EDM of Al7075-B_4C-flyash hybrid metal matrix nano-composites and optimization of sustainable measures using genetic algorithm

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Abstract: ***Sustainability is an important approach in today's manufacturing environment to achieve overall efficiency in terms of economic, environmental and social aspects. This research work aims to investigate the applicability of sustainability in electrical discharge machining (EDM) of Al7075-B_4C-flyash hybrid metal matrix nano-composites (HMMNCs). The machining experiments are conducted using central composite design with voltage (V), current (I), pulse-on-time (T_{on}) and pulse-off-time (T_{off}) as process parameters and surface roughness and power consumption are being sustainable measures. Mathematical predictive models were developed using response surface methodology (RSM). The predicted performance of the model shows an error percentage 3.76% and 3.97% for surface roughness and power consumption respectively. The experimental results obtained are analysed using 3D contour plots and current and pulse-on-time found most dominating parameters. The sustainable measures are optimized simultaneously using the popular optimization tool i.e., genetic algorithm. The Pareto optimal fronts provide different optimum cutting conditions for production of components with minimum power consumption satisfying the desired surface roughness value. The approach is found to be an effective tool and can be developed with minimum effort and help shop floor engineer towards sustainable machining approach***

Keywords: Sustainability, electrical discharge machining, surface roughness, power consumption, genetic algorithm.

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1. Introduction

Sustainable manufacturing is the process of producing products with processes that are cost effective, environmental friendly and conserves energy and natural resources thereby satisfying the employee and the community. Nowadays the amount of energy generated during any manufacturing process as amplified by its demand is responsible for the emission of carbon dioxide (CO_2) and climatic changes. Therefore aim towards reducing the use of energy is a major concern in achieving sustainable manufacturing. Also due to the excessive demand in energy throughout the world, the cost is growing rapidly. Hence reducing the energy consumption can boost the economy of a nation. Thus minimizing the utilization of energy can be related to the three sustainability pillars viz. economic, environmental and social.

Increase in the population around the world and standard of living due to the advancement of technology have amplified the amount of waste materials caused due to industries. There is increase in threat for environmental pollution as the waste materials are difficult as well as costly to dispose. The current researchers are trying to control the menace by reprocessing the industrial wastes into green materials and using in construction and automobile industries.

Kumar et al. [1] studied the effect of process parameters on power consumption (*PC*) along with other measures such as surface roughness (*SR*) and electrode wear rate (*EWR*) during EDM of aluminium hybrid metal matric composites (Al6351-SiC- B_4C). They used current (*I*), pulse-on-time (T_{on}), voltage (*V*) and pulse duty factor (*s*). *I* significantly affect the *PC*. The *PC* increases at higher T_{on} whereas decreases with increases in *s*. Kumar et al. [2] also carried out multi-response optimization of EDM parameters while machining the same hybrid metal matrix composites (MMCs). Response surface methodology (RSM) model coupled with genetic algorithm (GA) approach optimizes the sustainable measures such as material removal rate (*MRR*), surface roughness (*SR*) and power consumption (*PC*) using correct input parameter combinations. Three process responses one each from economic aspect (i.e., material removal rate), environmental aspect (i.e., power consumption) and social aspect (i.e., surface roughness being job quality for customers' satisfaction) are optimized simultaneously.In the area of conventional turning process, Pervaiz et al. [3] have studied the energy consumption pattern on dry and wet machining of Ti6Al4V using uncoated carbide inserts. They observed that increase in *MRR* enhances energy requirement. An increase in cutting speed leads to decrease in energy requirement and surface roughness value. Tamang et al. [4] focused on energy saving and associated CO_2 emission for sustainable turning of Inconel 825 aerospace alloy. They used Taguchi L_{27} experimental design in order to optimize spindle speed, feed and depth of cut for obtaining minimum energy required for machining. They used response surface methodology for evaluating the energy required and the CO_2 emission found that depth of cut and cutting velocity influences the energy consumption and thereby CO_2 emission. Chen and Wang [5] have developed an improved discharge circuit for use in wire-electrical discharge machining (WEDM). They used DC-DC and electronic voltage regulation technology to convert the energy originally dissipated in the resistor directly into the energy for use in machining. The Zero-Resistance Spark Circuit is the critical design to realize the energy saving effect. Experimental results indicate an energy saving potential of 10 to 15%. Thirugnanasambandam et al. [6] studied the effects of load factors of electrical motors and analyzed energy saving potential in a cement industry located in India. Here the CO_2 emission increases with increase in motor loading as power consumption also increases. They calculated CO_2 emission with 20%, 40% and 60% of motor loading through an energy audit approach. Malghan et al. [7] investigated on power consumption during milling of AA6061-4.5%Cu-5%SiCp MMC. The feed rate, spindle speed and depth of cut are considered as process parameters while cutting force, *SR* and *PC* are performance characteristics. ANOVA shows that the spindle speed has major effect followed by feed rate and depth of cut. The *PC* is directly proportional with cutting force. Sahu and Andhare [8] considered three sustainability factors viz., *PC*, *MRR* and *SR* in this study. They optimize input parameters (i.e., cutting speed, feed rate and depth of cut) by simultaneously maximizing all three process performances. In optimization multiple performance characteristics using GA, Pareto optimal fronts obtained helps machinist to obtain optimal combination of milling conditions.

