

**PERFORMANCE OF RBD PALM OIL BASED DIELECTRIC FLUID ON
SUSTAINABLE ELECTRICAL DISCHARGE MACHINING (EDM) PROCESS OF
TITANIUM ALLOYS**

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This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.



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ABSTRACT

In electrical discharge machining (EDM), the material removal is accomplished through a continuous discharge that occurs between the electrode and the workpiece in the presence of a dielectric fluid. Appropriate selection of dielectric medium is an important consideration due to the function of dielectric medium which greatly influences the performance of this process. Low machining efficiency and poor surface finish caused by using a conventional dielectric fluid that pollutes the environment and cause health problems in EDM processes have been issues that must be dealt well. The preliminary study aims to investigate the performance of biodegradable oil-based dielectric fluid compared to conventional dielectric fluid for titanium alloys (Ti-6Al-4V) with copper (Cu) electrode using a sustainable EDM. To achieve high EDM performance for this research, the main parameter of peak current (I_p); 6, 9 and 12A and pulse duration (t_{on}); 50, 100 and 150 μ s were selected. Refine, bleach, and deodorized (RBD) palm oil, modified RBD palm oil, and kerosene were used as dielectrics. The influence on the machinabilities of the material removal rate (MRR), electrode wear rate (EWR), and sparking characteristic were experimentally investigated. Some aspects of surface integrity, such as surface roughness (R_a), recast layer (R_L) and microhardness (MH) were also evaluated. The result shows that RBD palm oil has higher MRR, EWR, R_a and MH but lower R_L compared to modified RBD palm oil and kerosene in term of machinability and surface integrity. This is due to the density, viscosity and flash point of the dielectric fluid that play a vital role in the determination of the desired outcome in the EDM process. The highest improvement of MRR is 567.43% when RBD palm oil is compared to kerosene at $I_p=12A$ and $t_{on}=150\mu$ s. Overall, all dielectric fluids have almost similar trend. However, RBD palm oil based dielectric fluid is the best option for EDM machining of Ti-6Al-4V.

ABSTRAK

Di dalam penggunaan mesin discaj elektrik (EDM), bahan dinyah melalui discaj elektrik secara berturut-turut antara elektrod dan bahan kerja dengan kehadiran cecair dielektrik. Pemilihan medium dielektrik adalah penting kerana medium dielektrik mempengaruhi prestasi proses ini. Kecekapan pemesinan yang rendah dan kerosakan permukaan yang lemah disebabkan oleh penggunaan cecair dielektrik konvensional yang mencemarkan alam sekitar serta menyebabkan masalah kesihatan dalam proses EDM adalah isu yang harus ditangani dengan baik. Kajian awal ini bertujuan untuk mengkaji prestasi cecair dielektrik berasaskan minyak mudah terbakar dengan cecair dielektrik konvensional bagi aloi titanium (Ti-6Al-4V) dan elektrod tembaga dengan menggunakan EDM mampan. Untuk mencapai prestasi EDM yang tinggi bagi penyelidikan ini, parameter utama seperti arus puncak, I_p ; 6, 9 dan 12A dan tempoh denyutan, t_{on} ; 50, 100 dan 150 μ s telah dipilih. RBD minyak sawit, pengubahsuaian RBD minyak sawit dan minyak tanah digunakan sebagai dielektrik. Kesan daripada parameter terhadap kebolehmeseinan melalui kadar pembuangan bahan (MRR), kadar kehausan elektrod (EWR) dan ciri percikan api dikaji secara eksperimen. Beberapa aspek integrity permukaan seperti kekasaran permukaan (R_a), lapisan putih (R_L) dan kekerasan mikro (MH) juga dinilai. Keputusan menunjukkan bahawa RBD minyak sawit mempunyai MRR, EWR, R_a dan MH yang lebih tinggi tetapi R_L yang lebih rendah berbanding pengubahsuaian RBD minyak sawit dan minyak tanah dari segi kebolehmeseinan dan integriti permukaan. Hal ini disebabkan oleh ketumpatan, kelikatan dan takat kilat cecair dielektrik yang memainkan peranan penting dalam penentuan hasil yang dikehendaki dalam proses EDM. Peningkatan tertinggi MRR ialah 567.43% apabila RBD minyak sawit dibandingkan dengan minyak tanah pada $I_p=12A$ dan $t_{on}=150\mu$ s. Secara keseluruhan, semua cecair dielektrik mempunyai trend yang hampir serupa. Walau bagaimanapun, cecair dielektrik berasaskan RBD minyak sawit adalah pilihan terbaik untuk pemesinan EDM bagi Ti-6Al-4V.

