SiC/Cu green compact tool-electrode Int. J. Res. Mech. Eng. Technol. 3 274–8
[6] Brenner A 2013 Electrodeposition of Alloys: Principles And Practice. (Amsterdam: Elsevier)
[7] Chen X B, Biribilis N and Abbott T B 2011 Review of corrosion-resistant conversion coatings for magnesium and its alloys, Corrosion 67 15501–5
[8] Shibli S M A, Meena B N and Remya R 2015 A review on recent approaches in the field of hot dip zinc galvanizing process, Surf. Coatings Technol. 262 210–15
[9] Legg K O, Graham M, Chang P, Rastagar F, Gonzales A and Sarwell B 1996 The replacement of electroplating, Surf. Coatings Technol. 81 99–105
[10] Simao J, Lee H G, Aspinwall D K, Dewes R C and Aspinwall E M 2003 Workpiece surface modification using electrical discharge machining, Int. J. Mach. Tools Manuf. 43 121–8
[11] Patowari P K, Saha P and Mishra P K 2010 Artificial neural network model in surface modification by EDM using tungsten–copper powder metallurgy sintered electrodes Int. J. Adv. Manuf. Technol. 51 627–38
[12] Hammes G et al 2017 Effect of hexagonal boron nitride and graphite on mechanical and scuffing resistance of self lubricating iron based composite, Wear 376 1084–90
[13] Parucker M L, Klein A N, Binder C, Ristow Junior W and Binder R 2014 Development of self-lubricating composite materials of nickel with molybdenum disilicide, graphite and hexagonal boron nitride processed by powder metallurgy: preliminary study Mater. Res. 17 180–5
[14] Celik O N, Ay N and Gönçü Y 2013 Effect of nano hexagonal boron nitride lubricant additives on the friction and wear properties of AISI 4140 steel Part. Sci. Technol. 31 501–6
[15] Mussada E K and Patowari P K 2015 Characterisation of layer deposited by electric discharge coating process Surf. Eng. 31 796–802
[16] Eswara Krishna M and Patowari P K 2013 Parametric optimisation of electrical discharge coating process with powder metallurgy tools using taguchi analysis, Surf. Eng. 29 703–11
[17] Rao P S. Purnima N S and Prasad D S 2019 Surface alloying of D2 steel using EDM with WC/Co/P/M electrodes made of nano and micron sized particles Mater. Res. Express 6 063511
[18] Murray J W, Cook R B, Senin N, Algodì S J and Clare A T 2018 Defect-free TiC/Si multi-layer electrical discharge coatings, Mater. Des. 155 352–65
[19] Tyagi R, Mahto N K, Das A K and Mandal A 2020 Preparation of MoS₂ + Cu coating through the EDC process and its analysis, Surf. Eng. 36 86–93
[20] Yap C Y, Liew P J and Wang J 2020 Surface modification of tungsten carbide cobalt by electrical discharge coating with quarry dust powder: an optimisation study Mater. Res. Express 7 106407
[21] Elaiyarsan U, Sathesheekumvar V and Senthilkumar C 2018 Experimental analysis of electrical discharge coating characteristics of magnesium alloy using response surface methodology, Mater. Res. Express 5 86501
[22] Tyagi R, Pandey K, Das A K and Mandal A 2019 Deposition of hBN + Cu layer through electrical discharge process using green compact electrode, Mater. Manuf. Process. 34 1055–48
[23] Zaw H M, Fuh Y H, Nee A Y C and Lu L 1999 Formation of a new EDM electrode material using sintering techniques, J. Mater. Process. Technol. 89 182–6
[24] Moro T, Mohri N, Otsubo H, Goto A and Saiio N 2004 Study on the surface modification system with electrical discharge machine in the practical usage, J. Mater. Process. Technol. 149 65–70
[25] Gangadhar A, Shumugam M S and Philip P K 1991 Surface modification in electrode discharge processing with a powder compact tool electrode, Wear 143 45–55
[26] Kumar S, Singh R, Singh T P and Sethi B L 2009 Surface modification by electrical discharge machining: a review, J. Mater. Process. Technol. 209 5675–87
[27] Liew P J, Yap C Y, Wang J, Zhou T and Yan J 2020 Surface modification and functionalization by electrical discharge coating: a comprehensive review Int. J. Extrem. Manuf. 201 2004
[28] Ahmed N et al 2020 Formation of thick electrical discharge coatings, J. Mater. Process. Technol. 285 116801
[29] Murray J W et al 2020 Dry-sliding wear and hardness of thick electrical discharge coatings and laser clads, Tribol. Int. 150 106392