MATERIAL DEPOSITION ON ALUMINIUM BY ELECTRICAL DISCHARGE COATING (EDC) WITH A TUNGSTEN POWDER SUSPENSION

P.J. Liew[1], C.Y. Yap[1], Z. Nurlishafiqa[1], I.S. Othman[1], S.Y. Chang[1], A.R. Toibah[1] and J. Wang[2]

[1]Advanced Manufacturing Centre, Fakulti Kejuruteraan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia.

[2]Marine Engineering College, Dalian Maritime University,
[1]Linghai Road, Ganjingzi District, Dalian 116026, China.

Corresponding Author's Email: [1]payjun@utem.edu.my

Article History: Received 9 August 2018; Revised 25 October 2018; Accepted 17 November 2018

ABSTRACT: In this research, material deposition on an aluminium mould and die material was carried out via electrical discharge coating (EDC) with a tungsten powder suspension. The effects of EDC parameters, such as peak current (I_P), pulse-on time (T_{ON}) and discharge voltage (V), on the weight percentage of deposited elements and micro-hardness and surface topography of aluminium were experimentally investigated. Results showed that five elements, including carbon, aluminium, tungsten, oxygen and copper, were deposited on the aluminium surface. The amount of deposited materials was strongly affected by I_P, T_{ON} and V. Bulk deposition and globules formed on the material surface after EDC, and the micro-hardness of the material increased twofold compared with that of the base aluminium under the conditions of I_P = 3 A, T_{ON} = 150 μs and V = 40 V.

KEYWORDS: *Electrical Discharge Coating; Material Deposition; Aluminium; Tungsten Powder*

1.0 INTRODUCTION

The aluminium 6000 series is a group of promising metals that are widely used to manufacture mould and die materials. The series confers excellent properties, such as high hardness, tensile and yield strength, to moulds and dies[1]. However, aluminium corrodes and wears off with time. Wear and corrosion on the surface of aluminium moulds and dies may cause defects and decrease the service life of the workpiece due to reductions in its thickness and hardness [2]. Therefore, material deposition on the aluminium workpiece is necessary to improve the hardness and thickness of the coated surface.

Numerous technologies have been used to achieve material deposition, including dip coating [3], gel spin coating [4] and physical vapour deposition [5], all of which can improve the surface properties of the material. Electrical discharge coating (EDC) is a novel process that can rapidly deposit a coating material on the surface of a workpiece under a high current electrical pulse and in the presence of a dielectric fluid [6]. By using suitable control parameters, EDC can modify the surface of a workpiece by depositing a thick or thin layer of material as necessary [7].

Although some research works have been carried out by using EDC with different powder suspension, such as powder hydroxyapatite [8], aluminium [9] and titanium [10], surprisingly, the use of a tungsten powder suspension to modify the surface of aluminium via EDC has rarely been reported. Therefore, the main objective of this study is to investigate the effect of various EDC parameters, including peak current (I_P), pulse-on time (T_{ON}) and discharge voltage (V), on the weight percentage of the deposited elements on aluminium. The micro-hardness and surface topography of the surface obtained after EDC were then determined and analysed.

2.0 METHODOLOGY

2.1 Equipment and Materials

EDC was conducted by a Sodick AQ35L die-sinker EDM (Electrical Discharge Machining) machine, which consisted of a 3-axis linear motor drive system with a fast-response and vibration-free servo system. Aluminium 6061 specimens measuring 30 mm × 50 mm × 15 mm were selected as the workpiece material in this research. A copper electrode with a diameter of 6 mm was also obtained. Prior to the experiments, the electrode was polished and cleaned to achieve a flat surface. Some typical properties of the aluminium workpiece and copper electrode are listed in Tables 1 and 2, respectively.