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PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

%	-	Percentage
μm	-	Micro metre
μs	-	Micro second
A	-	Ampere
Al	-	Aluminium
AML	-	Advanced Machining Laboratory
ASTM	-	American standard for testing and material
C	-	Carbon
$\text{C}_3\text{H}_8\text{O}$	-	Propanol
CH_4O	-	Methanol
cm^3	-	Cubic centimetre
cP	-	Centipoise
cSt	-	Centistoke
Cu	-	Copper
EDM	-	Electro discharge machining
EN ISO	-	European standard
ERBDPO	-	Esterified RBD palm oil
EWR	-	Electrode wear rate
<i>F</i>	-	Load in kgf
Fe	-	Iron
FFA	-	Free fatty acid
g	-	Gram
G	-	Giga
H	-	Hydrogen
H_2O	-	Water
H_2SO_4	-	Sulphuric acid
HAZ	-	Heat affected zone
HCL	-	Hydrochloric acid
HRC	-	Rockwell hardness unit

HV	-	Vickers hardness unit
HV	-	Vickers hardness
I_p	-	Peak current
J	-	Joule
kg	-	Kilo gram
KOH	-	Potassium hydroxide
kV	-	Kilo volt
M	-	Mega
m	-	Metre
MH	-	Micro-hardness
min	-	Minutes
ml	-	Mililitre
mm	-	Milimetre
MRR	-	Material removal rate
m_w	-	Mass loss of workpiece
N	-	Nitrogen
N	-	Newton
N	-	Number of alkali concentration
NaOH	-	Sodium hydroxide
NCL	-	Nitric acid
O	-	Oxygen
°C	-	Degree celcius
OM	-	Optical microscope
Pa	-	Pascal
R_a	-	Surface roughness
RBD	-	Refined, bleach and deodorized
RBDPOME	-	RBD palm oil methy ester
R_L	-	Recast layer
rpm	-	Revolution per minute
s	-	second
SA	-	Surface area
SEM	-	Scanning electron microscopy
SI	-	Surface integrity
SiC	-	Silica carbide
Ti	-	Titanium
Ti-6Al-4V	-	Titanium alooys

LIST OF REFERENCES

- Abbas, N. M., Solomon, D. G., and Bahari M. F. (2007). A review on current research trends in electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture*, Vol. 47(7–8): pp.1214-1228.
- Abdullahi, U., Bashi, S., Member, I., Yunus, R. and Nurdin, H. (2004). The potentials of palm oil as a dielectric fluid. *National Power & Energy conference (Pecon) Proceedings*, Kuala Lumpur, Malaysia.
- Abu Zeid, O. A. (1997). On the effect of electro discharge machining parameters on the fatigue life of AISI D2 tool steel, *Journal of Materials Processing Technology*, Vol. 68, pp. 27-32.
- Ahmad, S., and Lajis, M. A. (2013). An electrical discharge machining (EDM) of inconel 718 using copper tungsten electrode with higher peak current and pulse duration. *International Journal of Mechanical and Mechatronics Engineering*, Vol. 15(5), pp. 39-47.
- Ahmed, Y. M., Sahari, K. S. M., Ishak, M. and Khidir, B. A. (2012). Titanium and its Alloys. *International journal of Science and Research*, Vol. 3, No. 10, pp. 1351 -1361.
- Ahsan, A. K., Mohammad, Y. A. and Mohafizul, M.H. (2009). A study of electrode shape configuration on the performance of die sinking EDM. *International Journal of Mechanical and Materials Engineering*, Vol. 4, No. 1, pp. 19 -23.
- Ali, M. Y., Moudood, M. A., Maleque, M. A., Hazza, M. and Adesta, E. Y. T. (2017). Electro-discharge Machining of alumina: Investigation of material

removal rate and surface roughness. *Journal of Mechanical Engineering and Sciences*. Vol. 11(4), pp. 3015-3026.

Amorim, F. L. and Weingaertner, W. L. (2004). Die sinking electrical discharge machining of a high strength copper based alloy for injection mold. *Journal of the Brazilian Society of Mechanical Science and Engineering*, Vol. 26(2), pp-137-143.

Asokan, T. Sudhakar, R. S., and De Costa, P. (2000). Electrical discharge drilling of titanium alloys for aerospace applications. *Proceedings of the 19th AIMTDR Conference*, p. 161-165.

Bashi, S., Abdullahi U., and Robia, Y. (2006). Use of natural vegetable Use of natural vegetable, *The Institution of Engineer Malaysia*, Vol. 67, pp. 4-9.

Beri, N., Kumar, A., and Maheswari, S. (2012). Machining efficiency evaluation of cryogenically treated copper electrode in additive mixed EDM. *Journal of Materials and Manufacturing Processes*, Vol. 27(10), pp. 1051-1058.

Bharti, P. S., Maheshwari, S., and Sharma, C. (2010). Experimental investigation of inconel 718 during die sinking electric discharge machining. *International Journal of Engineering Science and Technology*, Vol. 2(11), pp. 6464-6473.

