

**PERFORMANCE STUDY OF COPPER-GRAPHENE  
EDM TOOLS FABRICATED BY ADDITIVE  
MANUFACTURING AND PRESSURELESS  
MICROWAVE SINTERING**

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**AUGUST 2024**

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by

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**DEPARTMENT OF MECHANICAL ENGINEERING**

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**AUGUST 2024**

**DEDICATED TO**

**MY FAMILY**

## Certificate

This is to certify that the thesis entitled '**Performance study of copper-graphene EDM tools fabricated by additive manufacturing and pressureless microwave sintering**' submitted by **Mr. Shitanshu Arya** to the Indian Institute of Technology Delhi, for the award of the degree of *Doctor of Philosophy* is a record of the original bonafide research work carried out by him under my guidance and supervision. The results contained in it have not been submitted in part or full to any other institute or university for the award of any degree/diploma.



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(Shitanshu Arya)

## Abstract

The capability of electric discharge machine (EDM) to machine intricate shaped products without any physical damage to the part makes it one of the popular machine tools in fabrication industry. Prior to manufacturing an intricate shaped product, the EDM tool needs to be fabricated with the desired shape. Copper is a material that is widely used as an EDM tool due to its outstanding thermal and electrical properties. The rapid manufacturing (RM) techniques offers fabrication of parts with shape complexity within short time duration. Since, direct RM methods used for consolidation of copper parts results in poor quality products. Therefore, in present study, rapid tooling (RT), an indirect RM process along with pressureless microwave sintering was employed to fabricate complex shaped EDM tool. The investigation focused on exploring the impact of microwave sintering machine parameters - sintering temperature, heating rate, and holding time on density, volumetric shrinkage, and electrical conductivity of the tool. The dominance of the sintering temperature on responses was revealed over the heating rate and holding time. Using genetic algorithm (GA), a multi-objective optimization was conducted to achieve an optimized set of microwave sintering machine parameters, aiming for maximum density, electrical conductivity, and minimum volumetric shrinkage. A density of 7.32 g/cc, volumetric shrinkage of 8.36 % and electrical conductivity of 73.88 % IACS was obtained from samples sintered at optimized sintering parameters. The dimensions of the fabricated tool and machined cavity were compared with the computer-aided design (CAD) model. The results revealed an efficient process for fabricating complex shaped EDM tool.

Copper's low melting point led to high tool wear, necessitating the use of materials having higher melting points. Recently, graphene has emerged as a significant reinforcing material because of superior electrical, thermal properties and high melting point. Therefore, an investigation was conducted to identify the correct quantity of graphene to be included

into pure copper to improve tool performance. Four weight percentages of graphene (0.25 %, 0.5 %, 0.75 % and 1 %) were considered for study. Tool with 0.25 wt% of graphene outperformed other combinations in terms of machining performance and surface integrity. Additionally, upto 89% improvement in material removal rate, upto 14 % reduction in tool wear rate and upto 28 % in surface finish of the workpiece was obtained. Further, study was conducted to obtain an optimized set of EDM process parameters for copper-graphene composite tool having 0.25 wt% of graphene. The most influential process parameter was found to be discharge current majorly governing the responses. An optimized set of EDM process parameters obtained using multi-objective optimization were 6 A discharge current, 180  $\mu$ s pulse on time and 75 % duty factor. The responses obtained were 1.81 mg/min tool wear rate (TWR), 97.35 mg/min material removal rate (MRR) and 1.42 % dimensional deviation (DD). A dimensional comparison of machined cavity obtained after machining of D2 steel workpiece using the composite tool was performed with the CAD model and obtained dimensional deviations were within acceptable range.

High tool wear associated with copper owing to its low melting point results in increased tooling cost which ultimately enhances the final product price. To overcome this, one of the solutions is to provide the cooling assistance to the tool for dissipating the accumulated heat. However, this cooling mechanism need to be optimized to avoid the overuse of the coolant which again adds to the final product cost. Therefore, a multiphysics based study was conducted to obtain peak temperature attained by the copper tool during EDM of D2 steel workpiece. Single spark analysis was performed, and peak temperature attained by the standard tool was 1458 K. Further, the study was extended to the tool with cooling channels. The selection of cooling channel was made based on its cross-sectional shape, dimension and channel layout inside the tool. Peak temperatures reached by the tool for different cases were identified from the study. Four primitive cross-sectional shapes

(circle, square, ellipse and semi-circle) were considered. Among all the cases considered during study, the circular profile with 3 mm diameter was observed to provide maximum drop in the peak temperature by 28.25 % compared to the standard tool. Additionally, different channel layouts incorporated within the tool domain successfully reduced the peak temperature and maximum drop of 31.5 % was obtained by the profile involving channel of maximum length.

