Metallurgical and Materials Engineering *Research paper*
Association of Metallurgical Engineers of Serbia AMES *https://doi.org/10.30544/817*

EFFECT OF COPPER-GRAPHITE COMPOSITE ELECTRODE ON MATERIAL REMOVAL RATE AND SURFACE ROUGHNESS IN MONEL 400 DURING ELECTRICAL DISCHARGE MACHINING

Mustafa Hassan Hadi [*], *Abbas Fadhil Ibrahim*

Production Engineering and Metallurgy Department, University of Technology, Baghdad, Iraq

Received 01.04.2022

Accepted 29.05.2022

Abstract

Electrical Discharge Machining (EDM) is one of the non-traditional machining processes commonly used for machining of hard to cut metals. Monel 400 is a nickel based superalloy used in various applications. The composite electrode is developed and applied to enhance the machining process by reducing the time of the process and the cost of the electrode manufacturing**.** The presented work is aimed to study the effect of copper, graphite, and copper-graphite composite electrodes with different parameters on the Material Removal Rate and Surface Roughness of Monel 400. Influences of discharge current (Ip), pulse on time (Ton), and pulse off time (Toff) have been investigated. Based on the Taguchi method, experiments were analyzed using ANOVA through Minitab 20. The results have manifested that compared to copper and graphite electrodes, the copper-graphite electrode achieved better values of material removal rate and surface roughness. The lowest value of surface roughness is 3.1413 μm as a result of the added graphite reinforcement particles.

Keywords: Taguchi method; Metal matrix composites (MMCs); ANOVA; EDM; Stir casting process.

1. Introduction

Electrical discharge machining (EDM) is a non-conventional thermo-electrical technique in which material is removed by a discharge generated by a controlled spark in the gap between the electrode and the work material surface. Both the electrode and the workpiece are submerged in a dielectric medium and connected to opposite polarities. EDM is a widely used machining process that is capable of machining various types and properties of hard materials [1, 2]. Material is removed by the spark energy that creates the plasma channel between the electrode tool and the workpiece, which has a significant effect on the EDM process' material removal rate [3]. Surface

[*] Corresponding author: Mustafa Hadi, *pme.20.17@grad.uotechnology.edu.iq*

quality is significantly affected by the plasma channel's heating, the resulting spherical crater, and the discharges' interactions [4]. EDM is primarily used to machine difficult-to-cut materials, such as superalloys. Monel 400 is a nickel-copper based solid-solution superalloy. Monel 400 has high toughness and strength across a broad temperature range. In addition, the exceptional resistance to corrosion conditions makes Monel 400 popular in the marine and chemical processing industries [5].

Due to their high toughness, low weight, high strength, and excellent heat resistance, metal matrix composites (MMCs) are increasingly used in numerous applications, such as the automotive and aerospace industries. In comparison to other reinforced alloys, the properties of metal matrix composites are superior. Graphite is a low-cost and lightweight reinforcement material that is commonly used to improve metal matrix composites [6-8]. Stir casting is a cost-effective fabrication method for producing metal matrix composites. Copper-based metal matrix composites are regarded as one of the best metals due to their excellent electrical and thermal properties, machinability, and corrosion resistance [9-11].

Researchers have studied copper and graphite electrodes effect on the EDM process. *Hardeep Singhet al.* (2021) found that for copper, graphite, brass, and aluminium/graphite electrodes, material removal rate increased when discharge current and pulse on time are increased [12]. *K. Mouralova et al.* (2020) investigated the effect of the electrode materials (copper, graphite) and found that the graphite electrode provided better surface qualities than using copper electrode [13]. *C. Pavan et al.* (2019) analyzed the machinability of Inconel through Taguchi using copper, brass, and copper-tungsten electrodes. It was found that the most influential factor on the material removal rate was the discharge current [14]. *A. Torres et al.* (2014) studied the surface roughness and material removal rate of Inconel with different factors. Discharge current, pulse duration, and voltage were the parameters selected. It was found that the discharge current and pulse duration were the most influential variables. Increasing the discharge current and the pulse on time increases the material removal rate and surface roughness [15]. *Narendra Kumar Patel et al.* (2021) studied the effect of discharge current, pulse on time, and pulse off time on the AISI304 stainless steel using copper electrode. ANOVA results showed that the current has the highest significance followed by pulse on time [16]. *Abhishek Thakur et al.* (2020) investigated the effect of input parameters, including discharge current, pulse on time, and pulse off time on the Ti-6246 using graphite electrode. Analysis of surface roughness using RSM technique depicted that there was an enhancement in the surface roughness [17].

