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CONFERENCE PAPER

ELECTRICAL DISCHARGE SYNTHESIZED HBN–CU COATINGS FOR TRIBOLOGICAL ENHANCEMENT OF AA6062 IN SUSTAINABLE MANUFACTURING

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Abstract

In this study, a hexagonal boron nitride copper (hBN Cu) solid lubricant coating on an Aluminum 6062 substrate is investigated through Electrical discharge coating (EDC) process using green compact electrodes. The systematic analysis of the process parameters showed that the best coating density and uniformity are obtained using a 50:50 mixture of hBN and Cu and compaction pressure of 90T and top current of 9 A. Microstructural and compositional analysis with field emission scanning electron microscopy (FESEM) was conducted to determine the incorporation of BN, Cu, and Fe₂O₃ phases into the deposited coating. In the end, the results support EDC as a very feasible approach to the design of self-lubricating surfaces with an optimum level of hardness, which allows them to be used as exceptionally productive in the application of reversible motions in industrial settings.

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Introduction:-

The use of surface engineering techniques has lately drawn much attention due to its capability to utilize the spark energy of Electrical Discharge Machining (EDM) to form personalized surface layers. Previously designed to remove material, EDM has now made the conversion to a powerful surface modification plan that enhances wear resistance and improves the surface integrity of conductive substrates [1,2]. The EDC method is able to form thin and thick functional layers on a workpiece by changing the parameters of operation [36]. Although other established surface modification techniques such as ion implantation [7–8], electroless plating [9–10], pulsed electro-spark deposition [11], thermal spraying [12,13], chemical and physical vapor deposition [14,15], and laser cladding are commonly used, they often require complicated equipment, heavily controlled conditions, and significant capital expenditure. EDC, in its turn, offers a much more flexible and cost-effective alternative that does not require the use of vacuum and complex thermal processes without having to compromise control over the properties of the coating.

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Moreover, the technique enables machining and coating simultaneously in one process with a single electrode that does not need any post-processing and enables the coating of complex geometries with significant precision. The high temperature energy available in the plasma channel renders EDC to be highly skilled in deposition of hard compounds, including ceramics and materials that have a high melting point, which eventually extends service life and wear performance of industrial components. In this rapid production process, the coating material is moved off green compact electrodes that are developed through the method of powder compaction. These loosely consolidated particles are welded to the work piece surface driven by localized thermal actions and chemistries between the electrode and the substrate. Therefore, cutting, manufacturing dies and rolling mill machinery are also actively applied in EDC. In spite of these technological advancements, detailed understanding of the tribological behavior of EDC derived coating are still sparse and more studies are necessary to trace the precise influence of core operational variables. To fill this knowledge gap, the present study is focused on producing a composite solid lubricant coating of hexagonal boron nitride (hBN) and copper (Cu) on aluminum through the EDC process. The main aim is to methodically assess the influence of the changes in the peak current, as well as the powder mixing ratio on the surface integrity, adhesive strength, and the subsequent mechanical and tribological behavior of the deposited layer.

Materials and Coating Synthesis:-

Electrode Composition and the Coating Mechanism:-

The material used in this study is an Al-6062 alloy, a 6000 series, heat-treatable material that contains magnesium silicide and machined to size 10 mm x 10 mm x 4 mm. The electrode tool was produced using hexagonal boron nitride (hBN) powder (70 nm) and copper (Cu) powder (7 μ m). In the Electrical Discharge Coating (EDC) process, dielectric breakdown is caused by electrical discharges between the tool and the workpiece and leads to the emission of electrons and the formation of positive ions and secondary electrons. This effect forms a plasma channel between the closest spatial gaps between the electrodes. The high concentration of thermal energy produced by the intense spark that is confined in this channel produces localized extreme thermal energy, resulting in melting and material transfer. This is by passing a re-sputtering mechanism through the workpiece in the coating mode with the workpiece in the positive position and the tool in the negative position as the behavior is cathodic-like in the electroplating process. This is the negative polarity of the tool which is used to open the plasma channel and, therefore, decreases the density of the discharge and promotes the transport of material on the tool to the substrate surface. The final thickness and compositional structure of the coating is predetermined by certain process parameters, the intrinsic material properties, and the nature of the dielectric fluid. Moreover, the use of powder based green compact electrodes provides great elasticity to the process of adjusting the thickness and composition of the coating to suit a particular application need.