The complex shaped composite EDM tool fabrication was attempted using rapid tooling and pressureless microwave sintering. Tool was fabricated at optimized sintering machine parameters. To incorporate channel profile, the tool was fabricated in two halves which were then brazed with each other. The machining performance in terms of TWR, MRR and surface roughness (SR) was studied. TWR was found to be reduced by 38 % using cryogenic assistance. Additionally, less surface cracks, debris and globules on the machined workpiece surface and better shape retention of the complex features on the tool was observed after machining. An improvement in surface roughness of the machined surface by 58 % was obtained after machining with cryogenic assisted tool. A minimum dimensional deviation was obtained on comparing the feature dimensions generated on steel workpiece using tool with cooling assistance.

## सार

जटिल आकार के उत्पादों को बिना किसी भौतिक क्षति के मशीनीकृत करने की इलेक्ट्रिक डिस्चार्ज मशीन (ईडीएम) की क्षमता इसे निर्माण उद्योग में लोकप्रिय मशीन टूल्स में से एक बनाती है। एक जटिल आकार के उत्पाद के निर्माण से पहले, ईडीएम उपकरण को वांछित आकार के साथ निर्मित करने की आवश्यकता होती है। कॉपर एक ऐसी सामग्री है जिसका उपयोग इसके उत्कृष्ट तापीय और विद्युत गुणों के कारण ईडीएम उपकरण के रूप में व्यापक रूप से किया जाता है। तीव्र विनिर्माण (आरएम) तकनीक कम समय अवधि के भीतर आकार की जटिलता वाले भागों का निर्माण प्रदान करती है। चूंकि, तांबे के हिस्सों के समेकन के लिए उपयोग की जाने वाली प्रत्यक्ष आरएम विधियों के परिणामस्वरूप खराब गुणवत्ता वाले उत्पाद प्राप्त होते हैं। इसलिए, वर्तमान अध्ययन में, रैपिड टूलींग (आरटी), एक अप्रत्यक्ष आरएम प्रक्रिया के साथ-साथ दबाव रहित माइक्रोवेव सिंटरिंग को जटिल आकार के ईडीएम उपकरण बनाने के लिए नियोजित किया गया था। जांच में माइक्रोवेव सिंटरिंग मशीन मापदंडों के प्रभाव की खोज पर ध्यान केंद्रित किया गया - सिंटरिंग तापमान, हीटिंग दर, और घनत्व, वॉल्यूमेट्रिक संकोचन और उपकरण की विद्युत चालकता पर समय धारण करना। प्रतिक्रियाओं पर सिंटरिंग तापमान का प्रभुत्व हीटिंग दर और होल्डिंग समय पर प्रकट हुआ था। जेनेटिक एल्गोरिदम (जीए) का उपयोग करते हुए, अधिकतम घनत्व, विद्युत चालकता और न्यूनतम वॉल्यूमेट्रिक संकोचन के लक्ष्य के साथ, माइक्रोवेव सिंटरिंग मशीन मापदंडों के एक अनुकूलित सेट को प्राप्त करने के लिए एक बहुउद्देश्यीय अनुकूलन आयोजित किया गया था। अनुकूलित सिंटरिंग मापदंडों पर सिंटर किए गए नमूनों से 7.32 ग्राम/सीसी का घनत्व, 8.36% का वॉल्यूमेट्रिक संकोचन और 73.88% आईएसीएस की विद्युत चालकता प्राप्त की गई थी। निर्मित उपकरण और मशीनी गुहा के आयामों की तुलना कंप्यूटर-एडेड डिज़ाइन (सीएडी) मॉडल से की गई। परिणामों से जटिल आकार के ईडीएम उपकरण के निर्माण की एक कुशल प्रक्रिया का पता चला।