Table 1: Properties of aluminium 6061[11]

Properties	Values
Density, ϱ (g/cm³)	2.7
Modulus of elasticity, E (GPa)	68.9
Vickers hardness (HV)	69.95–139.70
Melting point (K)	800
Thermal conductivity (W/m ºC)	154–180

Table 2: Properties of the copper electrode[11]

Properties	Values
Density, ϱ (g/cm³)	8.95
Young's modulus, E (GPa)	129.8
Vickers hardness (HV)	44–180
Melting point (K)	1083
Thermal conductivity (W/m ºC)	399

2.2 Experimental Conditions

The dielectric fluid was prepared by mixing tungsten powder and the surfactant Span 83 into EDM low-smell kerosene oil. Span 83 was used to prevent agglomeration of the tungsten powder [12]. The effect of I_P, T_{ON} and V_{ON} the weight percentage of deposited elements was experimentally investigated, and the micro-hardness and surface topography of the deposited surface were examined after EDC. The experimental conditions are summarised in Table 3.

Table 3: Experimental conditions of the EDC process

Workpiece	Aluminium 6061
Electrode	Copper electrode
Dielectric fluid	EDM low-smell kerosene oil
Polarity	Aluminium workpiece – negative Copper electrode – positive
Powder	Tungsten powder
Powder concentration	8 g/L
Surfactant	Span 83
Machining time	30 min
Peak current (I_P)	3, 4, 5 A
Voltage (V)	20, 25, 30, 35, 40 V
Pulse-on time (T_{ON})	150, 200, 250 µs
Pulse-off time (T_{OFF})	20 µs

2.3 Measurement and Analysis

After the experiment, each sample was cleaned with ethanol by an ultrasonic cleaning machine to eliminate debris and dust. A scanning electron microscope (Zeiss EVO 50) was used to determine the surface topography of the deposited surface. Micro-hardness measurements were repeated thrice at different areas of each sample using a micro-hardness tester (Shimadzu HMV-G21) with a load of 9.807 N and duration of 10 s. The weight percentage of deposited elements was measured by an EMAX X-act energy dispersive X-ray detector.

3.0 RESULTS AND DISCUSSION

3.1 Material Deposition

Figure 1 shows that five elements were deposited on the aluminium surface: carbon, aluminium, tungsten, oxygen and copper. Tungsten particles deposited on the surface of the aluminium workpiece originated from the tungsten powder suspended in the dielectric fluid, while carbon may have been generated during the decomposition of kerosene oil at high temperature, which is necessary for EDC. The presence of carbon on the deposited surface is supported by Collins [13]. The kerosene oil used in the EDC process contains long hydrocarbon chains of C6–C16, and its boiling point is within the range of 150–300 °C. The EDM die sinker generates a spark at temperatures within the range of 8,000–12,000°C between the electrode and the workpiece, as reported by Abdulkareem et al. [14]. Therefore, the hydrocarbon chains of kerosene oil decompose under the extremely high temperature of the plasma channel and cause deposition of carbon particles on the workpiece, similar to the results of Syed and Palaniyandi [15].

Aluminium and copper were found on the deposited surface. These two elements mainly originated from the workpiece and electrode, respectively. However, the weight percentage of copper deposited on the aluminium surface was insignificant, and some results showed a negative weight percentage of copper, which means the signal level of copper is even lower than the background noise of the qualitative analytical instrument [16]. Oxygen was also detected by qualitative analysis as an oxide layer on the aluminium surface. This result is supported by Wang et al.'s study [17], which observed that oxygen is absorbed by the deposition layer during the cooling process when it is exposed to the atmosphere after EDC.

As shown in Figure 1, among the depositions observed, the weight percentage of carbon was the largest, followed by those of oxygen, aluminium, tungsten and copper. Therefore, the following analysis will focus on carbon and tungsten powder.