Machining of metal matrix composites (MMCs) are difficult due to the high abrasiveness of reinforcing constituents. The conventional machining processes such as turning, drilling, milling and grinding creates friction between work piece and tool (electrode) interfaces resulting in high temperatures. In the interest of ecological and environmental safety the global focus is towards achieving sustainable manufacturing. Out of all the non-conventional machining methods, the electrical discharge machining (EDM) is found to be economical as well as feasible as per many studies and is suitable for machining particle-reinforced MMCs [9]. The sustainability assessment during machining process is main area of emphasis for most researchers. This work aims to attempt sustainable machining of aluminium based hybrid metal matrix nano-composites (HMMNCs) during EDM process.

2. EDM investigation

In this investigation, aluminium 7075 (Al-Zn-Mg-Cu alloy) is selected as the matrix alloy. It has its major application in aerospace and defence industries. The hybrid metal matrix nano-composites (HMMNCs) are fabricated by stir casting method which is considered for bulk manufacturing of both MMC and HMMNC and is a cost effective process. The reinforcements used in the HMMNCs are 1.5% B_4C and 1.0 % flyash nano-particulates of 40 nm size each. B_4C is a considerably hard ceramic reinforcement and due to its low density (2.52 g/cm^3), thermal stability and excellent wettability, it is found ideal for aluminium matrix [10]. Fly ash is a waste material evolved in the power plants which can be highly utilised by the automobile and construction industries [11]. It is abundantly available, low cost and low density (approx. 0.8 g/cm^3) material. It is also a major constituent if silicon (Si) which helps in eliminating the hydrophilic aluminium carbide (Al_4C_3) from the Al-B_4C systems.

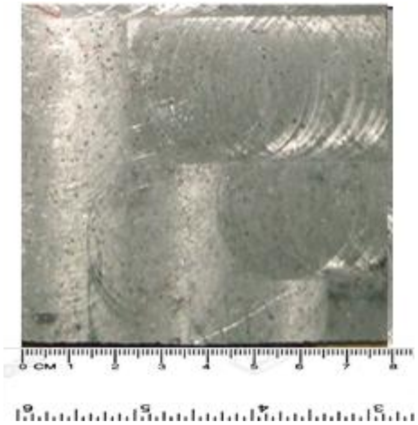

Figure 1(a) EDM work piece

Figure1 (b) Size of electrode used (12 mm)

The size of the fabricated workpiece was of size 80mm x 80mm x 20mm. A copper tool of diameter 12mm was used as electrode. Machining experiments are performed on die-sinking EDM (M/S JK Machine, Model No. CNC-450). Figure 1(a) and 1(b) shows the workpiece and copper electrode used during EDM. From the review of literature, four process parameters namely gap-voltage (V), current (I), pulse on time (T_{on}) and pulse off time (T_{off}), are chosen for investigation in the present study. All process parameters are considered at three different levels as V (factor A) in Volt (40, 50, 60), I (factor B) in Amp. (6, 9, 12), T_{on} (factor C) in µs (4, 6, 8) and T_{off} (factor D) in µs (6, 7, 8).The experiments were conducted following face centered central composite design. Total 30 experiments were conducted in designed combination of input parameters.

