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Original Research Article

Electrical discharge synthesized hBN–Cu solid lubricant coating on Aluminum 6062

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ABSTRACT
This study presents the development of a hexagonal boron nitride–copper (hBN–Cu) solid lubricant coating on Aluminium 6062 using the Electrical Discharge Coating (EDC) technique with green compact electrodes. The key parameters of the pulsed electrodeposition process were systematically analyzed, revealing that a dense and uniform coating is achieved at an hBN–Cu ratio of 50:50, a peak current of 10 A, and a duty factor of 70%. The deposited layer composition, examined through field emission scanning electron microscopy, confirmed the presence of BN, Cu, and Fe_2O_3 phases. The findings demonstrate that EDC is an effective technique for producing self-lubricating surfaces with an optimized hardness balance, making them suitable for reverse motion applications in industrial environments.

1. Introduction

Surface engineering methods like Electrical Discharge Coating (EDC) have received significant attention in the recent past, with the spark energy produced during Electrical Discharge Machining (EDM) using finely tuned surface properties. Although EDM was originally created to be used in machining processes, it has now become a useful process of surface modification, which can be used to increase wear resistance and improve the surface characteristics of conductive materials [1,2]. With the EDC process, both thin and thick layers of coating can be formed on a work piece based on the conditions of the process [3-6]. Though different traditional surface-modification techniques like ion implantation [7], electroless plating [9], pulsed electro-spark deposition [11], thermal spraying [12], chemical, physical vapor deposition [14], and laser cladding [16] have been extensively employed, they tend to be costly in terms of equipment, controlled conditions, and cost of operation. By comparison, EDC is less expensive and more versatile, since it does not involve using vacuum chambers or complicated thermal solutions but still allows a high level of control over the traits of coating. Furthermore, EDC enables the capability to machine and coating of the same electrode in one step, which removes any additional processing and allows the coating of intricate geometries with high precision [17,18]. EDC is especially commonly used to apply coating of hard materials such as ceramics and substances with high melting points, and therefore increasing the wear resistance and service life of engineering components due to the high temperatures created within the plasma channel. In this high-speed process, transfer of the coating material is done onto the work piece surface in the form of loosely bonded particles which are deposited by thermal effect and chemical reaction between the electrode and substrate during the manufacturing process [20]. EDC has been used in the plating of cutting tools [23,24], dies [25], and parts of the rolling mill [21,22,25]. Although the tribological behavior of EDC coatings has been the subject of continuous improvements, there is still no comprehensive comprehension of the phenomenon and further studies seek to determine the exact impact of the important process parameters. Here, the current study aims at depositing a hexagonal boron nitride (hBN) and copper (Cu) composite coating on an aluminum substrate by EDC process with the goal of addressing how peak current, duty factor, and powder mixing ratio will influence the surface integrity, adhesion strength, and subsequent mechanical and tribological properties of the developed coating.

2. Materials and methods

2.1 Material specification and working of EDC

The piece of work in this study is Al-6062 alloy which is a heat-treatable 6000 series material that includes magnesium silicide and had dimensions of 10 mm × 10 mm × 4 mm. An electrode tool was made ready with hexagonal boron nitride (hBN) powder (70 nm) and copper (Cu) powder (7 μm). During the Electrical Discharge Coating (EDC) process, electrical discharges between the tool and workpiece result in the occurrence of dielectric breakdown whereby, the electrons are emitted and the positive ions and secondary electrons are formed. This causes a plasma channel over the shortest distance between the electrodes. The high intensity spark in this channel produces localized heat and results in melting and transfer of material. The work piece in mode of coating (re-sputtering mechanism) is attached to the positive terminal and the tool to the negative terminal, similarly to cathodic behavior in electroplating. The adverse polarity of the tool causes the plasma channel to expand, leading to less discharge density and facilitating the movement of material off the tool into the work piece surface. The coating thickness and composition are determined by process parameters, material properties and dielectric characteristics. Also, green compact electrodes made of powder give the flexibility of adjusting coating thickness and composition to certain purposes.