Bhattacharya, A., Batish, A., and Kumar, N. (2013). Surface characterization and material migration during surface modification of die steels with silicon, graphite and tungsten powder in EDM process. *Journal of Mechanical Science and Technology*, Vol. 27(1), pp. 133-140.

Bilal, A., Jahan, M. P., Talamona, D., and Perveen, A. (2019). Electro-discharge machining of ceramics: A review. *Micromachines*. *Micromachines*, Vol. 10(1), pp. 10.

- Bocchetta, P., Chen, L., Tardelli, J. D. C., Reis, A. C., Almeraya-Calderon, F., and Leo, P. (2021). Passive layers and corrosion resistance of biomedical Ti-6Al-4V and β -Ti alloys. *Coatings*, Vol. 11(148), pp. 1-32.
- Bommeli, B. (1983). Study of the harmful emanations resulting from the machining by electro-erosion. In *Proceedings of the Seventh International Symposium on electro machining (ISEM VII)*, pp. 469-478.
- Chen, S. L., Yan, B. H., and Huang, T. Y. (1999). Influence of kerosene and distilled water on the electric discharge machining characteristics of Ti-6Al-4V. *Journal of Materials Processing Technology*, Vol. 87(1-3), pp. 107-111.
- Chen, Y., Zhang, L. C., Arsecularatne, J. A. and Montross, C. (2006). Polishing of polycrystalline diamond by the technique of dynamic friction, Part 1: Prediction of the interface temperature rise. *International Journal of Machining Tool Manufacturing*, Vol. 46(6), pp. 580-587.
- Cogun, C. (1990). A technique and its application for evaluation of material removal contributions of pulses in electrical discharge machining. *International Journal of Machine Tools and Manufacture*, Vol. 30(1), pp. 19-31.
- Dhanik, S., Joshi, S.S., Ramakrishnan, N. and Apte, P.R., (2005). Evolution of EDM process modelling and development towards modelling of the micro-EDM process, *International Journal of Manufacturing Technology and Management*, Volume 7, No.2/3/4, pp.157-180.
- DeGarmo, E. P., Black, J. T., and Kosher, R. A. (2003). Material and process in Manufacturing. 9th ed., International ed. New York: John Wiley and Sons Inc.
- Dhirendra N. M., Bhatia A., Rana V. (2014). Study on electro discharge machining (EDM). *The International Journal of Engineering and Science (IJES)*, Vol. 3(2), pp. 24-35.

- Ekmekci, B., Elkoca, O., and Erden, A. (2005). A comparative study on the surface integrity of plastic mold steel due to electric discharge machining. *Metallurgical and Materials Transaction. B: Process Metallurgy and Materials Processing Science*, Vol. 36, pp. 117–24.
- Elkaseer, A. M., Dimov, S. S., Popov, K. B., Minev, R. M. (2014). Tool Wear in Micro-Endmilling: Material Microstructure Effects, Modeling, and Experimental Validation. *Journal of Micro Nano-Manufacturing*, Vol, 2(4), pp. 044502.
- Elkaseer, A., Lambarri, J., Ander Sarasua, J., Cascón, I. (2017). On the development of a chip breaker in a metal-matrix polycrystalline diamond insert: Finite element-based design with ns-laser ablation and machining verification. *Journal of Micro Nano-Manufacturing*, Vol, 5(3), pp. 031007.
- Equbal, A., and Sood, A. K. (2014). Electrical Discharge Machining: An Overview on Various Areas of Research. *Manufacturing and Industrial Engineering*, Vol. 13, pp. 1–2.
- Fikri, A. (2012). Research of developments in die sinking electric discharge machining (EDM). *Journal of Materials Processing Technology*, Vol. 2(1), pp. 324-354.
- Garba, Z. N., Gimba, C. E., and Emmanuel, P. (2013). Production and characterisation of bio based transformer oil from *Jatropha curcas* seed. *Journal of Physic Science*, Vol. 24(2), pp. 49-61.
- Ghewade, D. and Nipanikar, S. (2011). Experimental study of electro discharge machining for inconel material. *Journal of Engineering Studies and Research*, Vol. 2(2), pp. 107-112.
- Giakoumis, E. G. (2013). A statistical investigation of biodiesel physical and chemical properties and their correlation with the degree of unsaturation. *Renew Energy*, Vol. 50, pp. 858-878.

