Effect of Various Process Parameters of EDC on Mild Steel Substrate and their Properties

RAKESH KUMAR PATEL (✉ rakesh1993patel@gmail.com)

Maulana Azad National Institute of Technology <https://orcid.org/0000-0001-5330-3126>

Mohan Kumar Pradhan

Maulana Azad National Institute of Technology

Original Article

Keywords: Electrical discharge coating (EDC), Powder mixing, Hexagonal Boron Nitride (HBN), molybdenum disulfide (MoS₂), Surface morphology.

Posted Date: October 27th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1005154/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

In the present study, A layer of the modified composite coated surface is made using Copper, molybdenum disulfide, and hexagonal boron nitride. For this process, Electrical discharge machine (EDM) is used but in reverse polarity. Various factors of the machine influenced the thickness of the deposited layer like the amplitude of peak current, duty factor, powder mixing ratio, used etc. For the deposition process, green compacted electrodes which was made after mixing the powder material in mortar for approximately 2.5 hour and post processing in Hot mount press moulding machine. After that the mixture powder was put in the Hot mounting press machine to made green compact electrode with specific parameters. Experiment was performed on EDM and many analysis were carried out to study the morphology of the coated surface. To get the morphology of the coated layer, FESEM images were examined and found the satisfying uniform distribution of deposited layer constituents with material powder mixing ratio of (Cu/HBN/MoS₂) at (20/40/40) got with 50% duty factor and 10 Ampere peak current amplitude. Also done XRD, for the evidence of Cu, MoS₂ and HBN.

1. Introduction

Coating is a process of covering the surface of substrate with the help of another material. Coating material usually different from substrate elements and it modifies the surface behaviour of substrate without changing the bulk properties of substrate [1-2]. Coating the surface now days a popular method to utter the substrate's surface specifications like hardness, Anti-friction properties like tear and wear resistance, low coefficient of friction, score resistance, corrosion and oxidation resistance etc. [3].

For surface coating there are various known methods like Electro-less plating [4-5], Electro-Plating, conversion coating [5], hot-dipping [6], chemical vapour deposition method, Roll-to-Roll coating process, thermal spraying and many more. These processes are efficient in their own area but with advantage they have some disadvantages [7] such as costly machine involvement, complexity during operation, complexity during setup of work-surface, specific (high/low) temperature and specific working environment requirement like inert environment or vacuums that somehow creates hindrance the easiness for some specific use and conditions. Also, with the help of some of the methods we get thin coating and some other provide thick coating.

Electrical discharge coating (EDC) is a reverse method of electrical discharge machining [8]. In this technique, we interchange the polarity of the operation. Unlike EDM, in EDC we connect the work piece to the positive terminal and the electrode to the negative terminal. Also, the substrate is dipped into the dielectric medium with the electrode. The dielectric medium is nothing just a hydro-carbon chemical compound like kerosine. This dielectric medium helps in the coating process just as in electrical discharge machine process. This process is somehow, easy to coat for flat surface and small area once at a time. Although all methods have their own advantage, so EDC also have its own advantage. For coating in the substrate surface using EDC, we need only dielectric medium which is at atmospheric pressure without any special vacuum or inert environment [9]. Surface coating with the help of EDC

doesn't require special arrangement, it needs only a Electro discharge machine with reverse polarity[3]. The other advantages are, it doesn't require special arrangement to form layer material. Only by mixing [10] required layer material powder we can ready our layer forming material for coating.

The main application of coating of the surface is to provide the protection from environmental deterioration, provide smooth surface with different properties like low coefficient of friction and high hardness etc [11] [12]. One of the applications of electro discharge coating used to increase tool-life of any cutting tool by decreasing the coefficient of friction and by increasing the hardness after coating with the help of EDC. Also, it may help in making the rubbing part smooth for low power loss in some specific applications [13].