EDC Experimental Configuration and Optimization:-

Experimental setup (Fig. 1) used a CNC die-sinking EDM machine (Model: +GF+ FORM E350) to perform the Electrical Discharge Coating (EDC) process, with a secure clamping assembly, servo-controlled head to hold the spark gap between electrodes constant, and an oscilloscope to monitor voltage and current waveforms in real-time. Reverse polarity was used to enable the deposition of the material, with the hBN-Cu powder compact tool attached to the negative terminal, and the workpiece, an Al-6062, to the positive terminal. After initial trials to determine stable operating regimes and to counteract damaging arcing - which degrades coating integrity and leads to formation of globules - the study systematically explored three key process parameters: peak current (3-9 A), and the hBN-Cu powder mixing ratio (70:30, 50:50, 60:40). In order to isolate the effects of these main variables and to bring the effects under a steady and uniform self-lubricating layer, secondary parameters, such as the applied voltage (40 V), pulse-on time, and duration of deposition in the entire experiment, were kept constant.



Fig. 1. Internal configuration of the EDM work tank modified for Electrical Discharge Coating.

Preparation of green compact electrodes:-

The green compact electrodes were prepared by mixing hexagonal boron nitride (hBN) and copper (Cu) powders in a mixer over a period of one hour so as to have a homogenous dispersion of the feed material. Copper has been chosen as the main binder because of its high electrical conductivity, availability and because it will offer structural integrity to the miniature, which will result in a stronger electrode in the process of Electrical Discharge Coating (EDC). Though low binding energy of powder compact tools may result in higher Tool Wear Rate (TWR), copper melt faster than hBN, which is considered a glue to transfer material onto the workpiece. Moreover, copper helps to stabilize the sparks and makes the coating layer more even. In this study, hBN-to-Cu mixing ratios of 40: 60 and 50: 50 were used. A hot mounting press was used in the compaction process to make 15 mm diameter discs under certain conditions: a compacting pressure of 200 kg/cm², a sintering temperature of 180 C, 10 minutes heating time, 5 minutes cooling down time.

Results and Discussions:-

Influence of Powder Mixing Ratio on Coating Microstructure:-

The influence of the mixing ratio of hBN and Cu on the coating properties, in particular, 40: 60 and 50: 50. The 40:60 ratio with more copper concentration resulted in a very thin and non-uniform layer of coating (around 0.112 mm) that was characterized by the presence of fine surface pores. Although the higher output of copper content improves the conductivity of the electrode and reduces the machining of the tool as copper has a lower melting point, the higher output of copper content seems to reduce the effectiveness of the material transfer to the workpiece. On the other hand, the 50:50 ratio resulted in a much thicker and higher quality coating with an average of 0.213 mm and excellent surface morphology. The improvements in this performance are ascribed to the synergy of copper as a high-deposition binder and the higher proportion of hBN, which decreases the compactness of electrodes. This

reduced compactness enables it to be more eroded and transferred during the discharge system leading to the enhancement of its thickness and surface quality. The ratio of 50:50 hBN:Cu, therefore, showed better coating properties compared to the 40:60 mixture.