- Goh, C. L., and Ho, S. F. (1993). Contact dermatitis from dielectric fluids in electro discharge machining, *Contact Dermatitis*, Vol. 28, pp. 134-138.
- Gostimirovic, M., Kovac, P. P., Skoric, B, and Sekulic, M. (2012). Effect of electrical pulse parameters on machining performance of EDM. *Indian Journal of Engineering and Material Sciences*, Vol. 18(6), pp. 411-415.
- Guitrau, E. B. (1997). *The electrical discharge machining handbook*. Cincinnati: Hanser Gardner Publication.
- Gutowski, T., Dahmus, J., and Thirez, A. (2006), Electrical energy requirements for manufacturing processes, *In Proceeding of the 13th CIRP International Conferences Life Cycle Engineering*, Lueven.
- Guo, D.M., Zhang, M., Jin, Z.J. and Zuo, B.X., (2008). Particle strengthening of the surface of copper electrode for electrical discharge machining, *International Journal of Materials and Product Technology*, Volume 31, No.1, pp.81- 87.
- Guu, Y. H., Hocheng, H., Chou, C. Y., and Deng, C. S. (2003). Effect of electrical discharge machining on surface characteristics and machining damage of AISI D2 tool steel. *Materials Science and Engineering*, Vol 358, pp. 37-43.
- Han, F., Wang, Y., and Zhou, M. (2009). High-speed EDM milling with moving electric arcs. *International Journal of Machine Tools and Manufacture*. Vol. 49(1), pp. 20-24.
- Harlal, S. M. and Kumar, N. (2016). Investigating feasibility of waste vegetable oil for sustainability EDM. Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur, India.
- Haron, C.C.H., Ghani, J.A., Burhanuddin, Y., Seong, Y.K. and Swee, C.Y., (2008). Copper and graphite electrodes performance in electrical-discharge

machining of XW42 tool steel, *Journal of Materials Processing Technology*, Volume 201, No.1-3, pp.570-573.

Harpreet, S. and Amandeep, S. (2012). Examination of surface Roughness using different machining parameter in EDM. *International Journal of Modern Engineering Research*. Vol. 2(6), pp. 4478-4479.

Hascalik, A. A., Caydas, U., and Gurun, H. (2007). Effect of transverse speed on abrasive water jet machining of Ti-6Al-4V alloy. *Journal of Surface Engineered Material and Advanced Technology*, Vol 7(2), pp. 34-35.

Ho, K. H. and Newman, S. T. (2003). State of the art electrical discharge machining (EDM). *International Journal of Machine Tool and Manufacture*, Vol 43(13) pp. 1287-1300.

Hsue, A. W. J., and Chung, C. H. (2010). Novel jump control for debris process of electrical discharge machining with direct-drive spindle. *Adv. Mater. Res.*, Vol. 97-101, pp. 4178-4181.

Huang, C. A., Tu, G. C., Yao, H. T., and Kuo, H. H. (2004). Characteristics of the rough-cut surface of quenched and tempered martensitic stainless steel using wire electrical discharge machining. *Metallurgical and Materials Transaction A*, Vol. 35A, pp. 1351–1357.

Jahan, M. P., Kakavand, P., and Alavi, F. (2017). A Comparative Study on Micro-Electro-Discharge-Machined Surface Characteristics of Ni-Ti and Ti-6Al-4V with Respect to Biocompatibility. *Procedia Manufacturing*, Vol. 10, pp. 232–242.

Jameson, E. C. *Electrical discharge machining*. Society of Manufacturing Engineers Dearbon, Michigan. 2001.

- Jawahir, I. S., Wanigarathne P. C., and Wang, X. (2006). Product design and manufacturing processes for sustainability. *Mechanical Engineers' Handbook Manufacturing and Management*, Vol. 3, pp. 414-443.
- Jilani, S., and Pandey, P. (1984). Experimental investigation into the performance of water as dielectric in EDM, *International Journal of Machine Tool Design and Research*, no. 24, pp. 31-43.
- Junkar, M. and Valentincic, J. (1999). Towards intelligent control of electrical discharge machining. *Journal of Manufacturing Systems*, Vol. 29(5), pp. 453-457.
- Kalpajian, S. and Schmid S. *Manufacturing Engineering and Technology*. Fifth edition, Prentice Hall, Singapore. 2016.
- Kang, S., and Kim, D. (2003). "Investigation of EDM characteristics of nickel-based heat resistant alloy. *Journal of Mechanical Science and Technology* Vol. 17(10), pp. 1475-1484.
- Kansal, H. K., Singh, S., and Kumar, P. (2005). Parametric optimization of powder mixed electrical discharge machining by response surface methodology. *Journal of Materials Processing Technology*, Vol. 169(3), pp. 427-436.
- Kansal, H. K., Singh, S., and Kumar, P. (2007). Application of Taguchi method for optimization of powder mixed electrical discharge machining. *International Journal of Manufacturing Technology and Management*, Vol. 2(3-4), pp. 329.
- Kansal, H. K., Singh, S., and Kumar, P. (2007). Technology and research developments in powder mixed electric discharge machining (PMEDM). *Journal of Materials Processing Technology*, Vol. 184(1-3), pp. 32-41.