Also, above liquid lubricants, solid lubricants have some specific advantages like firmly tackiness to the substrate area, high temperature stability as compared to liquid or air lubrication, no change in properties in variable pressure, also inert to radiation and for reactive environment etc. In complicated areas where applying lubrication all the time is possible can be encountered by using solid surface lubrication, just by coating the rubbing surface by special lubricating property materials. Somehow the coating process needs some processing costs but it also minimises the breakdown probability of machine which also can help to minimise the overall running cost. Also, in traditional machining process we are using metal cutters which rubs and the surface deteriorates. This rubbing vanishes the surface finish of the product. So, if tool tips would able to coat then it is possible that the surface finish of final product can be enhanced. Hence, for industrial and research perspective Electric discharge coating is feasible and a perfect choice. Mostly Hexagonal boron nitride, graphite, molybdenum disulfide etc. are used for surface modifications where lubrication effect needed [14], [15].

Here, are some technical terms associated with the process like Duty factor. It's a term define that for how much time current flows from the set-up over the period of one cycle as shown in figure.1.

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

Here;

T_{high} = Time for which current flows with its peak amplitude.

T_{period} = Time period of one cycle.

1.1. Lubricating action of MoS₂ and HBN

Molybdenum disulfide (MoS₂) is a well-known solid lubricant used in industries such as in forging industries to lubricate dies to reduce friction between die and forged material. Molybdenum disulfide which is same as graphite is heavily used in industrial lubricating oils to enhance the tribological properties of lubricating oil. MoS₂ can used up-to 350 degrees Celsius in oxidising environment and 1100

degree Celsius in reducing environment. The lubrication behaviour of Molybdenum disulfide is due to the hexagonal structure of it like graphite. These hexagonal structure crystals are flat and joint to each other and make a chain. Between each layer there is a gap. The gap between two hexagonal layer is high enough so that little external force can make them slide on each other. So as the external force is applied it overcomes the vander-walls force between the layers and each layers starts sliding on each other. This sliding creates a lubricating effect just like in viscous fluids and hence it helps in reducing the frictional effect. This phenomenon helps to create the lubrication property of molybdenum disulfide.

Hexagonal Boron Nitride (HBN) is also known by other name called “white graphite”. It has similar crystal structure as molybdenum disulfide and graphite. Although, HBN has superior properties than graphite, like 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, Hence, it is a suitable material to choose as a coating material [16].

Algodi et al [1] performed electro discharge coating on Mild steel surface with the help of Ti-Fe cermets in Die sinking EDM machine and got hardness of the coated surface 4-8 times harder than the substrate surface. Mussada et al. [17] coated the mild steel surface with (W-Cu) :(75:25) with the help of powder mixed green compact compacted electrode in EDM machine. The input parameters selected was current(A), compaction load (Tons) to make green compact electrode and pulse on and off time (micro-seconds). As an output parameters material transfer rate (mg/min) and surface roughness were measured. Also, for confirmation of material in the coated surface XRD analysis were performed which confirmed the presence of Cu, W, WC and W₂C. Krishna et al. [18] studied the effect of EDC on Mild steel surface with the help of (W-Cu) :(75:25) and got mass transfer rate of 281 mg/min and coated layer thickness of 1262.90 µm with 5-6 times harder than surface of substrate. Many studies have been carried for coating of Mild steel surface with the help of EDC with different materials and their after-process properties. However, there has not been a lot of attention given to Cu/HBN/MoS₂ material with different mixing ratio and various process parameters. So, in our case we are using Mild steel substrate and Cu, HBN and MoS₂ as a coating material. Input parameters are Powder mixing ratio, Current and Duty factor. As an output parameter, we studied mass deposition rate on the substrate surface, coating layer thickness with powder mixing ratio, FESEM analysis for uniformity and pores detection and kinematic coefficient of friction of coated surface.

1.2. Working principle of Electrical discharge coating:

This coating techniques is practically interchangeable to EDM. The only difference is here we are using reverse polarity to coat the surface unlike straight polarity used in Electrical discharge machining. Basically, as shown in figure.2, in this method the substrate in which coating we want is being connected to the positive terminal of machine setup and the electrode used is being connected to the negative terminal, which is just opposite to the machining process. After that we dip the whole setup in the dielectric medium so that spark ignites under dielectric (inert medium) medium for die sinking effect.