The experiments were carried out at a constant machining time of 20 minutes each. A constant spark gap of 0.025-0.05 mm was maintained between the electrode and workpiece by a servomotor. The material removal is caused by the localized melting and vaporization on the HMMNC workpiece and the copper tool. The two important sustainability measures in EDM, surface roughness (social) and power consumption (environmental) were considered. The environmental concern was evaluated by the power consumed during the machining process. The economic and environmental response (power consumption) was measured using the power harmonic analyzer from the three-phase input power supply and the social response (surface roughness) was measured using a portable stylus type profilometer having a transverse length of 7 mm and a transverse speed of 0.25mm/s.

3. Mathematical modelling

Response surface methodology (RSM) is a commonly used mathematical and statistical optimization technique used for modelling, analysis and optimization of performance measures of a process for the different independent variables. RSM gains the relationship between the input parameters and the output parameters. The effects of input parameters on the various sustainable measures (*SR* and *PC*) are modeled in the form of second order polynomial regression equation. The standard form of the model is as given in Eqn. 1.

$$Y = C_o + \sum_{i=1}^{n} C_i X_i + \sum_{i=1}^{n} C_{ii} X_i^2 + \sum_{i=1}^{n-1}\sum_{j=1}^{n} C_{ij} X_i X_j, \quad (1)$$

where, C_o is constant or free terms, C_i, C_{ii}, and C_{ij} are coefficients of linear, quadratic and interaction terms. The RSM model is obtained using MINITAB17® statistical software for the experimental data. The obtained model equations for *SR* and *PC* with their R² values are given in Eqn. (2) and (3) respectively.

$$\begin{aligned} SR = {} & 37.4776 - 1.14928V + 1.37633I + 6.34455T_{on} \\ & - 8.67598T_{off} + 0.00895868V^2 - 0.0366813I^2 \\ & - 0.522783\, T_{on}^2 + 0.559868T_{off}^2 + 0.00247708VI \\ & + 0.000671875VT_{on} + 0.0342438VT_{off} + 0.0934688IT_{on} \\ & - 0.135729\, IT_{off} - 0.0547813T_{on}T_{off} \end{aligned} \quad (2)$$

(R²=98.82%)

$$\begin{aligned} PC = {} & 5.09759 - 0.0336674V + 1.33455I - 1.12372T_{on} \\ & - 1.54312T_{off} - 4.69298E-04V^2 - 0.0179922I^2 \\ & + 0.0920175T_{on}^2 + 0.0730702T_{off}^2 - 0.00312500VI \\ & + 0.00418750VT_{on} + 0.0131250VT_{off} - 0.0835417IT_{on} \\ & - 0.0645833IT_{off} + 0.0918750T_{on}T_{off} \end{aligned} \quad (3)$$

(R²=96.75%)

The predictive capability of the models shows minimum average percentage error as 3.76 % and 3.97% for *SR* and *PC* respectively. The maximum percentage error of *SR* is 10.27 % and for *PC* is 10.31%. Thus the mathematical models can be used for determining the sustainable measures with significant accuracy.

3.1 Model analysis

The sustainable measures, *SR* and *PC* are significant response parameters during machining of HMMNCs by EDM process, as they play important role on industrial economy and production of quality goods. The effects of all the process parameters on the sustainable measures have been studied with 3D surface plots as shown in Fig. 2(a) and 2(b). Fig. 2(a) shows the interaction plot between I and T_{on} that affects the *SR*. Low values of I and T_{on} produces minimum *SR*. Due to low I and T_{on} there is lower melting and evaporation rate, due to which a smaller crater is formed in the machined surface. The interaction plot of I and T_{on} affecting *PC* is shown in Fig. 2(b). It may be noted that *PC* reduces as I reduces. The prolonged duration of pulse on time (i.e., at high T_{on}) increases electrical load which in turn increases power consumption. Minimum power consumption was noticed at low *I* and T_{on}.