2.2 Experimentation setup

To conduct a controlled Electrical Discharge Coating (EDC) process in an experimental setup, a CNC die-sinking EDM machine (Model: +GF+ FORME350) was used to create the setup (Fig. 1). The machining tank contained a work piece, a clamping vice, magnetic base, tool holder, and extension to provide the correct alignment and rigidity. A head was under servo control to ensure a constant spark gap, with manual X -Y adjustments allowing fine positioning. A pressure gauge was attached to measure the dielectric fluid pressure and an oscilloscope was attached across electrodes to measure the real-time voltage and current waveforms. The electrode of the powder compact tool was attached to the negative polarity, and the work piece of aluminum was attached to the positive polarity so that the material can transfer. Trial experiments were done to decide on the appropriate parameter ranges, and to find out the unstable situations like arcing, which adversely influences the quality of the coating. The main process parameters affecting the performance of the coating included the peak current (3-9 A), duty factor (30-90%), as well as the powder mixing ratio (70:30, 50:50, and 60:40). Increasing the value of parameters raised the frequency of arcing, causing the instability of coating and the generation of globules. The rest of the parameters such as applied voltage (40 V), pulse-on time, and coating duration remained constant because their effects were relatively minor. The study mainly focused on optimizing key EDC parameters to achieve a stable and uniform coating.

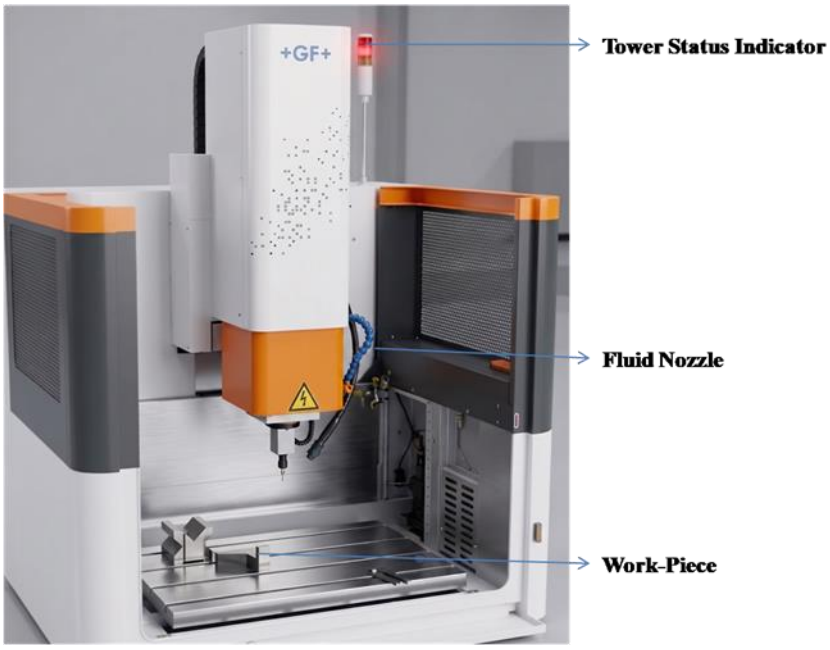

Figure 1: Schematic of die-sinking EDM with EDC set-up inside work tank.

2.3 Preparation of green compact electrodes

Due to this reason, the green compact electrodes were pressed under a constant temperature and pressure of a hot mounting press. The hBN powder (hexagonal boron nitride) and copper (Cu) powders were placed in a mixer and stirred 1 hour long to ensure that the mixture had a good mix. Copper is selected mainly due to its electrical conductivity, availability and as green compact provides an appropriate strength to the green compact such that the electrode becomes relatively tougher to possess a durable Electric Discharge Coating (EDC). Given that the inherent low binding energy of the powder compact tools, more TWR is noted. Since copper has the lowest melting point of all known elements, it melts faster than hBN, thus copper is a bonding material and the material facilitates the movement of the material to the work-piece [4]. Besides this, copper offers prevention of sparking stabilisation that brings the coating layer to be uniformly distributed. Different percentage wise hBN to Cu mixed ratio were finalised for the such investigations as 40:60 and 50:50 with the view to serve the effective powder mixture before performing the trial runs. Hot mounting press parameters used in compaction process such as compacting pressure (200 kg/cm2), sintering temperature (130 °C), heating (10 min), and cooling time (5 min) were used during the hot mounting press [7]. It was made in the form of a disc with the diameter of 15.