After dipping, we start the EDM machine and reverse the polarity and set-up the required process parameters from the control console. After applying the appropriate voltage, there generates a voltage gap between substrate and electrode. This voltage gap created a dielectric breakdown and due to this spark generates between nearest part of the electrode surface and substrate surface. Due to this spark, heat generates and it melts down the loosely compacted electrodes surface particles. After melting, the melted particles move towards the substrate because of electromotive force generated due to applied voltage. Then these particles get settled down in the substrate surface and make uniform coating layer by layer [19] [20] if suitable process parameters are used. So, this process goes periodically and continuously for stipulated time and due to it layer by layer coating process happens and its thickness depends upon the timing of coating process and other parameters.

The thickness of coating depends upon various parameters. The chemical composition of substrate material and electrode material, electric conductivity of materials, green compact electrodes bond strength, applied various parameters like current, voltage, duty factor, peak current amplitude etc.

2. Research Objective

The main objective of this research paper is, to analyse the effect of various process parameters on the coating process of mild steel surface as a substrate with the help of EDC. Power form of Molybdenum disulfide (MoS_2), Hexagonal Boron Nitride and copper were mixed extensively and were used as a green compact electrode formed using powder metallurgy method. Substrate surface was coated using EDC process which is reverse of EDM. To study the effect of various process parameters effect on EDC, we have performed several experiments by changing different parameters like peak current amplitude, duty factor and powder mixing ratio. After that, to analyse the morphology of the coated surface, we took the help of FESEM and also, to study the components present in to coated surface XRD were used. Apart from that, we calculated the mass deposition rate on substrate surface and tool wear rate with respect to current, duty factor and powder mixing ratio.

3. Experimental Setup And Procedure

3.1. Specification of Material

As a work piece, mild steel plate is selected with material constituents of (Fe - 96.8%, C – 0.29 %, P - 0.04 %, Cu - 0.30 % and Mg – 1.04 %,) with dimension of (measurement: 15 mm × 15 mm × 5 mm). Further cleaning and crushing of work piece have done with the assistance of cleaning paper of coarseness size of 900 μm .

MoS_2 , hBN and copper powder were bringing into play to create green compact cathode electrode comprising hBN nano particles of size 60 nm, Copper nano particles of size 10 μm and MoS_2 nano particles of size 110 nm. The density of MoS_2 used was 5.07 g/cm³, hBN particles was of 2.26 g/cm³ and Cu was of 8.97 g/cm³.

3.2. Experimental setup:

The set-up for Electro discharge machining is shown in fig.4. In fig.4. (a), it is showing the machine for the coating process and in fig.4. (b), it is showing the arrangement of electrode and workpiece holder inside the EDM machine. The work piece is held in the magnetic vice with the help of clamp and the magnetic vice is stick to the machine base due to magnetic action so that during operation it doesn't move. The electrode is clamped to the machine head vertically upward to the work-piece arrangement. Special attention is given for parallel arrangement of electrode and substrate upper surface so that uniform spacing between both surface we get during operation. After that, by adjusting the machine head we setup the electrode just above the substrate so that substrate upper surface is fully covered by electrode for direct projection. After that, we close the side gates of the machine and start the pump which fills the arrangement space with dielectric fluid. We made sure that the fluid is continuously flowing through the working area so that it takes out the debris particles and die sinking process proceeds. After that, we reversed the polarity of the process as we used in EDM process and setup current, duty-factor and voltage parameters from the controlling console of the machine. During experiment we can see the voltage and current fluctuation with the help of controlling console and oscilloscope installed.