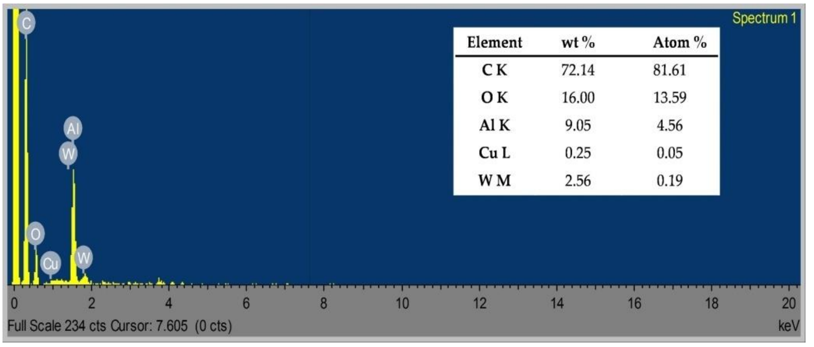


Figure 1: EDX spectral analysis of the deposited surface (I_P = 3 A, T_{ON} = 200 μs, V = 30 V)

3.2 Effect of Peak Current

Figure 2 shows the effect of IP on the weight percentage of deposited tungsten and carbon. The average weight percentage of tungsten increased as I_P rose from 3 A to 5 A. I_P is a highly important parameter in the setup of the discharge system and helps achieve a suitable sparking temperature. This parameter allows for the easy transfer of the material suspended in the dielectric fluid to the surface of the workpiece [18]. Moreover, increases in I_P could result in large segments of melted material and promote powder deposition and decomposition during EDC [19]. Therefore, a higher weight percentage of tungsten is deposited on the workpiece as I_P increases.

Interestingly, the average weight percentage of the deposited carbon decreased as I_P rose from 3 A to 5 A. This result may be due to the occurrence of sparking on the surface of workpiece, which became stronger as I_P increased and ejected more molten material from the surface of the workpiece [17–20]. This result can also be explained by the low deposition rate observed under a high I_P supply, which results in a low-quality discharge and improper cooling of the workpiece, similar to Ranjan's findings [24].

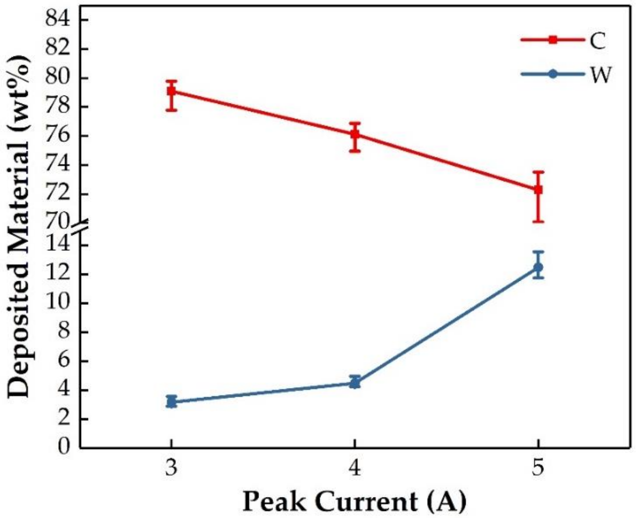


Figure 2: Effect of peak current on the weight percentage of deposited tungsten and carbon under a pulse-on time of 150 μs, pulse-off time of 20 μs and discharge voltage of 40 V

3.3 Effect of Pulse-On Time

The effect of T_{ON} on the weight percentage of deposited tungsten and carbon is shown in Figure 3. To conduct this experiment, I_P, T_{ON} and V were fixed to 5 A, 20 μs and 40 V, respectively. Figure 3 reveals that the average weight percentage of tungsten and carbon decreased as T_{ON} increased. According to Ekmekci et al. [19], the diameter of the plasma channel expands as T_{ON} increases, and, hence, the distance travelled by the particle suspension towards the surface of the workpiece increases. Another study on the effect of T_{ON} on an aluminium workpiece was carried out by Tijo and Manoj [25]. According to Tijo and Manoj [25], a rough and brittle coating was achieved at high T_{ON}, causing poor bonding of the deposited material to the workpiece. These previous studies provide mixed evidence of why the weight percentage of tungsten and carbon decreases as T_{ON} increases from 150 μs to 250 μs.