Few works have been conducted to investigate the process variables effect on the Monel superalloy. *R. L. Balaji et al.* (2016) conducted the experiments on Monel using copper electrode tool, and it was shown that the SR is affected by discharge current (72.6%), pulse on time (5.2%) and pulse off time (3.4%) [18]. *S. Gowthaman et al.* (2018) reported that in the machining of Monel through the GRA using copper electrode, the discharge current had the main effect on the material removal rate with a contribution of (71%) and a contribution of (81%) for surface roughness [19].

From the previous literature review we can deduce that a number of researchers have examined the effect of copper and graphite electrodes on various work materials with varying parameters, while others have conducted experiments on the Monel alloy workpiece using various electrode materials. No studies have yet been conducted on the effect of copper composite electrode tool materials on the material removal rate and surface roughness of Monel 400 during the EDM process. The significance of this research lies in the stir casting process for producing copper-graphite electrodes. In order to improve the machining time and cost of the EDM process, the copper-graphite electrode was created to improve the surface roughness of the product, as product quality is of utmost importance and is carefully considered during the machining process. The purpose of this study is to examine the influence of copper, graphite, and copper-graphite composite electrodes on the electrical discharge machining of Monel 400. (EDM). The discharge current, pulse on time, and pulse off time were used as process parameters, while the material removal rate and surface roughness were studied as process response parameters.

2. Experimental Work

A workpiece made of Monel 400 was used in the presented work. Table 1. shows the chemical composition. The work material was cut by water jet machining (WJM) into square shapes of dimensions (30x30x2) mm, as shown in Fig. 1.

Table 1. Chemical composition of the workpiece (Monel 400).

Element	Ni	C	Mn	Fe	S	Si	Cu	Al	Ti
Weight%	63.6	0.117	0.851	1.94	0.0073	0.106	33	0.0912	0.0372

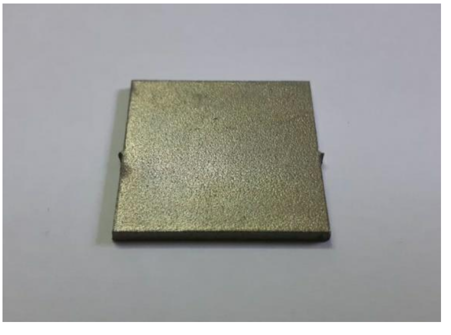


Fig. 1. Monel 400 workpiece.

Electrode materials used in the experiment were copper (Cu), graphite (Gr), and copper-graphite (Cu-Gr) metal matrix composite tool materials, as shown in Fig. 2. The electrodes were made with 9 mm of diameter and 100 mm of length. The copper-graphite electrode was fabricated using stir casting method.

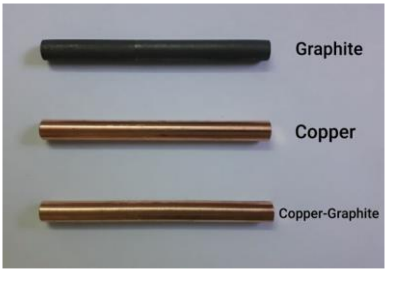


Fig. 2. Tool electrode materials.