3.3. Preparation of green compact electrode

The MoS₂, HBN [21] and Cu powder used have normal molecule size of 110 nm, 60 nm and 10 μ m separately. For extremely proper mixing Cu, HBN and MoS₂ were mixed in mortar for 2.5 hour continuously. The decision of 2.5 hour of mixing of powders has taken by trial experiments, 60-minutes of mixing time gives us improper coating. And due to improper mixing, it is almost difficult to get uniform distribution of material all over the substrate surface [22]. So, time greater than 2.5 hours for mixing the powder were chosen. After this process, using hot mounting press the green compact electrode was prepared by putting the mixed powder in the machine by applying appropriate pressure [23] [24]. Also, pressure plays an important role here. So, appropriate pressure was taken for further procedure. The pressure gauge shows the current pressure applied on the mixture continuously. And due to compacting the pressure gradually decreases all the time, we had maintained the appropriate pressure manually all the time. After that, cooling was done for 20 minutes. The first 10-minute cooling was normal cooling and the next 10-minute cooling was done by running water outside the hot mould. To produce green compact electrode of size 5mm thickness and 15 mm diameter, we had chosen appropriate amount of power. As the coating process involves current, so all the constituents in this process should be conductive, hence the Copper bar and the green compact electrode were stick together by using silver paste [25], which is highly conductive in nature.

As the EDC process involves current, the materials used should be highly conductive so that current can pass easily and efficiently. As we know, HBN and MoS₂ are not good conductor of electricity, so copper is blended with them to enhance the conductivity of the green compact electrode. Also, copper enhance the stickiness between HBN and MoS₂ and helps to form a firm electrode structure. Also, copper helps to generate good spark. During spark, heat generates and as copper has low melting temperature it melts

down earlier than HBN and MoS₂ and allows the process to distribute the coating uniformly over the substrate surface.

Previously, during so many trial experiments we have tried to make appropriate mixing ratio for efficient electrode formation for uniform deposition of mass on substrate surface. But out of several mixing ratio of Cu, HBN and MoS₂ only few were capable to provide satisfactory results. Mixing ratio (Cu/HBN/MoS₂) of (20/40/40), (30/35/35) and (40/30/30) were used for further investigation.

3.4 Process parameters:

Table.1. Process parameters.

PARAMETERS	VALUES
COMPOSITION	CU/HBN/MoS ₂
PRESSURE	250 kg/cm ²
TEMPERATURE	150°C
TIME	10 + 10 min

3.5 Selection of process parameters

For satisfactory results various experiments were carried out with different parameters and mixing ratio. The substrate was associated with positive terminal and the apparatus was associated with negative terminal. To check the spark event the oscilloscope was associated over the terminals, which is nothing but an appropriate condition for covering process. Several trial experiments were carried out and after that, mixing ratio of (Cu/HBN/MoS₂) -(20/40/40), (30/35/35), (40/30/30), duty factor (50%) and peak current (5,7 and 10 ampere) were giving good results without sparking and considered as suitable parameters. Parameters used beyond these values created unusual arcing before proper coating time and due to that an island type structure formed in the substrate surface which is the closest point. The process was carried out for 4 minute each to stop further arcing for the selected process parameters.

4. Observation Table

Table.2. observation table of experiments for various parameters.

Exp. No	Composition (Cu/HBN/MoS ₂)	Current (Ampere)	Duty factor (%)	Mass deposition rate (gram/minute)	Tool wear rate (gram/minute)
1	(20/40/40)	5	50	0.08753	0.09453
2		7	50	0.18973	0.22973
3		10	50	0.22420	0.26420
1	(30/35/35)	5	50	0.06273	0.34751
2		7	50	0.12532	0.13120
3		10	50	0.14241	0.17241
1	(40/30/30)	5	50	0.02984	0.09984
2		7	50	0.09762	0.14352
3		10	50	0.13123	0.21209

5. Results And Discussion

5.1. Chemical composition and micro-structure

To study the chemical composition and morphology a small-scale basic investigation was carried out with the assistance of FESEM. Fig.6. and Fig.7. shows the FESEM picture of covered surfaces with the modification of peak current and powder blending proportion. In the accompanying area point by point examination is portrayed.