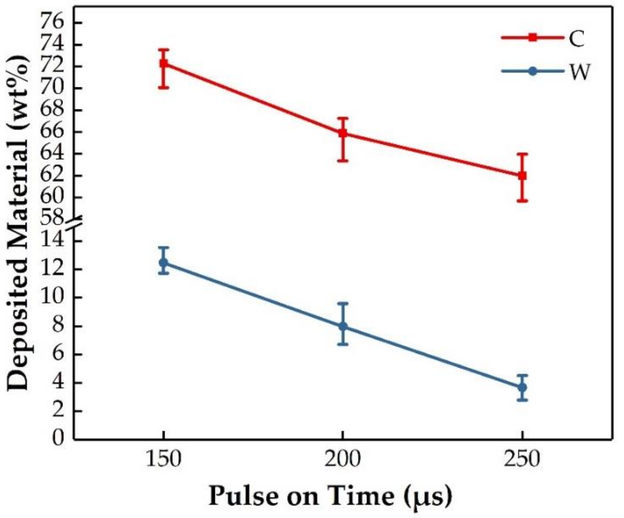


Figure 3: Effect of pulse-on time on the weight percentage of deposited tungsten and carbon under a peak current of 5 A, pulse-off time of 20 μs and discharge voltage of 40 V

3.4 Effect of Discharge Voltage

Figure 4 shows the average weight percentage of tungsten and carbon as a function of V. The weight percentage of tungsten and carbon decreased as V increased from 20 V to 40 V. V is an important parameter related to the spark gap and breakdown strength of dielectric fluids. The open gap voltage increases to form a plasma channel before the current flow. Once the current starts to flow, the voltage drops to maintain and stabilise the spark gap. The gap size between the electrode and surface of the workpiece is controlled by the V. Thus, as V increases, the material removal rate also increases, resulting in poor material deposition on the surface of the workpiece due to the increase in electric field strength. This explanation is supported by Ranjan [24]. Liew et al. [26] also noted that V influences the size of the spark gap. Hence, molten elements are easily removed and flushed away by the circulating kerosene oil. Therefore, the weight percentage of the tungsten and carbon decreases as V increases.

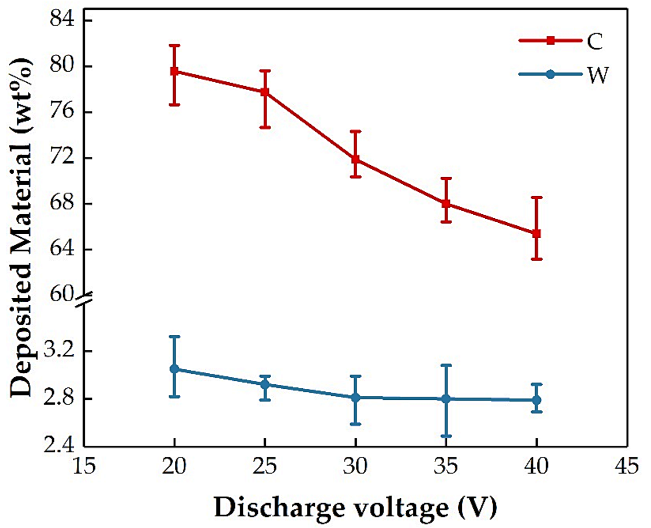


Figure 4: Effect of discharge voltage on the weight percentage of deposited tungsten and carbon under a peak current of 3 A, pulse-on time of 250 μs and pulse-off time of 20 μs

3.5 Micro-Hardness

Table 4 depicts the micro-hardness of the aluminium workpiece before and after EDC. The base workpiece had an average micro-hardness of 106.67 HV. However, after EDC, the micro-hardness of the aluminium surface increased to 218.33 HV, which is the optimal average obtained by using machining parameters of I_P = 3 A, V = 40 V and T_{ON} = 150 μs. The micro-hardness obtained after EDC is twofold that of the original aluminium workpiece. This increase in micro-hardness may be explained from the viewpoint of oxidation.