Figure 2: Powder metallurgy-based tool fabrication process and prepared hBN–Cu composite tool electrode.

3. Results and discussions

3.1 Variation of coating microstructure with respect to mixing ratio

The performance of coating is compared between hBN:Cu ratios 40: 60 and 50: 50. The 40:60 ratio resulted in a thin (0.112 mm), non-uniform coating with surface voids since it contained more copper and thus, minimized material transfer although enhancing machinability. Conversely, the 50: 50 ratio produced a more uniform (0.213 mm) coating more even with higher quality of the surface. This is made possible by balanced copper binding and increased hBN content, which increases material erosion and transfer. In general, the 50:50 ratio had better coating properties.

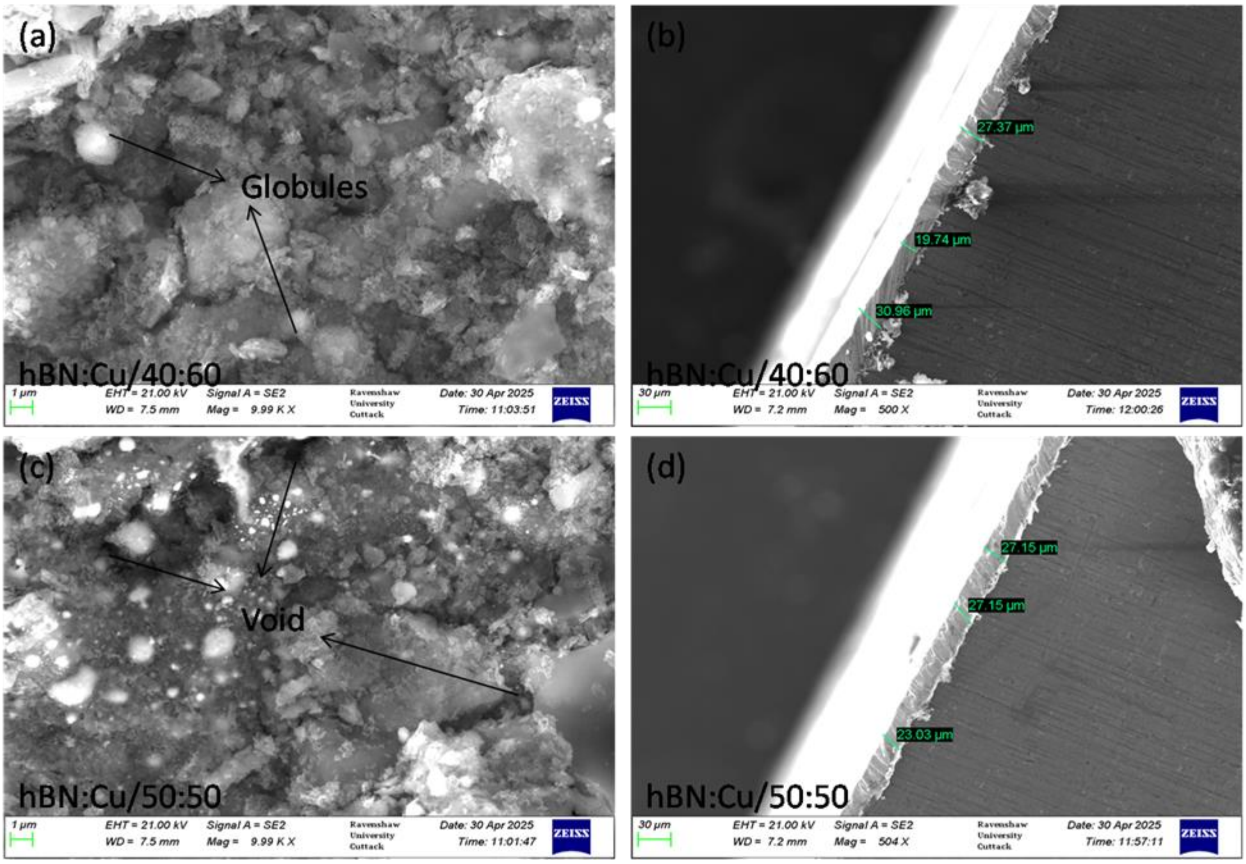

Figure 3: FESEM micrographs of coating surface and cross-sectional interface at varying hBN–Cu mixing ratios (peak current: 10 A, duty factor: 70%).

Fig. 3(a) shows that the cross-sectional microstructure for the hBN:Cu (40:60) mixing ratio exhibits a very thin and non-uniform coating layer (Fig. 3b), which facilitates easier machining due to the higher copper content in the tool electrode. The hBN:Cu (40:60) ratio results in a thin (0.112 mm) and non-uniform coating with low material deposition but allows easier machining with a higher copper content. Conversely, the 50:50 ratio provides a coating that is thicker (0.213 mm), more uniform and of better surface quality. This is attributed to copper binding capacity and lower melting temperature and higher hBN which makes the electrodes less compact, thus improving erosion, transfer of material and the overall performance of the coating.

3.2 Effect of peak current on coating microstructure

At 4 A, 7 A and 10 A, that is, the peak currents, the hBN:Cu (50:50) coating was examined, but at 4 A, there was not enough heat to form a continuous coating. At 7 A there was an improvement in deposition but with voids and irregularities still present. The energy giving the best discharge produced a high quality, uniform and dense coating at 10 A. In general, the increase in peak current leads to a considerable improvement in the thickness of the coating, its uniformity, and its morphology.

3.3 Variation of coating microstructure with respect to duty factor

Effects of duty factor (30090) on hBNCu (5050) coating microstructure were tested at constant peak current(10A) Energy and heat input in the EDC process are dependent on duty factor. At low duty rates (30-50 percent) the insufficient energy caused unstable plasma, poor bonding and discontinuous and porous coatings because of incomplete melting and loss of material. Stable discharge conditions at 70 percent allowed even melting and deposition to create an irregular coating, which was dense, smooth and adhered well. Nevertheless, overheating, arcing and the buildup of debris were experienced at 90, leading to non-uniform deposition and larger voids. In general, the best coating quality was achieved with 70% duty factor.