5.1.1. Variation of cross-section morphology with powder mixing ratio

The FESEM image of top cross section of is shown in fig.5 with three different powder mixing ratios of Cu/HBN/MoS₂;(20:40:40), Cu/HBN/MoS₂;(30:35:35) and Cu/HBN/MoS₂;(40:30:30) respectively, with 50% duty factor and 5 Ampere peak current amplitude.

Fig.6.(a) shows no crack development between the substrate and coating. But the diffusion between them is mild with the powder mixing ratio of Cu/HBN/MoS₂ (20/40/40). Whereas, Fig.6. (b) and shows minor cracks between the coating and substrate. This may happen because of non-compatibility between the mixture and the substrate surface, also process parameters have an important role. In fig.6. (c), there is a good diffusion between the substrate and coating material. Also, there is a difference in the coating thickness w.r.t mixing ration [26]. Also, the average coating thickness is shown in the Fig.6. d. The coating thickness decreases with copper content in the mixing ratio. This may be because of high binding of particles as the copper content is increasing.

5.1.2. Surface morphology of coated surface

FESEM images of coated surface is shown in Fig.7. (a–c) to study the surface morphology, separately with (Cu/HBN/MoS₂) : (20:40:40). In Electrical discharge machining, the pinnacle flow perhaps demonstrates the capacity to get an ideal spark temperature to move the anode material into the work-piece. To deposit uniform material with high density with high material deposition rate at substrate surface, we need to take appropriate high peak current that an appropriate high peak current. Some voids or pores with non-uniform coating may create with low current because it will not provide enough spark energy to melt down the green compact electrode. So appropriate parameters should have to melt down the anode material for uniform testimony of the melted material on the substrate surface layer.

In fig.7. (a), we can see that with mixing ratio of (20/40/40) of (Cu/HBN/MoS₂) with duty factor of 50% and 7A peak current have uniform mass deposition rate but some big pores are found. In fig.7. (b), we can see that, with same mixing ratio and duty factor but with high peak current (10 A), the coating material deposition is uniform as well less very less big voids are noticed. This may occur due to excessive energy produced due to high current flow that helped to generate good spark, also results in easily melt-down and deposit the materials uniformly.

5.1.3.x-ray diffraction analysis

The chemical composition of the coated surface during EDC is examined with the help of XRD analysis. The result is showing in fig.8 and X'PERT programming was used to examine the X-ray diffraction to get the diffraction tops. The diffraction angle (2θ) was used between 20° to 80°. With this result, we found various constituents like Fe₂B, MoS₂, BN, Cu, CuS and BC.

5.1.4. Effect of peak current amplitude to the mass deposition rate

The material deposition rate is shown in the fig.9. This graph is drawn using observation data for Table.2. Here we found that for mixing ratio (Cu/HBN/MoS₂) : (20/40/40), the material deposition rate is increasing with respect to temperature. Also, for other mixing ratios the phenomena are same.

Hence, we can conclude that the mass deposition rate is directly proportional to the peak current used. Also, from the graph we found that the rate of change of mass deposition rate is high from 5 to 7 Ampere current, after that we found that the rate of increase of mass deposition rate decreases from 7 to 10 A. May be, this happens due to excessive heat generation which cause more mass removal rate of substrate than the mass deposition rate on substrate.

5.2. coefficient of kinematic friction of the coating surface

The coefficient of kinematic friction of the coated surface was obtained with the help of a pin-on-disc test [1]. In fig.10. (a) it is showing the uncoated workpiece and fig.10. (b) showing the coated wok-piece. This coated work-piece was used to analyse the tribological behaviour. Pin-on-disc test was performed between a Mild steel circular plate and the Coated surface sample as shown in fig.10. (a). A Mild steel disc with of radius 120 mm and thickness 25 mm was used for the pin-on disc test. The test was carried

out in the radius of 90 mm and the time duration was 5 minutes. The load applied for the test was 2 kgf (20 N). From the test, we found the variation in the coefficient of friction during the time because of shearing off of the layers of coating [27].