- Kao, J.Y. and Tarng, Y.S. (1997). A Neural-Network Approach for the On-Line Monitoring of the Electrical Discharge Machining Process. *Journal of Material Processing Technology*, Vol. 69, pp. 112-119.
- Kayak, M., Aldemir, B. E., Altan, E. (2015) Effect of discharge energy density on wear rate and surface roughness in EDM. *International Journal of Advanced Manufacturing Technology*. Vol. 79(1-4), pp. 513-518.
- Khan, A.A. and Mridha, S., (2007). Performance of Copper and Aluminum Electrodes during EDM of Stainless Steel and Carbide, *The International Journal for Manufacturing Science and Production*, Volume7(1), pp.1-7.
- Khan, A.A., (2008). Electrode Wear and material Removal Rate during EDM of Aluminum and Brass Electrodes, *International Journal of Advanced Manufacturing Technology*, Volume39, No.5-6, pp.482-487.
- Khan, M. L., Chetri, A. B., and Islam, M. R. (2007). Analyzing sustainability of community based energy technologies. *Energy Sources*, Vol. 3, pp. 403-419.
- Konig, W. and Jorres, L. (1987). Aqueous solutions of organic compounds as dielectric for EDM sinking, *CIRP Annals*, Vol. 36, pp. 105-109.
- Kumar S. (2013). Current research trends in electrical discharge machining: a review, *Research Journal of Engineering Sciences*, Vol. 2(2), pp. 56-60.
- Kumar, M., Datta, S., and Kumar, R. (2019). Electro-discharge machining performance of Ti-6Al-4V alloy: studies on parametric effect, and the phenomenon of electrode wear. *Arabian Journal for Science, and Engineering*, Vol. 44, pp. 1553-1568.
- Kunieda, B. M., Furuoya, S., and Taniguchi, N. (1991). Improvement of EDM efficiency by supplying oxygen into gap, *CIRP Annals Manufacturing technology*, Vol. 40, pp. 215-218.

- Kunieda, M., and Yoshida, M. and Taniguchi, N. (1997). Electrical Discharge machining in gas. *CIRP Annals*, Vol. 46(1), pp. 143-146.
- Kunieda, M. and Muto, H., (2000). Development of multispark EDM, *Annals of CIRP*, Volume49, No.1, pp.119-122.
- Kunieda, M. and Kobayashi, T., (2004). Clarifying mechanism of determining too electrode wear ratio in EDM using spectroscopic measurement of vapor density, *Journal of Materials Processing Technology*, Volume149, pp.284-288.
- Kuppan, P., Rajadurai, A., and Narayanan, S. (2008). Influence of EDM process parameters in deep hole drilling of Inconel 718. *International Journal Advance Manufacturing Technology*, Vol. 38, pp. 74-84.
- Leao, F. N., and Pashby, I. R., (2004). A review on the use of environmentally friendly dielectric fluids in electrical discharge machining. *Journal of Materials Processing Technology*, Vol 149, pp. 341-346.
- Lee, H. T., and Tai, T. Y. (2003). Relationship between EDM parameters and surface crack formation. *Journal of Material Technology*, Vol. 142, pp. 676–83.
- Lee, H. T., Hsu, F. C., and Tai, T. Y. (2004). Study of surface integrity using the small area EDM process with a copper–tungsten electrode. *Journal of Materials Science and Engineering*, Vol. 364(1–2), pp. 346-356.
- Lee, L. C., Lim, L. C. Wong, Y. S. and Fong, H. S. (1992). Crack susceptibility of electro discharge machined surfaces. *Journal of Materials Processing Technology*, Vol. 29, pp. 213–221.
- Lee, L. C., Lim, L. C. Wong, Y. S. and Lu. H. H. (1990). Towards a better understanding of the surface features of electro discharge machined tool steels. *Journal of Materials Processing Technology*, Vol. 24, pp. 513–523.

- Lee, L. C., Lim, L.C., Narayanan V. and Venkatesh, V.C. (1988). Quantification of surface damage of tool steels after EDM. *International Journal of Machine Tools and Manufacture*, Vol. 28(4), pp. 359-372.
- Lee, S. H., and Li, X. P. (2001). Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. *Journal of Materials Processing Technology* Vol. 115(3):pp. 344-358.
- Li, L., Guo, Y. B., Wei, X. T., and Li, W. (2013). Surface integrity characteristics in wire EDM of Inconel 718 at different discharge energy. *Procedia CIRP*, Vol. 6, pp. 220-225.
- Lin, Y. C., Yan, B. H, and Chang, Y. S. (2000). Machining characteristics of titanium alloys (Ti-6Al-4V) using a combination process of EDM with USM. *Journal of Materials Processing Technology*, Vol. 104(3), pp. 171-177.
- Liu, H. S., and Tarn, Y. S. (1997). Monitoring Of The Electrical Discharge Machining Process By Abductive Networks. *The International Journal of Advanced Manufacturing Technology*, Vol. 13, pp. 264-270.
- Luo, Y. F. (1997). The dependence of interspaces discharges transitivity upon the gap debris in precision electro discharge machining, *Journal of Material Process Technology*, Vol. 68, pp.127-131.
- Mamalis, A. G., Voaniakos, G.C., Vaxevanidis, N. M., and Prohaszka, J. (1987). An experiment investigation in macroscopic and microscopic phenomena of electro-discharge machined steel surface. *Journal of Mechanical Working Technology*, Vol. 15, pp. 33-56.
- Marafona, J. (2009). Black layer affects the thermal conductivity of the surface of copper–tungsten electrode. *International Journal of Advanced Manufacturing Technology*. Vol. 42(5), pp. 482-488.