तांबे के कम गलनांक के कारण उपकरण अधिक घिस गए, जिससे उच्च गलनांक वाली सामग्रियों के उपयोग की आवश्यकता पड़ी। हाल ही में, बेहतर विद्युत, थर्मल गुणों और उच्च पिघलने बिंदु के कारण ग्राफीन एक महत्वपूर्ण सुदृढ़ीकरण सामग्री के रूप में उभरा है। इसलिए, उपकरण के प्रदर्शन को बेहतर बनाने के लिए शुद्ध तांबे में शामिल किए जाने वाले ग्राफीन की सही मात्रा की पहचान करने के लिए एक जांच की गई। अध्ययन के लिए ग्राफीन के चार वजन प्रतिशत (0.25%, 0.5%, 0.75% और 1%) पर विचार किया गया। 0.25 wt% ग्राफीन वाले उपकरण ने मशीनिंग प्रदर्शन और सतह अखंडता के मामले में अन्य संयोजनों से बेहतर प्रदर्शन किया। इसके अतिरिक्त, सामग्री हटाने की दर में 89% तक सुधार, उपकरण पहनने की दर में 14% तक की कमी और वर्कपीस की सतह फिनिश में 28% तक की कमी प्राप्त की गई। इसके अलावा, 0.25 wt% ग्राफीन वाले कॉपर-ग्राफीन मिश्रित उपकरण के लिए ईडीएम प्रक्रिया मापदंडों का एक अनुकूलित सेट प्राप्त करने के लिए अध्ययन किया गया था। सबसे प्रभावशाली प्रक्रिया पैरामीटर डिस्चार्ज करंट पाया गया जो मुख्य रूप से प्रतिक्रियाओं को नियंत्रित करता है। बहुउद्देश्यीय अनुकूलन का उपयोग करके प्राप्त ईडीएम प्रक्रिया मापदंडों का एक अनुकूलित सेट 6 ए डिस्चार्ज करंट, समय पर 180  $\mu$ s पल्स और 75% कर्तव्य कारक था। प्राप्त प्रतिक्रियाएं 1.81 मिलीग्राम/मिनट उपकरण घिसाव दर (टीडब्ल्यूआर), 97.35 मिलीग्राम/मिनट सामग्री निष्कासन दर (एमआरआर) और 1.42% आयामी विचलन (डीडी) थीं। मिश्रित उपकरण का उपयोग करके डी2 स्टील वर्कपीस की मशीनिंग के बाद प्राप्त मशीनीकृत गुहा की एक आयामी तुलना सीएडी मॉडल के साथ की गई थी और प्राप्त आयामी विचलन स्वीकार्य सीमा के भीतर थे।

तांबे के कम गलनांक के कारण उससे जुड़े उच्च उपकरण घिसाव के परिणामस्वरूप उपकरण लागत में वृद्धि होती है जो अंततः अंतिम उत्पाद की कीमत को बढ़ाती है। इसे दूर करने के लिए, समाधानों में से एक संचित गर्मी को खत्म करने के लिए उपकरण को शीतलन सहायता प्रदान करना है। हालाँकि, शीतलक के अत्यधिक उपयोग से बचने के लिए इस शीतलन तंत्र को अनुकूलित

करने की आवश्यकता है जो फिर से अंतिम उत्पाद लागत में इजाफा करता है। इसलिए, डी2 स्टील वर्कपीस के ईडीएम के दौरान तांबे के उपकरण द्वारा प्राप्त अधिकतम तापमान प्राप्त करने के लिए एक बहुभौतिकी आधारित अध्ययन आयोजित किया गया था। एकल स्पार्क विश्लेषण किया गया था, और मानक उपकरण द्वारा प्राप्त अधिकतम तापमान 1458 K था। इसके अलावा, अध्ययन को शीतलन चैनलों वाले उपकरण तक बढ़ाया गया था। कूलिंग चैनल का चयन उपकरण के अंदर उसके क्रॉस-अनुभागीय आकार, आयाम और चैनल लेआउट के आधार पर किया गया था। अध्ययन से विभिन्न मामलों के लिए उपकरण द्वारा पहुँचे गए चरम तापमान की पहचान की गई। चार आदिम क्रॉस-अनुभागीय आकृतियों (वृत्त, वर्ग, दीर्घवृत्त और अर्ध-वृत्त) पर विचार किया गया। अध्ययन के दौरान विचार किए गए सभी मामलों में, 3 मिमी व्यास वाली गोलाकार प्रोफाइल में मानक उपकरण की तुलना में चरम तापमान में 28.25% की अधिकतम गिरावट देखी गई। इसके अतिरिक्त, टूल डोमेन के भीतर शामिल किए गए विभिन्न चैनल लेआउट ने अधिकतम तापमान को सफलतापूर्वक कम कर दिया और अधिकतम लंबाई के चैनल वाले प्रोफाइल द्वारा 31.5% की अधिकतम गिरावट प्राप्त की गई।