So, from the fig.11 we can get that the average coefficient of friction is 0.290, standard deviation is 0.051 and variance of 0.003. although, Mild steel's coefficient of kinematic friction lie between 0.09 to 0.6. Also, in fig.10. (c), we can see the FESEM image of wear track. So, we found that due to coating the coefficient of kinematic friction decreased by somehow due to presence of HBN and MoS₂, as they have hexagonal packing structure and slides over each other layer easily which helps to decrease friction.

6. Conclusion

In this research work, to make the green compact electrode the powder material with mixing ratio of (Cu/HBN/MoS₂) is used with the help of hot mounting press machine in the mixing ratio of (20/40/40), (30/35/35) and (40/30/30). With the help of EDC, developed a coating surface over the substrate. Total 36 experiments were performed and out of which 9 are shown here, which show better results. Several methods and equipment are used to study the effect of various parameters. The conclusions and effects can be summarised as follows:

1. Bonding strength between HBN and MoS₂ is not good enough, so that they don't stick together firmly and so it is not possible to coat substrate. So, to make the powders stick together we used Cu as a binder which helps to stick all constituents together. It helps to form green compact electrode with ease and provides firmness to the green compact electrode. Also, HBN and MoS₂ are not a good conductor of electricity and for EDC process electricity needs to pass easily over it for efficient coating [12]. Hence, copper is added to increase the green compact electrodes conductivity. Apart from that, Cu has low melting temperature and during heat generation it melts down first and allows HBN and MoS₂ to get detached from electrode and deposit in the substrate with ease. So, these are the main reason behind using of copper instead of other material
2. Substrate's coating which was made with the use of powder mixing ratio of (20/40/40), peak current amplitude of 10A and 50% duty factor has better surface morphology obtained with less voids or pores above all other samples. Although, to perform the experiment, binder selection with appropriate mixing ratio were obtained to enhance the better morphology of the coated surface after so many trial experiments.
3. The material fusion between substrate and coated surface is found better in mixing ratio of (40/30/30) with 50% duty factor and 5 A peak current.
4. Presence of Cu, BN and MoS₂ was found through XRD analysis, phases of Mo, BN and Cu-S are also showed with the inter-metallic compound formation. The results showed that there is a uniform distribution of compounds all over the coating surface.
5. The process parameters have high impact on mass deposition rate. From observation table.2, we can see that the mass deposition rate is increasing with peak current amplitude. Although, the

maximum rate of mass deposition rate found between 5 to 7 Ampere.

6. Peak current is the most important factor in electrical discharge coating to control the coating thickness. High amount of peak current amplitude is required to high amount of spark energy which means spark energy is directly proportional to peak current, so that more amount of electrode tool melts down and deposits on the substrate due to cumulative effect of plasma and gravity. So, peak current applied is directly proportional to coating thickness obtained.
7. The layer formed onto substrate's surface were analysed with the help of FESEM and XRD, and we found uniform coating onto the substrate with evidence of MoS₂, BN and Cu compounds.
8. Also, Wear test were performed on the pin-on disc to analyse the coating surface tribological behaviour. We found that the coefficient of kinematic friction between coated surface and mild steel is lowered due to coating.

Declarations

Funding- Not get any funding from any sources.

Data availability- There is no need to mention the availability of data and materials in the present study.

Ethical approval- Not applicable.

Consent to participate- There is no consent to participate needed in the present study.

Consent to publish- There is no consent to publish needed in the present study.

References

Reference

- [1] S. J. Algodí, J. W. Murray, P. D. Brown, and A. T. Clare, "Wear performance of TiC/Fe cermet electrical discharge coatings," *Wear*, vol. 402, pp. 109–123, 2018.
- [2] S. Zhang, K. Han, and L. Cheng, "The effect of SiC particles added in electroless Ni–P plating solution on the properties of composite coatings," *Surf. Coatings Technol.*, vol. 202, no. 12, pp. 2807–2812, 2008.
- [3] D. Kumar, K. Mittal, S. Kataria, S. Kadiyan, and S. Sharma, "Experimental investigation on surface modification of Wc-Co by electric discharge coating process using SiC/Cu green compact tool-electrode," *Int. J. Res. Mech. Eng. Technol.*, vol. 3, no. 2, pp. 274–278, 2013.
- [4] A. Brenner, *Electrodeposition of alloys: principles and practice*. Elsevier, 2013.