- Marafona, J., and Wykes, C. (2000). A new method of optimising material removal rate using EDM with copper–tungsten electrodes. *International Journal of Machine Tools and Manufacture*. Vol. 40(2), pp. 153-164.
- Matthew, J. and Donachie, Jr. Titanium; A Technical Guide, 2nd Edition. ASM International, 2000.
- Mcshane, C. P. (2002). Vegetable oil based dielectric coolant. *IEEE Industry Applications Magaines*, Vol. 8, pp. 34-41.
- Ming, W., Shen, F., Zhang, G., Liu, G., Du, J., and Chen, Z. (2020). Green machining: A framework for optimization of cutting parameters to minimize energy consumption and exhaust emissions during electrical discharge machining of Al 6061 and SKD 11. *Journal of Cleaner Production*, Vol. 285(7-8), pp. 124889.
- Modica, F., Marrocco, V., Copani, G., and Fassi, I. (2011). Sustainable micro-manufacturing of micro-components via micro electrical discharge machining. Institute of Industrial technologies and Automation, National research Council (ITIA-CNR), Italy.
- Munz, M., Risto., and Haas, R. (2016). The phenomenon of polarity in EDM drilling process using water based dielectrics. *Procedia CIRP*, Vol. 42, no Isem xviii, pp. 532-536.
- Muthramalingam, T., and Mohan, B. (2014). A review on influence of electrical process parameters in EDM. Department of Mechanical Engineering CEG Campus, Anna University, Chennai, India.
- Nanu, D., and Nanu, A. (2008), Perspectives of the dimensional processing through electric erosion processing, *Non conventional Technology Review*, Vol. 3, pp.61–64.

- Naveen, B., Maheshwari, S., Sharma, C., and Kumar, A., (2008). Performance evaluation of powder metallurgy electrode in electrical discharge machining of AISI D2 steel using taguchi method. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, Vol 2, No 2.
- Ndaliman, M. B., Khan A. A., and Ali, M. Y. (2013). Influence of electrical discharge machining process parameters on surface micro-hardness of titanium alloy. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. Vol. 227(3), pp. 460-464.
- Ndaliman, M. B., Khan, A.A., and Zain, Z. M. (2011). Performance of PM compacted Cu-TaC electrodes during EDM. *International Journal of Integrated Engineering*.
- Niamat, M., Sarfraz, A., Hariz, A., Mirza, J., Shebab, E., Wasim, A., and Salman, H. (2017). Effect of different dielectrics on material removal rate, electrode wear rate and microstructures in EDM. *Science Direct*, Vol. 60, pp. 2-7.
- Nimbalkar, V. S., and Shete, P. M. T. (2017). Experimental Investigation of Machining Parameters Using Solid and Hollow Electrode for EDM of Ti-6Al-4V. *International Research Journal of Engineering and Technology*, Vol. 4(5), pp. 2345-2352.
- Patel, K. M., Pandey, P. M., and Venkateswara, R. P. (2009). Surface integrity and material removal mechanisms associated with the EDM of Al₂O₃ ceramic composite. *International Journal of Refractory Metals and Hard Materials*, Vol. 27(5), pp. 892-899.
- Payal, H. Choudhary, R., and Singh, S. (2008). Analysis of electro discharge machined surfaces of EN-31 tool steel. *Journal of Scientific and Industrial Research*, Vol 67(12), pp. 1072-1077.

- Payal, H. S., Choudhary, R., and Singh, S. (2008). Analysis of electro discharge machined surfaces of EN-31 tool steel. *Journal of Scientific & Industrial Research*, Vol. 67, pp. 1072-1077.
- Prabu, S., and Vinayagam, B. K. (2011). Fractal dimension surface analysis of AISI D2 tool steel material with nano fluids in grinding process using atomic force microscopy, SRM University, School of Mechanical Engineering, Chennai, India.
- Pramanik, A. and Basak, A. K. (2019). Effect of wire electrical discharge machining (EDM) parameters on fatigue life of Ti-6Al-4V alloy. *International Journal of Fatigue*, Vol. 128, pp. 105186.
- Puertas, I., Luis, C.J. and Alvarez, L., (2004). Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC-Co. *Journal of Materials Processing Technology*, Volume 153-154, pp.1026- 1032.
- Qudeiri, J. E. A., Mourad, A. H. I., Ziout, A., Abidi, M. H., Elkaseer, A. (2018). Electric discharge machining of titanium and its alloys: A review. *The International Journal of Advances Manufacturing Technology*, Vol. 96(9), pp. 1319–1339.
- Qudeiri, J. E. A., Mourad, A. H. I., Ziout, A., Abidi, M. H., Elkaseer, A. (2020). Principles and characteristics of different EDM processes in machining tool and die steels. *Applied Sciences*, Vol. 10(6), pp. 2082.
- Qudeiri, J. E. A., Saleh, A., Mourad, A. H. I., Ziout, A., Abidi, M. H., Elkaseer, A. (2019). Advanced electric discharge machining of stainless steels: Assessment of the state of the art, gaps and future prospect. *Materials*, Vol. 12(6), pp. 907.
- Rahman, M., Wang, Z. G., and Wong, Y. S. (2005). A Review on High-Speed Machining of Titanium Alloys. *JSME International Journal*, Vol. 49(1), pp. 11–20.