2.1 Fabrication of the composite tool material

The copper-graphite MMCs electrode is manufactured using the stir casting method depicted in Fig. 3. Copper-coated graphite reinforcement particles with a mean particle size of 14 m were added to copper (99.9% pure) as the base metal matrix at a ratio of 95% copper and 5% copper-coated graphite. First, copper was melted at a temperature of 1150°C, followed by the addition of copper-coated graphite particles. To evenly distribute the reinforcement particles throughout the molten metal, a stir caster with an output speed of 600 rpm was utilized to mix the molten metal. The mixture was poured into a 500°C-preheated cast iron mold. The matrix of cast metal was machined to the desired dimensions.

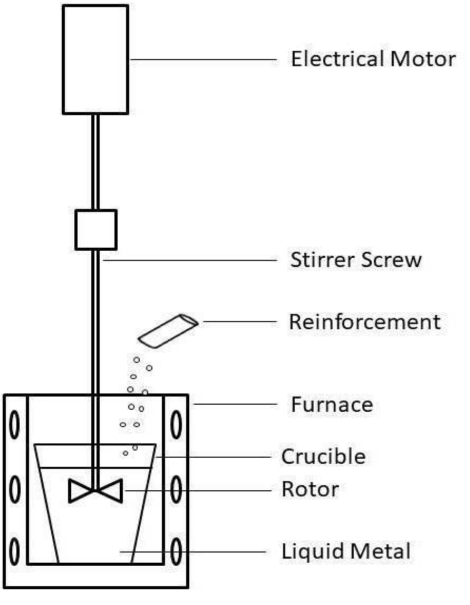


Fig. 3. Stir casting method.

2.2 Design of experiment

In the experiment, Taguchi L9 was used to analyze the effect of each parameter on each electrode tool material based on parameters such as discharge current, pulse on time, and pulse off time. To reduce the impact of noise, test pieces were performed arbitrarily. Minitab 20 software utilized the Signal-to-Noise (S/N) ratio followed by Analysis of Variance (ANOVA) based on the Taguchi method.

2.3 Signal to noise (S/N) ratio

To identify the occurrence of response deviations, it is crucial to calculate the S/N ratio. Response outcomes are contingent on controllable and uncontrollable parameters. The S/N ratio is calculated using Equations 1 and 2 in order to determine the maximum MRR and the minimum SR values [20].

$$\text{Smaller the better: } S/N_{SB} = -10log10[\frac{1}{n}(\sum_{i=1}^{n} y^2)] \quad (1)$$

Where, y: The observed response value, and n: The total number of experiment performed.

$$\text{Larger the better: } S/N_{LB} = -10log10[\frac{1}{n}(\sum_{i=1}^{n} 1/y^2)] \quad 2$$

Where, y: The observed response value, and n: The total number of experiment performed.

2.4 Machining parameters and their levels

Electrical Discharge Machine (CHMER) model (CM 323+50N) was used to machine the workpieces, which is located in University of Technology (Workshops and Training Center). As a dielectric medium, transformer oil was used. The positive polarity of electrodes was chosen. The process parameters and their corresponding levels are depicted in Table 2.

Table 2. Machining parameters.

Parameters	Symbol	Level 1	Level 2	Level 3
Discharge current (A)	Ip	10	24	42
Pulse on time (μs)	Ton	50	100	200
Pulse off time (μs)	Toff	12	25	37

2.5 Material Removal Rate (MRR) and its measurement

Material removal rate refers to the rate at which material is removed from the workpiece during machining. MRR is a desirable characteristic because it influences machining time and output. The MRR is primarily determined by the discharge current, polarity of the electrodes, pulse on time, and pulse off time [21]. In the present study, the MRR is determined using a digital weight balance and the following equation.

$$MRR = \frac{Wtb-Wta}{Tm} \text{ mg/min} \quad 3$$

Where:

MRR: Material removal rate (mg/min), Wtb: Workpiece weight before machining (mg), Wta: Workpiece weight after machining (mg), and Tm: Machining time in (minutes).

2.6 Surface Roughness (SR)

The work material is eroded due to the production of sparks. As a result, deep craters appear on the surface of the work material. The relationship between product quality and surface roughness is predominate. Lower surface roughness values result in higher surface quality [22]. Measuring of surface roughness was performed using the portable profilometer (Marsurf) provided by Maher Federal Company.