- [5] X. B. Chen, N. Birbilis, and T. B. Abbott, "Review of corrosion-resistant conversion coatings for magnesium and its alloys," *Corrosion*, vol. 67, no. 3, pp. 35001–35005, 2011.
- [6] S. M. A. Shibli, B. N. Meena, and R. Remya, "A review on recent approaches in the field of hot dip zinc galvanizing process," *Surf. Coatings Technol.*, vol. 262, pp. 210–215, 2015.
- [7] K. O. Legg, M. Graham, P. Chang, F. Rastagar, A. Gonzales, and B. Sartwell, "The replacement of electroplating," *Surf. Coatings Technol.*, vol. 81, no. 1, pp. 99–105, 1996.
- [8] J. Simao, H. G. Lee, D. K. Aspinwall, R. C. Dewes, and E. M. Aspinwall, "Workpiece surface modification using electrical discharge machining," *Int. J. Mach. Tools Manuf.*, vol. 43, no. 2, pp. 121–128, 2003.
- [9] A. Goto, "Development of electrical discharge coating method," in *Proceeding of International Symposium for Electro-Machining (ISEM XIII)*, 2001, vol. 2, pp. 581–588.
- [10] P. K. Patowari, P. Saha, and P. K. Mishra, "Artificial neural network model in surface modification by EDM using tungsten–copper powder metallurgy sintered electrodes," *Int. J. Adv. Manuf. Technol.*, vol. 51, no. 5–8, pp. 627–638, 2010.
- [11] P. A. Sørensen, S. Kiil, K. Dam-Johansen, and C. E. Weinell, "Anticorrosive coatings: a review," *J. Coatings Technol. Res.*, vol. 6, no. 2, pp. 135–176, 2009, doi: 10.1007/s11998-008-9144-2.
- [12] P. J. Liew, C. Y. Yap, J. Wang, T. Zhou, and J. Yan, "Surface modification and functionalization by electrical discharge coating: a comprehensive review," *Int. J. Extrem. Manuf.*, vol. 2, no. 1, p. 12004, 2020.
- [13] U. Elaiyaran, V. Satheeshkumar, and C. Senthilkumar, "Experimental analysis of electrical discharge coating characteristics of magnesium alloy using response surface methodology," *Mater. Res. Express*, vol. 5, no. 8, p. 86501, 2018.
- [14] G. Hammes *et al.*, "Effect of hexagonal boron nitride and graphite on mechanical and scuffing resistance of self lubricating iron based composite," *Wear*, vol. 376, pp. 1084–1090, 2017.
- [15] M. L. Parucker, A. N. Klein, C. Binder, W. Ristow Junior, and R. Binder, "Development of self-lubricating composite materials of nickel with molybdenum disulfide, graphite and hexagonal boron nitride processed by powder metallurgy: preliminary study," *Mater. Res.*, vol. 17, pp. 180–185, 2014.
- [16] O. N. Çelik, N. Ay, and Y. Göncü, "Effect of Nano Hexagonal Boron Nitride Lubricant Additives on the Friction and Wear Properties of AISI 4140 Steel," *Part. Sci. Technol.*, vol. 31, no. 5, pp. 501–506, Sep. 2013, doi: 10.1080/02726351.2013.779336.
- [17] E. K. Mussada and P. K. Patowari, "Characterisation of layer deposited by electric discharge coating process," *Surf. Eng.*, vol. 31, no. 10, pp. 796–802, 2015.