- Rajasha, S., Sharma, A., and Kumar, P. (2010). Some aspects of surface integrity study of electro discharge machined Inconel 718. *Proceeding of the 36th International Matador Conference*, pp. 439-444.
- Ramani, V. and Cassidenti, M. (1985). Inert Gas Electrical Discharge Machining NASA, National Technology Transfer Center (NTTC), Wheeling, WV.
- Ramasawmy, H. and Blunt, L., (2001). 3D Surface characterization of electropolished EDMed surface and quantitative assessment of process variables using Taguchi methodology, *International Journal of Machine Tools and Manufacture*, Volume 42, No.10, pp.1129-1133.
- Ramasawmy, H., Blunt, L. and Rajukar, K. P. (2005). Investigation of the relationship between the white layer thickness and 3D surface texture parameters in the die sinking EDM process. *Precision Engineering*, Vol. 29(4), pp. 479-490.
- Rao, P. S., Ramji, K., and Satyanarayana, B. (2014). Experimental Investigation and Optimization of Wire EDM Parameters for Surface Roughness, MRR and White Layer in Machining of Alloys. *Procedia Mater. Sci.*, Vol 5, pp. 2197-2206.
- Rotella G, Lu T., Settineri L., Dillon O. W., Jawahir, I.S. (2011). Dry and cryogenic machining: comparison from the sustainability perspective. *In 9th global conference on sustainable manufacturing*, Vol. 2, pp 99-104.
- Sabyrov, N., Jahan, M. P., Bilal, P., and Perwown, A. (2019). Ultrasonic vibration assisted electro-discharge machining (EDM) : An overview. *Materials*, Vol. 12(13), pp. 522.
- Sadagopan, P., and Mouliprasanth, B. (2017). Investigation on the influence of different types of dielectrics in electrical discharge machining. *International Journal of advanced Manufacturing Technology*, Vol. 92, pp. 277-291.

- Satishkumar, D. (2011). Investigation of wire electrical discharge characteristic of A16063/SiCp composites, *International Journal of Advanced Manufacturing and Technology*, 48, 2(2), pp. 234-242.
- Shah, Z., Tahir Q., and Town, C. (2011). Dielectric properties of vegetable oil, *Scientific Research*, Vol. 3(3), pp. 481-492.
- Singaravel, B., Shekar, K. C., Reddy, G. G., and Prasad, S. D. (2019). Experimental investigation of vegetable oil as dielectric fluid in Electric discharge machining of Ti-6Al-4V. *Ain Shams Engineering Journal*, Vol. 11(1), pp. 143-147.
- Singh, A. K., Kumar, S. and Singh, V. P. (2013). Electrical Discharge machining of superalloys: A review, *International Journal of Research in Mechanical Engineering*, Vol. 3(2), ISSN: 2249-5762.
- Singh, G., Ablyaz, T. R., Shlykov, E. S., Muratov, K. R., Bhui, A. S., and Sidhu, S. S. (2020). Enhancing corrosion and wear resistance of Ti6Al4V alloy using CNTs mixed electro-discharge process. *Micromachines*, Vol. 11(9), pp. 850.
- Singh, S. and Bhardwaj, A. (2011). Review to EDM by using water and powder mixed dielectric fluid. *Journal of Minerals and Materials Characterization and Engineering*, Vol. 10(2), pp. 199-230.
- Singh, S., Maheshwari, S. and Pandey, P. C. (2004). Some investigations into the electric discharge machining of hardened tool steel using different electrode materials. *Journal of Materials Processing Technology* Vol. 149(1-3), pp. 272- 277.
- Sommer. C., and Sommer, S. (2009). *Complete EDM Handbook*. Reliable EDM, Texas, USA.