3. Results and Discussion

Experimental results of the machined Monel 400 workpiece at the selected parameters are revealed in Table 3. Minitab 20 software was used to analyze the MRR and the SR.

Table 3. Values for MRR and SR and their S/N ratio.

Exp. No	Electrode Material	Ip (A)	Ton (μs)	Toff (μs)	MRR (mg/min)	S/N Ratio	SR (μm)	S/N Ratio
1	Cu	10	50	12	110.16	40.841	3.4163	-10.671
2	Cu	10	100	25	115.22	41.231	4.0846	-12.223
3	Cu	10	200	37	123.27	41.817	4.2250	-12.516
4	Cu	24	50	25	232.59	47.331	4.2003	-12.465
5	Cu	24	100	37	323.76	50.204	4.5033	-13.070
6	Cu	24	200	12	405.20	52.153	5.1642	-14.260
7	Cu	42	50	37	238.23	47.539	4.2337	-12.534
8	Cu	42	100	12	491.78	53.835	5.0210	-14.015
9	Cu	42	200	25	527.20	54.439	6.1193	-15.734
10	Gr	10	50	12	91.027	39.183	3.4036	-10.638
11	Gr	10	100	25	66.048	36.397	3.5666	-11.045
12	Gr	10	200	37	59.779	35.531	3.5083	-10.902
13	Gr	24	50	25	140.66	42.963	4.1183	-12.294
14	Gr	24	100	37	162.40	44.211	4.5713	-13.200
15	Gr	24	200	12	166.22	44.413	4.3025	-12.674
16	Gr	42	50	37	149.09	43.469	4.0573	-12.164
17	Gr	42	100	12	158.66	44.009	5.1576	-14.249
18	Gr	42	200	25	137.09	42.740	4.5780	-13.213
19	Cu-Gr	10	50	12	78.535	37.901	3.1413	-9.9423
20	Cu-Gr	10	100	25	94.472	39.506	3.7056	-11.377
21	Cu-Gr	10	200	37	103.34	40.285	3.9846	-12.007
22	Cu-Gr	24	50	25	172.89	44.755	4.0406	-12.129
23	Cu-Gr	24	100	37	276.34	48.829	4.2986	-12.666
24	Cu-Gr	24	200	12	411.81	52.294	4.3580	-12.785
25	Cu-Gr	42	50	37	201.10	46.068	4.3696	-12.809
26	Cu-Gr	42	100	12	514.30	54.224	4.5692	-13.196
27	Cu-Gr	42	200	25	580.00	55.268	4.6923	-13.427

3.1 Analysis of Material Removal Rate

According to Table 4, the ANOVA for the S/N ratio of copper electrode in terms of material removal rate for Monel 400 indicates that the discharge current contributes the most 82.20%, as supported by [15, 19], as it represents the highest machining value, in addition to pulse on time 12.53%, pulse off time 3.78%, and error contribution 1.49%.

Table 4. ANOVA for S/N ratio of Cu electrode material removal rate.

Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	191.375	95.687	55.04	0.018	82.20%
Ton	2	29.161	14.581	8.39	0.107	12.53%
Toff	2	8.812	4.406	2.53	0.283	3.78%
Error	2	3.477	1.738			1.49%
Total	8	232.825				

From Table 5. the ANOVA for the S/N ratio of graphite electrode in terms of material removal rate for Monel 400 manifests that the most contributing factor is the discharge current 90.35%, which represents the highest machining value. In addition, the low percentage of pulse on time 1.53% and pulse off time 5.84% were determined, and the error contribution was 2.27%.

Table 5. ANOVA for S/N ratio of Gr electrode material removal rate.

Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	87.368	43.6838	39.75	0.025	90.35%
Ton	2	1.481	0.7404	0.67	0.597	1.53%
Toff	2	5.651	2.8257	2.57	0.280	5.84%
Error	2	2.198	1.0988			2.27%
Total	8	96.697				

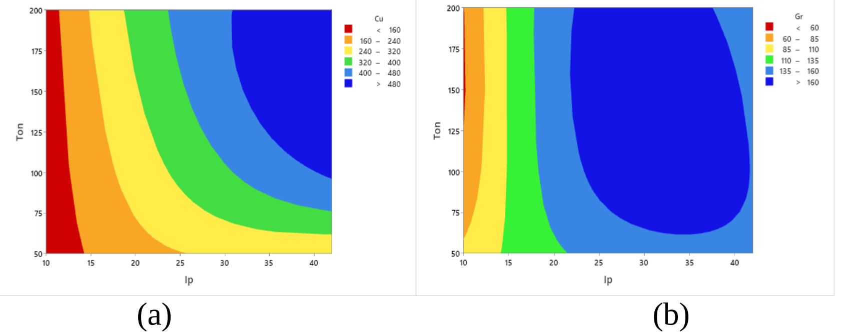
From Table 6. the ANOVA for the S/N ratio of copper-graphite electrode in terms of material removal rate for Monel 400 elucidates that the most contributing factor is the discharge current 75.84%, which represents the highest machining value, in addition to pulse on time 19.11%, pulse off time 4.18%, and error contribution 0.86%.

Table 6. ANOVA for S/N ratio of Cu-Gr electrode material removal rate.

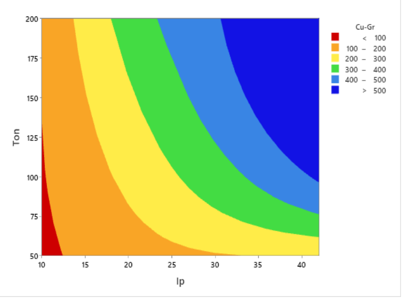
Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	258.025	129.012	87.69	0.011	75.84%
Ton	2	65.003	32.501	22.09	0.043	19.11%
Toff	2	14.235	7.118	4.84	0.171	4.18%
Error	2	2.942	1.471			0.86%
Total	8	340.205				

3.2 Effects of process parameters on electrode materials for MRR

MRR is primarily studied in relation to the pulse on time and discharge current, as they have the greatest impact on the performance of the process. Figure 4 depicts contour plots for the effect of discharge current and pulse on time on the material removal rate for various electrode materials. As depicted in Fig. 4(a) and Fig. 4(c), for copper and copper-graphite electrodes, an increase in pulse on time and discharge current results in greater MRR values, which is consistent with the findings of [12]. This can be interpreted as a result of the increase in energy density as the pulse on time at higher discharge current levels increases. In contrast, for the graphite electrode in Fig. 4(b), higher MRR values are obtained at higher discharge current levels because the graphite electrode requires more energy to produce the spark.



(a) (b)



(c)

Fig. 4. Contour plots for MRR; (a) copper electrode, (b) graphite electrode, and (c) copper-graphite electrode.

3.3 Analysis of Surface Roughness

From Table 7. the ANOVA for the S/N ratio of copper electrode in terms of surface roughness for Monel 400 indicates that the most contributing factor is the discharge current 47.96%, which is supported by [15, 19], as it represents the highest machining value, in addition to pulse on time 46.37%, pulse off time 5.38%, and error contribution 0.29%.

Table 7. ANOVA for S/N ratio of Cu electrode surface roughness.

Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	8.0743	4.03715	165.62	0.006	47.96%
Ton	2	7.8068	3.90340	160.13	0.006	46.37%
Toff	2	0.9061	0.45303	18.59	0.051	5.38%
Error	2	0.0488	0.02438			0.29%
Total	8	16.8359				

From Table 8. the ANOVA for the S/N ratio of graphite electrode in terms of surface roughness for Monel 400 demonstrates that the most contributing factor is the discharge current 77.51%, which represents the highest machining value, in addition to pulse on time 16.19%, pulse off time 2.60%, and error contribution 3.70%.

Table 8. ANOVA for S/N ratio of Gr electrode surface roughness.

Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	9.2087	4.6044	20.95	0.046	77.51%
Ton	2	1.9233	0.9616	4.37	0.186	16.19%
Toff	2	0.3085	0.1542	0.70	0.588	2.60%
Error	2	0.4396	0.2198			3.70%
Total	8	11.8801				

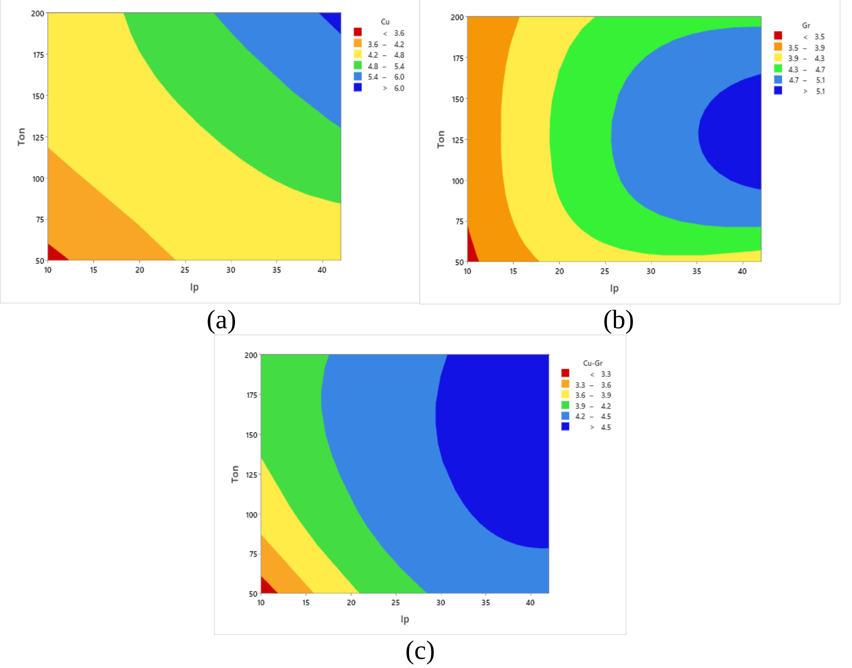
From Table 9. the ANOVA for the S/N ratio of copper-graphite electrode in terms of surface roughness for Monel 400 exhibits that the most contributing factor is the discharge current 70.90%, which represents the highest machining value in addition to pulse on time 21.33%, pulse off time 4.52%, and error contribution 3.24%.

Table 9. ANOVA for S/N ratio of Cu-Gr electrode surface roughness.

Source	DF	SS	MS	F-Value	P-Value	Contribution
Ip	2	6.5348	3.2674	21.88	0.044	70.90%
Ton	2	1.9663	0.9831	6.58	0.132	21.33%
Toff	2	0.4166	0.2083	1.39	0.418	4.52%
Error	2	0.2987	0.1493			3.24%
Total	8	9.2163				

3.4 Effects of process parameters on electrode materials for SR

SR is primarily studied in relation to the discharge current and pulse on time, as they have the greatest impact on the performance of the process. Figure 5 depicts contour plots for the effect of discharge current and pulse on time on surface roughness for various electrode materials. For copper and copper-graphite electrodes, as depicted in Figure 5(a) and Figure 5(c), the best surface roughness measurements are obtained at low discharge current and pulse on time, as supported by [15]. This occurs as a result of the low spark density, which results in a lower temperature and the removal of less material, thereby reducing surface roughness. As with the graphite electrode depicted in Fig. 5. (b), the lowest surface roughness values can be obtained at the lowest discharge current values.



(a) (b)

(c)

Fig. 5. Contour plots for SR; (a) copper electrode, (b) graphite electrode, and (c) copper-graphite electrode.