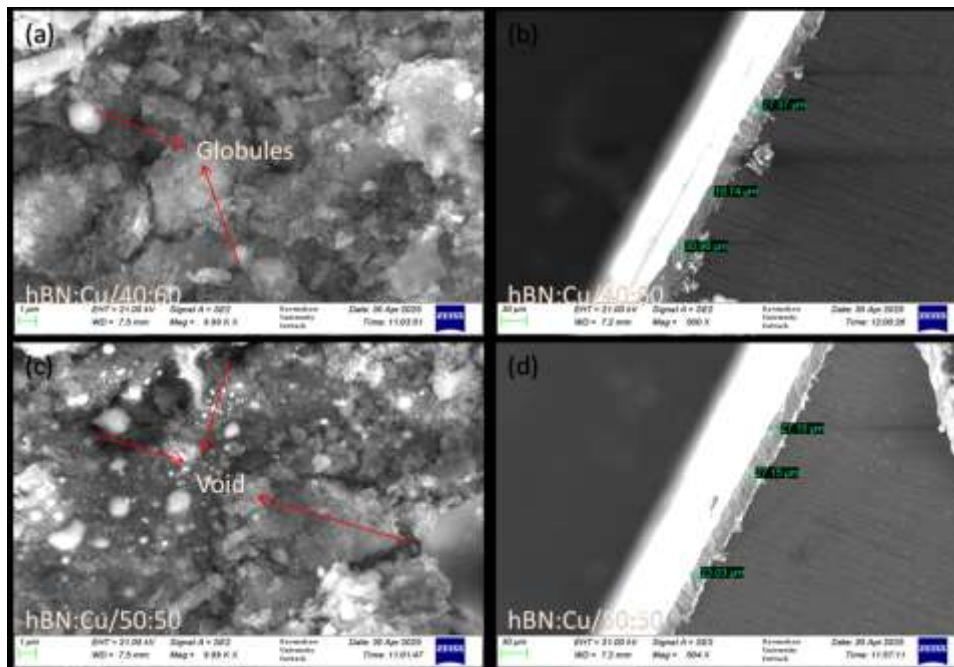


Fig 2.FESEM micrographs of coating surface and cross-sectional interface at varying hBN–Cu mixing ratios (peak current: 10 A)

In Figure 2(a) the cross-sectional microstructure of the 40:60 hBN:Cu mixing ratio shows a very thin and discontinuous coating layer. The increased concentration of copper to allow easy machining of the electrode also limits the deposition of the material leading to an uneven layer on the surface. Conversely, the 50:50 hBN:Cu ratio has a much thicker and more homogeneous coating (Fig. 2c, d), and the average thickness of the coating is almost twice, almost doubling the value of 0.182 mm to 0.343 mm, due to the dual roles of copper as a binder and a deposition agent; copper has a relatively low melting point. Moreover, the increased hBN content of the 50:50 ratio decreases the size of the green compact electrode, which facilitates increased erosion and faster transfer of material in the electrical discharge. Since copper is easier to melt than hBN, it is aided in the quick dissolution of the electrode and transports both materials to the workpiece. Although this reduced melting point provides a greater tool wear rate (TWR), it ultimately is used to enhance the effective coating formation. The 50:50 ratio therefore produces a more stable and robust coating of better morphology making it the superior composition to use in Electrical Discharge Coating (EDC) processes.

Influence of Peak Current on the Microstructural Evolution of EDC Layers:-

The impact of peak current on microstructural development of EDC layers will be examined. The quality of the coating on the 50:50 hBN:Cu was tested in peaks of currents of 4 A, 7 A and 10 A. Being one of the key parameters in Electrical Discharge Machining (EDM), peak current determines the intensity of sparks and thermal energy needed to transfer materials efficiently. When the current was reduced to 4 A, the energy of discharge was not sufficient to sustain continuous melting, so the coating was porous and fragmented. An increase to 7 A current increased the deposition rate and layer thickness but the surface was still identified with persistent voids and morphological irregularities. The best outcomes were obtained at 10 A whereby the higher discharge energy allowed even melting and the constant redistribution of material throughout the substrate. This formed a thicker, more uniform coating and the surface integrity was greatly increased. These results highlight the importance of peak current in EDC whereby a lack of current inhibits deposition, but the optimal enhancement in discharge energy is needed to produce high quality coating thickness, uniformity, and microstructural quality. 3.3 EBSD Microstructure of 50:50 vs. 40:60 hBN:Cu electrode mixtures.

EBSD Microstructure of 50:50 vs. 40:60 hBN:Cu electrode mixtures:-

In the EBSD (Electron Backscatter Diffraction) maps, it can be seen that the CU/HBN 50/50 composition is better than the 40/60 variant since it has a more homogenous grain structure and has a higher matrix continuity. The copper grains (the colored orientations in the 50/50 map) are more extended and interlocking, indicating a well-established plastic flow and regular load-bearing network. Comparatively, the 40/60 composition presents a more dominant amount of white parts (probably the hexagonal Boron Nitride or non-indexed phases) that seem to shred the copper matrix even further. This discontinuity and grain refinement of the 40/60 sample also results in a large percentage of grain refinement and discontinuity, which generally enhances brittleness and decreases electrical/thermal conductivity. The 50/50 ratio ensures the preservation of a cohesive metallic structure, and the effective inclusion of the lubricant phase at the same time, which leads to a more stable microstructure that is less likely to concentrate stress at the interface boundaries.