- Sudhakara, D., Naik, B. V., and Sreenivasulu, B. (2012). The experimental analysis of surface characteristics of Inconel-718 using electrical discharge machining. *International Journal and Mechanical Engineering and Robotic Research*, Vol. 1(3), pp.371-388.
- Sultan, T., Kumar, A., and Rahul, D. (2014). Material removal rate, electrode wear rate and surface roughness evaluation in die sinking EDM with hollow tool through response surface methodology. *International Journal of Manufacturing Engineering*, Vol. 1, pp. 1-16.
- Sushil Kumar, Choudhary, D., Jadoun, R. S. (2014). Current advanced research development of electrical discharge machining (EDM): A review, *International Journal of research in Advent Technology*, Vol. 2(3).
- Suzuki, K., Iwai, M., Sharma, A., Sano, S. and Uematsu, T., (2006). Low-wear diamond electrode for microEDM of die-steel', *International Journal of Manufacturing Technology and Management*, Volume9, No.1/2, pp.94-108.
- Suzuki, K., Zhang, D., Shiraishi, Y., and Iwai, M. (2007). Manufacturing porous diamond with skeleton structure from PCD by EDM and its application to grinding tools. *Key Engineering Materials*, Vol. 329, pp. 471-476.
- Swiercz, R.; and Oniszczyk-swiercz, D. (2019). The Effects of Reduced Graphene Oxide Flakes in the Dielectric on Electrical Discharge Machining. *Nanomaterials* Vol. 9(3), pp. 335.
- Talla, G., Gangopadhyay, S., and Biswas, C. K. (2017). Influence of graphite powder mixed EDM on the surface integrity characteristics of Inconel 625. *Particulate Science and Technology*, Vol. 35(2), pp. 219–226.
- Taweel T. A. (2009). Multi-purpose optimization of EDM with Al-Cu-Si-tic P/M composite electrode. *International Journal Advance Manufacturing Technology*, Vol 44(1-2), pp. 100-113.

- Tee, K. T. P., Hosseinneshad, R., Brandt, M., and Mo, J. (2013). Pulse discrimination for electrical discharge machining with rotating electrode. *Mach. Sci. Technol.*, Vol. 17(2), pp. 292-311.
- Tee, K. T. P., Hosseinneshad, R., Brandt, M., and Mo, J. (2013). Pulse discrimination for electrical discharge machining with rotating electrode
electrical discharge machining (EDM) is a process involving the removal of conductive materials by a series of rapidly recurring current discharges between electrode and workpiece.
- Theisen, W. and Schuermann, A. (2004). Electro discharge machining of nickel–titanium shape memory alloys. *Materials Science and Engineering A*, Vol. 378, pp. 200–204.
- Ulutun, D. and Ozel, T. (2011). Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools & Manufacture*, Vol. 51, pp. 250-280.
- Valaki, J. B., and Rathod, P. P. (2015). Investigations feasibility through performance analysis of green dielectrics for sustainable electric discharge machining (EDM), *Materials and Manufacturing Processes*, Vol. 31(4), pp. 1-9.
- Valaki, J. B., Rathod, P. P., and Khatri, B. C. (2015). Environmental impact, personnel health and operational safety aspects of electric discharge machining: A review. *Proceeding of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 229(9), pp. 1481.
- Valaki, J. B., Rathod, P. P., and Sankhavara, C. (2016). Investigations on technical feasibility of Jatropha curcas oil based bio dielectric fluid for sustainable electric discharge machining (EDM), *Journal of Manufacturing Processes*, Vol. 22, pp. 151-160.

- Valaki, J. B., Rathod, P. P., and Sidpara, A. M. (2018). Sustainability Issues in Electric Discharge Machining. *Innovations in Manufacturing for Sustainability*, pp. 53-75.
- Wang, X., Yi, S., Guo, H., Li, C., and Ding, S. (2020). Erosion Characteristics of Electrical Discharge Machining Using Graphene Powder in Deionized Water as Dielectric. *International Journal of Advanced Manufacturing Technology*, Vol. 108, pp. 357–368.
- Yadav, A., Singh, Y., Singh, S., and Negi, P. (2021). Sustainability of vegetable oil based bio-diesel as dielectric fluid during EDM process – A review. *Materials Today: Proceedings*, Vol. 45(20), pp. 11155-11158.
- Yeo, S. H., Aligiri, E., Tan, P. C., and Zarepour, H. (2009). A new pulse discrimination for micro-EDM. *Material and Manufacturing Process*, Vol. 24(12), pp. 1397-1305.
- Yeo, S., Tan, H., and New, A. (1998). Assessment of waste streams in electric discharge machining for environmental impact analysis. *Journal of Engineering Manufacture*, Vol. 212, pp. 393-401.
- Zhang, Y., Liu, Y., Ji, R., Cai, B., and Shen, Y. (2013). Sinking EDM in water and oil emulsion. *International Journal of Advance Manufacturing Technology*, Vol. 24, pp. 705-716.
- Zhoa, W. S., Meng, Q.G., and Wang, Z. L. (2002). The application of research on powder mixed EDM in rough machining. *Journal of Material and Process Technology*, Vol. 129, pp. 30-33.

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