Table 4: Micro-hardness of the workpiece before and after EDC

Workpiece	Micro-hardness (HV)		
	Before machining	After machining	% increase
3A, 150 μs, 40V	106.67	218.33	104.86

Oxidation occurs when the exposed aluminium (base material) spontaneously reacts with air and forms aluminium oxide during cooling; this explanation is supported by Knight [27] because aluminium is a reactive metal. Equation (1) shows the chemical reaction of aluminium oxide formation [28].

$$
\begin{array}{c}
4Al\ (s) \longrightarrow 4Al^{3+}\ (s) + 12e^{-} \\
3O_2\ (g) + 12e^{-} \longrightarrow 6O^{2-}\ (s) \\
\text{---} \\
4Al\ (s) + 3O_2\ (g) \longrightarrow 2Al_2O_3\ (s)
\end{array} \qquad (1)
$$

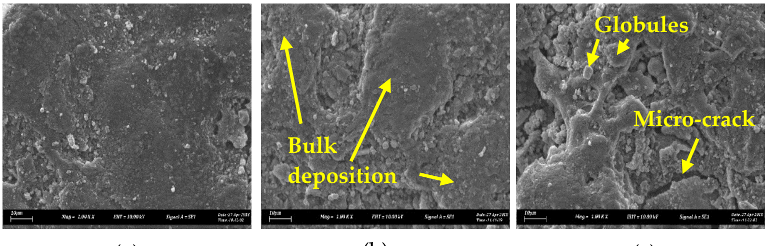
Table 5: The Vickers hardness of the tungsten, carbon and aluminium oxide [29]

Element	Hardness – Vickers (GPa)
Tungsten	3.04
Carbon	0.0686
Aluminium oxide	13.39

Besides, based on Table 5, aluminium oxide, which has a Vickers hardness of 13.39 GPa, is harder than tungsten and carbon. Therefore, the formation of oxides on the surface of aluminium leads to an increase in its micro-hardness from 106.67 HV to 218.33 HV.

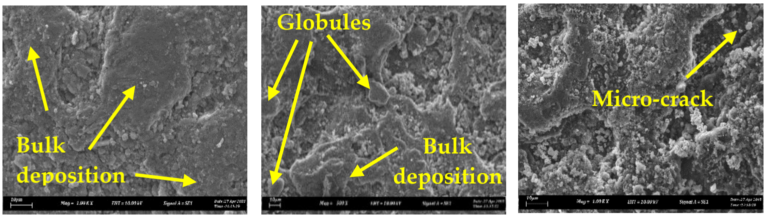
3.6 Surface Topography

Figures 5 and 6 show the surface topography of the deposited surface under various T_{ON} and I_P, respectively. As T_{ON} and I_P increased, bulk deposition, globules and micro-cracks formed on the deposited surface. Material deposition was non-uniform on the surface of the workpiece, and this phenomenon is supported by Ahmed [30]. When I_P and T_{ON} increase, the discharge energy generated between the workpiece surface and the electrode is strengthened; hence, more material is melted per discharge and deposited on the surface of workpiece, resulting in bulk deposition and globules. This finding is similar to the research results of Algodi and his co-worker [31], who found that the width of micro-cracks is elongated, cracks formed become interconnected, and voids become larger and denser as I_P and T_{ON} increase.



(a) (b) (c)

Figure 5: Surface topography of the deposited surface obtained with a constant peak current of 3 A and different pulse-on times of (a) T_{ON} = 150 μs, (b) T_{ON} = 200 μs and (c) T_{ON} = 250 μs



(a) (b) (c)

Figure 6: Surface topography of the deposited surface obtained with a constant pulse-on time of 200 μs and different peak currents of (a) I_P = 3 A, (b) I_P = 4 A and (c) I_P = 5 A

4.0 CONCLUSION

In this research, material deposition on aluminium was experimentally investigated using different EDC parameters, including I_P, T_{ON} and V, with a tungsten powder suspension. After EDC, the deposition materials, micro-hardness and surface topography of the aluminium workpiece were investigated. The following conclusions can be drawn:

i. When T_{ON} and V are increased, the average weight percentages of deposited carbon and tungsten decrease.

ii. When I_P increases, the average weight percentage of tungsten increases whereas that of carbon decreases.

iii. After EDC, the micro-hardness of the aluminium workpiece improves to 218.33 HV, which is approximately twofold that of the original value.

iv. As T_{ON} and I_P increase, bulk deposition and globules form on the deposited surface.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Universiti Teknikal Malaysia Melaka (UTeM) for their provision of the equipment and materials used in this research.