जटिल आकार के समग्र ईडीएम उपकरण निर्माण का प्रयास तेजी से टूलींग और दबाव रहित माइक्रोवेव सिंटरिंग का उपयोग करके किया गया था। उपकरण को अनुकूलित सिंटरिंग मशीन मापदंडों पर निर्मित किया गया था। चैनल प्रोफाइल को शामिल करने के लिए, उपकरण को दो हिस्सों में बनाया गया था, जिन्हें फिर एक-दूसरे से जोड़ा गया था। टीडब्ल्यूआर, एमआरआर और सतह खुरदरापन (एसआर) के संदर्भ में मशीनिंग प्रदर्शन का अध्ययन किया गया था। क्रायोजेनिक सहायता का उपयोग करके TWR को 38% तक कम पाया गया। इसके अतिरिक्त, मशीनिंग के बाद मशीनीकृत वर्कपीस की सतह पर कम सतह दरारें, मलबे और ग्लोब्यूल्स और उपकरण पर जटिल विशेषताओं का बेहतर आकार प्रतिधारण देखा गया। क्रायोजेनिक सहायता प्राप्त उपकरण के साथ मशीनिंग के बाद मशीनीकृत सतह की सतह खुरदरापन में 58% का सुधार प्राप्त हुआ। शीतलन

सहायता वाले उपकरण का उपयोग करके स्टील वर्कपीस पर उत्पन्न फीचर आयामों की तुलना करने पर एक न्यूनतम आयामी विचलन प्राप्त किया गया था।

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## Abbreviations

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CCD	Central Composite Design
CNT	Carbon Nano Tubes
CT	Composite Tool
CTCC	Composite Tool with Cooling Channel
D	Density
DC	Discharge Current
DD	Dimensional Deviation
DF	Duty Factor
DOF	Degree of Freedom
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EC	Electrical Conductivity
EDM	Electric Discharge Machining
EWR	Electrode Wear Rate
EDX	Electron Diffraction X-ray
FEA	Finite Element Analysis
FESEM	Field Emission Scanning Electron Microscopy
GA	Genetic Algorithm
HR	Heating Rate
HT	Holding Time
IP	Image Processing

IPA	Isopropyl Alcohol
IACS	International Annealed Copper Standard
LH	Latent Heat
LN <sub>2</sub>	Liquid Nitrogen
MRR	Material Removal Rate
MS	Mean of Squares
NSGA-II	Non-dominated Sorting Genetic Algorithm
RM	Rapid Manufacturing
RT	Rapid Tooling
SR	Surface Roughness
SEM	Scanning Emission Microscopy
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SS	Sum of Squares
ST	Sintering Temperature
TWR	Tool Wear Rate
VS	Volumetric Shrinkage
XRD	X-ray Diffraction

## Nomenclature

Cu	Copper
Gn	Graphene
Cu-Gn	Copper-Graphene
$Y$	Response variable
$D_S$	Sintered density
$P$	Mass of sintered sample
$Q$	Mass of oil-impregnated sintered sample
$R$	Mass of oil- impregnated sintered sample and sample support immersed in liquid
$S$	Mass of sample support immersed in liquid
$\rho_l$	Density of liquid
$V_r$	Volume of sintered sample
$V_D$	Volume of mould cavity
$W_{WBM}$	Weight of workpiece before machining
$W_{WAM}$	Weight of workpiece after machining
$W_{EBM}$	Weight of electrode before machining
$W_{EAM}$	Weight of electrode after machining
$wt\%$	Weight percentage
$\Omega$	Resistance
$\rho'$	Resistivity
$L$	Conductor length
$a$	Cross section area of conductor
$T_{on}$	Pulse on time

$l_o$	Mean free path
$R_p$	Pore size
$k$	Thermal conductivity
$k_o$	Thermal conductivity (at $\varphi = 0$ )
$\rho$	Density of copper
$C_p$	Specific heat capacity of copper
$T$	Absolute temperature
$q$	Heat flux by conduction
$Q$	Additional heat sources
$t$	Time
$u$	Translational velocity
$r$	Radial distance from plasma centre
$R$	Spark radius
$V$	Discharge voltage
$I$	Discharge current
$F_c$	Cathode energy fraction
$p$	Pressure
$F$	External force
$\mu$	Dynamic viscosity of fluid
$\mu_T$	Turbulent viscosity of the fluid
$n$	Normal vector
$h'$	Convective heat flux
$q'$	Inward heat flux
$T_{ext}$	Dielectric temperature
$C_v$	Crater volume

$C_e$	Effective specific heat
$r_c$	Crater radius
$h$	Crater depth
$T_{\max}$	Peak temperature
$A$	Channel cross-section area
$T_t$	Tool temperature
$T_c$	Coolant temperature
$Nu_D$	Nusselt number
$Re_D$	Reynold's number
$Pr$	Prandtl's number
$v$	Fluid velocity
$D_h$	Hydraulic diameter
$T_s$	Surface temperature
$R_a$	Average roughness
$R_q$	Root mean square roughness
$R_{sk}$	Surface skewness
$R_{ku}$	Surface kurtosis