- [18] M. Eswara Krishna and P. K. Patowari, "Parametric optimisation of electric discharge coating process with powder metallurgy tools using Taguchi analysis," *Surf. Eng.*, vol. 29, no. 9, pp. 703–711, 2013.
- [19] J. W. Murray, R. B. Cook, N. Senin, S. J. Algodí, and A. T. Clare, "Defect-free TiC/Si multi-layer electrical discharge coatings," *Mater. Des.*, vol. 155, pp. 352–365, 2018.
- [20] R. Tyagi, N. K. Mahto, A. K. Das, and A. Mandal, "Preparation of MoS₂+ Cu coating through the EDC process and its analysis," *Surf. Eng.*, vol. 36, no. 1, pp. 86–93, 2020.
- [21] R. Tyagi, K. Pandey, A. K. Das, and A. Mandal, "Deposition of hBN+ Cu layer through electrical discharge process using green compact electrode," *Mater. Manuf. Process.*, vol. 34, no. 9, pp. 1035–1048, 2019.
- [22] H. M. Zaw, J. Y. H. Fuh, A. Y. C. Nee, and L. Lu, "Formation of a new EDM electrode material using sintering techniques," *J. Mater. Process. Technol.*, vol. 89, pp. 182–186, 1999.
- [23] T. Moro, N. Mohri, H. Otsubo, A. Goto, and N. Saito, "Study on the surface modification system with electrical discharge machine in the practical usage," *J. Mater. Process. Technol.*, vol. 149, no. 1–3, pp. 65–70, 2004.
- [24] A. Gangadhar, M. S. Shunmugam, and P. K. Philip, "Surface modification in electrodischarge processing with a powder compact tool electrode," *Wear*, vol. 143, no. 1, pp. 45–55, 1991.
- [25] S. Kumar, R. Singh, T. P. Singh, and B. L. Sethi, "Surface modification by electrical discharge machining: A review," *J. Mater. Process. Technol.*, vol. 209, no. 8, pp. 3675–3687, 2009.
- [26] N. Ahmed *et al.*, "Formation of thick electrical discharge coatings," *J. Mater. Process. Technol.*, vol. 285, p. 116801, 2020.
- [27] J. W. Murray *et al.*, "Dry-sliding wear and hardness of thick electrical discharge coatings and laser clads," *Tribol. Int.*, vol. 150, p. 106392, 2020.

Figures

Figure 1

Duty factor graph showing the time period of peak amplitude.

Figure 2

(a) schematic diagram of sparking process, (b) material deposition after sparking.

Figure 3

FESEM images and EDS analysis of (a), (b) MoS₂ and (c), (d) Cu powder respectively.

Figure 4

(a) EDM (Electro Discharge Machine) setup (b) Set-up for EDC inside the working tank.

(a)

(b)

(c)

(d).

Figure 5

(a) Image showing powder mixing process in mortar manually, (b) Moulding machine (Hot mounting press), (c) Green compact electrode after removing from Moulding machine (d) Copper electrode after getting stick to green compact electrode using silver paste.

Figure 6

FESEM image of cross-sectional view of coating of powder mixing (Cu/HBN/MoS₂) ratio, (a) 20:40:40, (b) 30:35:35, (c) 40:30:30, (d) graph of average coating layer thickness w. r. t. powder mixing ratio at duty factor of 50% and 5A current.

Figure 7

Top cross-section's FESEM image of coated surface with powder mixing ratio (Cu/HBN/MoS₂) (20/40/40) at different current (a) 7 ampere peak current (b) 10 ampere peak current (c) zoomed FESEM image of figure (b), with (constant parameters: composition, duty factor (50%) and sparking of time 4 minute).

Figure 8

XRD peak graph showing analysis of (Cu/HBN/MoS2) with mixing ratio of (20/40/40) with 4-minute machining time, 50% duty factor and peak current of 10 A

Figure 9

Showing the variation of mass deposition rate on substrate surface with respect to peak current at different powder mixing ratio.

Figure 10

Showing images of (a) uncoated mild steel sample, (b) Coated sample, (c) FESEM image of Coated surface, (d) FESEM image of coated surface after pin-on-disc test.

Figure 11

Variation of kinematic coefficient of friction with time.