Conclusions

In this study, the results of electrical discharge machining process for Monel 400 by three different electrodes have been studied, where the effect of the parameters have been discussed. The following conclusions can be drawn:

1. It was observed that the main parameters affecting MRR and SR are the discharge current (Ip) followed by pulse on time (Ton).
2. For the copper and copper-graphite electrodes, MRR increases with the increasing in discharge current (Ip) and pulse on time (Ton).
3. At higher values of discharge current (Ip), the MRR when using copper and copper-graphite is significantly higher.
4. The SR of copper and copper-graphite manifested an increase when the values of pulse on time (Ton) are increased. And, the SR for all electrodes increased when the discharge current (Ip) is increased.
5. For the copper-graphite electrode, it was noted that SR is lower; the lowest SR value is 3.1413 μm in comparison with the copper and graphite electrodes.

From the above conclusions, it has been shown that with the use of copper-graphite electrode, a higher surface quality with similar material removal rate can be achieved compared to the copper electrode.

References

[1] V. S. Gaikwad, and V. S. Jatti, S. S. Chinchanikar, K. N. Nandurkar: Materials Today: Proceedings, 44 (2021) 1478-1487.

[2] N. S. Purnima, P. S. Rao, S. P. Dora: Metallurgical and Materials Engineering, 27 (2021) 331-350.

[3] S. Rajamanickam, R. Manjunathan, R. Palani, J. P. Mohamed, D. Monesh, and A. Aakash: International Journal of Engineering & Technology, 7 (2018) 1302-1304

[4] V. V. Lyubimov, V. M. Volgin, I. V. Gnidina, and M. S. Salomatnikov: Procedia CIRP, 68 (2018) 319-324.

[5] M. Mahalingam, and R. Varahamoorthi: Materials Today: Proceedings, 26 (2020) 1213-1220.

[6] K. Archana, and P. Kumara: International Journal of Applied Engineering Research, (2018) 189-193.

[7] A.F. Ibrahim: IIUM Engineering Journal, 23(2022) 349-357.

[8] Hareesha G, Chikkanna N, S. Doddamani, and A. S. Kallimani: Metallurgical and Materials Engineering, 27 (2021) 49-56.

[9] M.K. Singh, and R. Singh: Engineering and Technology Journal for Research and Innovation, 3 (2020).

[10] Titus Thankachan, K. Soorya Prakash, and V. Kavimani, Composites Part B (2019), 174 (2019) 107057.

[11] Mohamed Abu–Okaila, W. M. Shewakhb, Ayman M. Brishad, Yasmin A. Abdelraoufe, and Ahmed Abu-Oqailb, Ceramics International, 46 (2020) 18037-18045.

[12] Hardeep Singh, Jujhar Singh, Shubham Sharma, S. P. Dwivedi, and Ahmed J. Obaid: Journal of Green Engineering, 11 (2021) 922-938.

[13] K. Mouralova, J. Bednar, L. Benes, P. Hrabec, M. Kalivoda1, and J. Fries: Archives of Civil and Mechanical Engineering, 20 (2020) 130.

[14] C. Pavan, N. Sateesh, and R. subbiah: Materials Today: Proceedings, 46 (2020) 9281-9286.
[15] A. Torres, I. Puertas, and C. J. Luis: Precision Engineering, (2014) 2334-2340.
[16] N. K. Patel, and T. Choudhary: Materials Today: Proceedings, 47 (2021) 6262-6268.
[17] A. Thakur, P. Sudhakar Rao, and Mohd. Y. Khan: Materials Today: Proceedings, 44 (2020) 838-847.
[18] R. L. Balaji, and J. P. Kumar: Journal of Engineering, Scientific Research and Applications, (2016) 2455-3964.
[19] S. Gowthaman, K. Balamurungan, P. M. Kumar, S. K. Ahamad Ali, K. L. Mohan Kumar, and N. V. Ram Gopal: Procedia Manufacturing, 20 (2018) 386-391.
[20] Ch. M. Rao, and K. M. Saheb: Metallurgical and Materials Engineering, 27 (2021) 57-73.
[21] J. Laxman, K. Guru Raj, and P. Venkateswara Rao: International Research Journal of Engineering and Technology, 2 (2015) 508-513.
[22] F. Rachman, D. A. Purnomo, R. A. Fajardini, and R. R. Umami: Jurnal Teori dan Aplikasi Matematika, 5 (2021) 50-59.