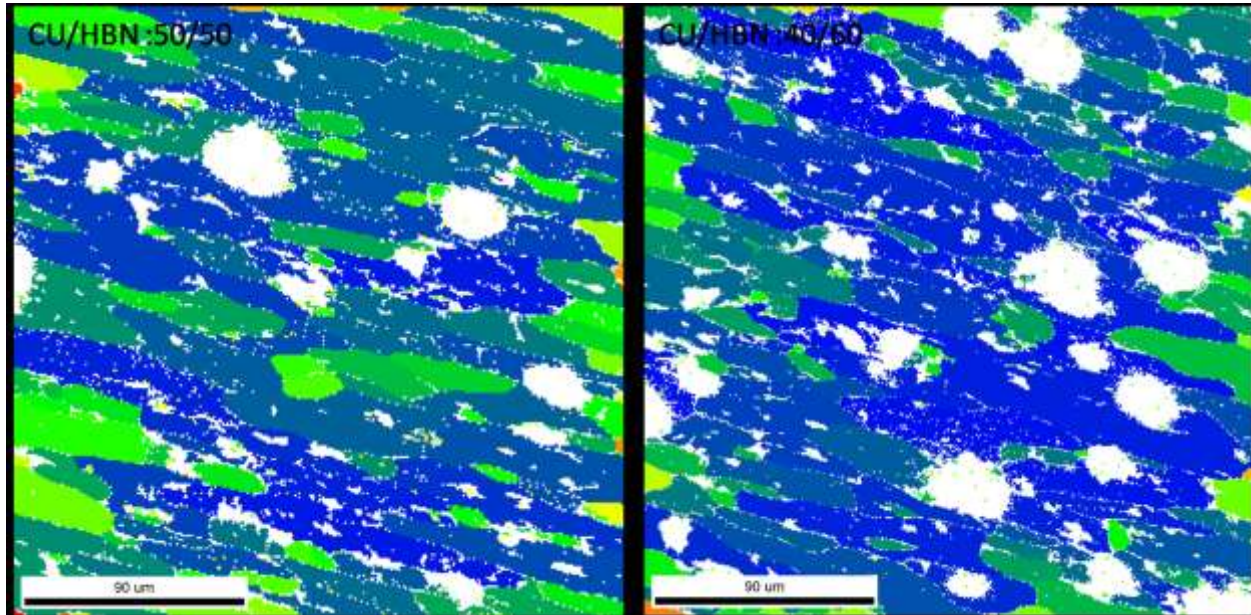


Fig.3 Comparative EBSD Circular Phase Maps of Cu/hBN Composites at Varying Volumetric Ratios (50/50 vs. 40/60)

Conclusions:-

The study was successful in confirming the efficiency of Electrical Discharge Coating (EDC) method to deposit hBN–Cu composite coating on AA6061 aluminum alloy using compact electrodes that were produced in green using powder metallurgy. Of the tested compositions, a 50:50 hBN:Cu ratio was found to have a better compaction integrity, consistent sparking, and material transfer when compared to other ratios. This mixture produced a thick and uniform coating with little porosity and high adhesion, but the 40:60 (hBN:Cu) ratio yielded thinner and less uniform layers. It was established that coating quality increased with the increase in peak current, with 10 A being the best condition that made the process of thermal melting and deposition of material uniform. Successful elemental transfer and formation of main phases of BN, Cu, and Fe₂O₃ were confirmed by FESEM analysis, which showed that there was a strong metallurgical bond between the coating and the substrate. In general, the EDC process turned out to be an effective and inexpensive method of producing composite coatings that had superior tribological characteristics. It is the structural superiority of the 50:50 composition that is related to the maintenance of continuous copper matrix and homogeneous grain morphology that are more stable and functionally reliable than the more fragmented and brittle structure at higher hBN content.

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