REFERENCES

[1] S. Kalpakjian and S. Schmid, *Manufacturing Engineering and Technology, SI Edition.* Singapore: Pearson Publications, 2013.

[2] C. Vargel, *Corrosion of Aluminium, 1st Edition.* Oxford: Elsevier, 2004.

[3] R.F. Munawar, A.B. Arif, W.N.F.W.A. Shani, N. Mohamad, J.A. Razak, H.E.A. Maulod, Q. Ahsan, M.S. Salleh and N.H.M. Hassan, "Water-repellent improvement of green composite sheet surface by hydrophobic modified-silica coating", *Journal of Advanced Manufacturing Technology,* vol. 12, no. 1(1), pp. 491–500, 2018.

[4] M.H.M. Akmal, M.W.A. Rashid, U.A.A. Azlan and N.A. Azmi, "The effects of different annealing temperature and number of deposition layers on the crystallographic properties of potassium sodium niobate (KNN) thin films synthesized by sol-gel spin coating technique", *Journal of Advanced Manufacturing Technology,* vol. 11, no. 1, pp. 91–102, 2017.

[5] A.R. Nizam, M.Z. Izani, D. Fairuz and M. Mazliah, "Effect of substrate chemical surface treatment on surface energy and the influence towards coating adhesion", *Journal of Advanced Manufacturing Technology,* vol. 7, no. 2, pp. 29–41, 2013.

[6] *Handbook of Aluminum: Alloy Production and Material Manufacturing,* 1st ed., Marcel Dekker Inc., New York, 2003, pp. 549–551.

[7] S. Kumari, "Study of TiC coating on different type steel by electro discharge coating," M.Tech thesis, Department of Mechanical Engineering, National Institute of Technology, Rourkela, Odisha, 2015.

[8] C. Prakash and M.S. Uddin, "Surface modification of β-phase Ti implant by hydroaxyapatite mixed electric discharge machining to enhance the corrosion resistance and in-vitro bioactivity", *Surface and Coatings Technology,* vol. 326, pp. 134–145, 2017.

[9] A.M. Abdul-Rani, A.M. Nanimina, T.L. Ginta and M.A. Razak, "Machined surface quality in nano aluminum mixed electrical discharge machining", *Procedia Manufacturing,* vol. 7, pp. 510–517, 2017.

[10] S.L. Chen, M.H. Lin, G.X. Huang and C.C. Wang, "Research of the recast layer on implant surface modified by micro-current electrical discharge machining using deionized water mixed with titanium powder as dielectric solvent", *Applied Surface Science,* vol. 311, pp. 47–53, 2014.

[11] W.F. Gale and T.C. Totemeier, *Smithells Metals Reference Book, 8th Edition.* Oxford: Elsevier Butterworth-Heinemann, 2004.

[12] M.R.A. Razak, P.J. Liew, N.I.S. Hussein, Q. Ahsan, and J. Yan, "Effect of surfactants and additives on electrical discharge machining of Reaction Bonded Silicon Carbide", *ARPN Journal of Engineering and Applied Sciences,* vol. 12, no. 14, pp. 4334–4339, 2017.

[13] C.D. Collins, "Implementing phytoremediation of petroleum hydrocarbons", *Phytoremediation,* vol. 23, no. 2, pp. 99–108, 2007.

[14] S. Abdulkareem, A.A. Khan and M. Konneh, "Cooling effect on electrode and process parameters in EDM", *Materials and Manufacturing Processes,* vol. 25, no. 6, pp. 462–466, 2010.

[15] K.H. Syed and K. Palaniyandi, "Performance of electrical discharge machining using aluminium powder suspended distilled water", *Turkish Journal of Engineering and Environmental Sciences,* vol. 36, no. 3, pp. 195–207, 2012.