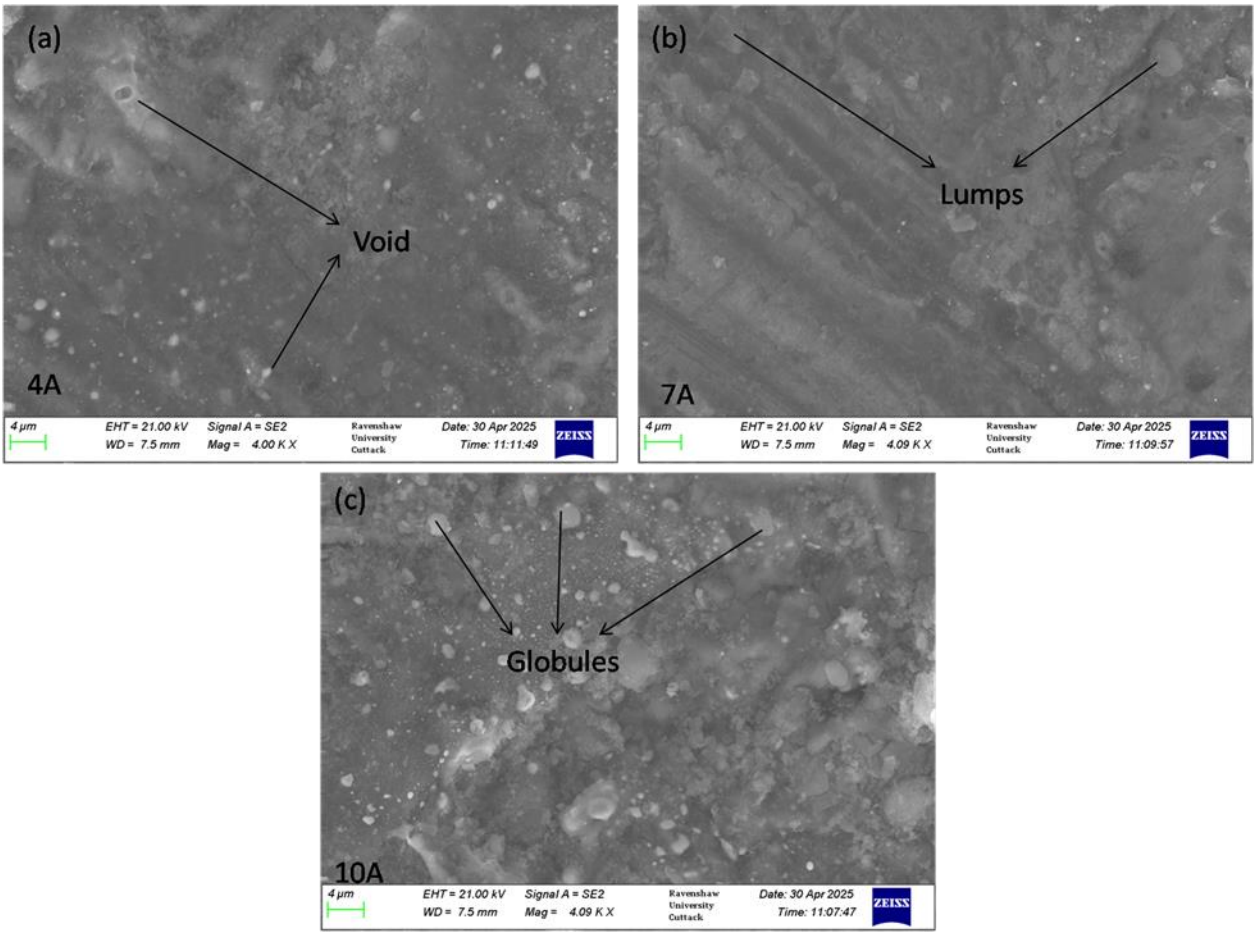

Figure 4: FESEM micrographs of coating top surface at varying peak currents for hBN–Cu (50:50) at 70% duty factor.

3.4 Microhardness

This rise in microhardness is explained by the fact that a dense and resolidified hBN–Cu composite structure was formed. The molten copper is quickly solidified during coating, entraping hBN particles and creating thick and fused layers. The hBN is a hard-reinforcing phase enhancing indentation resistance, whereas Cu is a ductile binder, which guarantees uniform distribution of the particles and minimizes porosity. This highly compacted, bonded composite structure can greatly increase surface microhardness.

3.5 Wear test

Pin-on-disk tribometric dry sliding wear behavior experiments were performed to determine the tribological behavior of hBN–Cu composites. Despite its high conductivity, copper has a low wear resistance and high friction. Incorporating hBN, a solid lubricant, forms a self-lubricating composite. When sliding, hBN with its layered structure shears readily, creating a protective tribofilm which minimizes friction and wear. The plastic deformation and adhesive wear of the copper matrix in this film is restricted and it is substantiated by the observation of SEM that lubricating layers were formed on the worn surfaces.

4. Conclusions

- In the EDC process, the green electrodes in powder metallurgy were used successfully to deposit hBN-Cu coatings onto AA6061.

- The 50:50 hBNCu mixture exhibited the best compaction, steady sparking and even transfer of material.
- The result of this ratio was thick, smooth coating that was low in porosity with high adhesiveness, which was not the case with higher Cu content (40:60).
- A current of 10 A was found to give the best quality of coating with better melting and bonding.
- FESEM confirmed the transfer of elements, metallurgical bonding, and the formation of phases such as BN, Cu, and Fe_2O_3.
- EDC is an easy and inexpensive way of preparing composite surfaces which have superior tribology.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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