[16] R. Gangadhar, K.A. Jaleeli and A. Ahmad, "Energy dispersive x-ray analysis of ovine scapular cartilage", *International Journal of Science, Environment and Technology*, vol. 4, no. 4, pp. 1195–1198, 2015.

[17] Y.K. Wang, W.M. Wang, X.H. Cu, X.Y. Cheng, B.S. Li, L.F. Xia and T.Q. Lei, "A study of the oxide layer on the surface of a TiN coating", *Materials Chemistry and Physics,* vol. 36, no. 1–2, pp. 80–83, 1993.

[18] A. Das and J.P. Misra, "Experimental investigation on surface modification of aluminum by electric discharge coating process using TiC/Cu green compact tool-electrode", *Machining Science and Technology,* vol. 16, no. 4, pp. 601–623, 2012.

[19] B. Ekmekci, F. Ulusöz, N. Ekmekci and H. Yaşar, "Suspended SiC particle deposition on plastic mold steel surfaces in powder-mixed electrical discharge machining", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 229, no. 3, pp. 475–486, 2014.

[20] A.S. Gill and S. Kumar, "Surface alloying of H11 die steel by tungsten using EDM process", *The International Journal of Advanced Manufacturing Technology*, vol. 78, no. 9–12, pp. 1585–1593, 2015.

[21] N.A.J. Hosni and M.A. Lajis, "The influence of Span-20 surfactant and micro-/nano-Chromium (Cr) powder mixed electrical discharge machining (PMEDM) on the surface characteristics of AISI D2 hardened steel," in IOP Conference Series: Materials and Engineering, vol. 342, 2018, pp. 1-11.

[22] N. Beri, H. Pungotra and A. Kumar, "To study the effect of polarity and current during electric discharge machining of inconel 718 with CuW powder metallurgy electrode", in Proceedings of the National Conference on Trends and Advances in Mechanical Engineering, Faridabad, Haryana, 2012, pp. 476-481.

[23] C. Prakash, H.K. Kansal, B.S. Pabla and S. Puri, "Experimental investigations in powder mixed electric discharge machining of Ti–35Nb–7Ta–5Zrβ-titanium alloy", *Materials and Manufacturing Processes*, vol. 32, no. 3, pp. 274–285, 2017.

[24] R. Ranjan, "Surface modification by electro-discharge coating (EDC) with TiC-Cu P/M electrode tool," B.Tech. thesis, Department of Mechanical Engineering, National Institute of Technology, Rourkela, Odisha, 2014.

[25] D. Tijo and M. Masanta, "Surface modification of aluminum by electrical discharge coating with tungsten and copper mixed powder green compact electrodes", in 5th International and 26th All India Manufacturing Technology, Design and Research Conference, Guwahati, Assam, 2014, pp. 190(1)-190(6).

[26] P.J. Liew, J. Yan and T. Kuriyagawa, "Experimental investigation on material migration phenomena in micro-EDM of reaction-bonded silicon carbide", *Applied Surface Science,* vol. 276, pp. 731–743, 2013.

[27] R. Knight. (2014). *The oxidation of aluminum* [Online]. Available: http://www.corrosionpro.com/blog/the-oxidation-of-aluminum/

[28] W.D. Callister, *Materials Science and Engineering: An Introduction, Eighth Edition.* New Jersey: John Wiley and Son, Inc, 2010.

[29] MatWeb. (2018). *Search MatWeb for property information* [Online]. Available: http://www.matweb.com/search/search.aspx

[30] A. Ahmed, "Deposition and analysis of composite coating on aluminum using Ti-B_4C powder metallurgy tools in EDM", *Materials and Manufacturing Processes,* vol. 31, no. 4, pp. 467–474, 2016.

[31] S.J. Algodi, J.W. Murray, M.W. Fay, A.T. Clare and P.D. Brown, "Electrical discharge coating of nanostructured TiC-Fe cermets on 304 stainless steel", *Surface and Coatings Technology,* vol. 307, pp. 639–649, 2016.