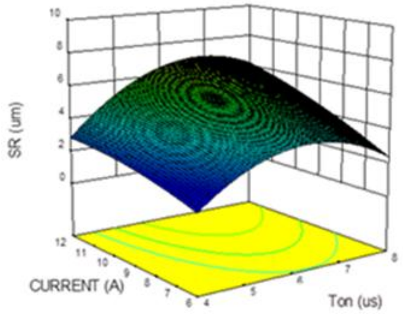

Figure 2(a) Surface plot for *SR*

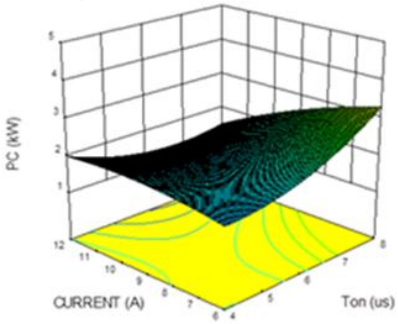

Figure 2(b) Surface plot for *PC*

4. Simultaneous Optimization using Genetic Algorithm

Genetic algorithm (GA) is a popular optimization techniques based on natural genetics which states ‘survival of the fittest’. After developing the RSM model the process parameters are optimized using popular soft computing technique i.e., genetic algorithm. The formulation of the optimization problem is as follows:

Objective 1: Minimize *SR* (V, I, T_{on}, T_{off})*:* The *SR* value is to be minimized to provide better quality surface.

Objective 2: Minimize *PC* (V, I, T_{on}, T_{off})*:* The *PC* is to be reduced for minimum energy consumption.

The above objectives are optimized subjected to parametric bounds of different process variable. The lower bound (LB) and upper bound (UB) are given as $40 \leq V \leq 60$, $6 \leq I \leq 12$; $4 \leq T_{\mathrm{on}} \leq 8$; $6 \leq T_{\mathrm{off}} \leq 8$.

The problem is optimized using GA tool box of MATLAB. The different GA parameters viz., population size; cross over probability; mutation rate; selection function and number of generation, are crucial to obtain the best optimum parameters. The selected GA parameters of present optimization work are: (a) population in numbers=20, (b) iterations=127, (c) probability of cross over=0.8 and (d) probability of mutation=0.05. The optimization of *SR* and *PC* is carried out simultaneously using genetic algorithm in MATLAB 7.10® and Figure 3 shows Pareto optimal plots and provides 21 Pareto-optimal fronts as listed in table 1. The solutions are arranged such that it provides optimal parameters combination for different values of *SR* with minimum *PC*

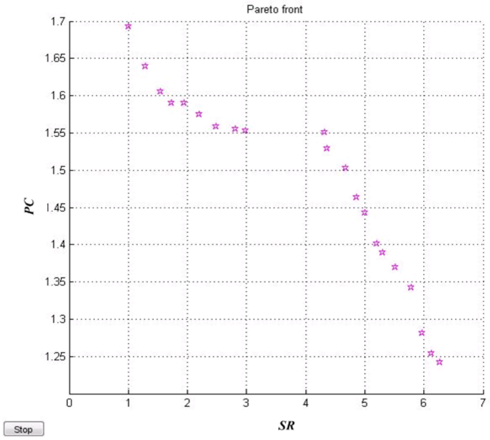

Figure 3 Pareto optimal plots

TABLE 1: PARETO OPTIMAL SOLUTIONS

Sl. No.	*V*	*I*	T_{on}	T_{off}	*SR*	*PC*
1	42.14	12.00	6.50	7.73	6.27	1.24
2	42.21	11.98	6.31	7.85	6.13	1.25
3	42.19	11.98	6.03	7.83	5.97	1.28
4	46.24	11.99	6.03	7.73	5.78	1.34
5	45.65	11.97	5.76	7.87	5.51	1.37
6	44.30	11.97	5.54	7.90	5.30	1.39
7	44.29	11.96	5.47	7.93	5.20	1.40
8	43.60	11.99	5.28	7.80	5.00	1.44
9	44.35	11.94	5.23	7.87	4.86	1.46
10	45.27	11.95	5.13	7.83	4.67	1.50
11	45.14	11.96	4.97	7.98	4.37	1.53
12	46.70	11.94	4.97	7.99	4.32	1.55
13	40.38	6.00	4.52	6.74	2.99	1.55
14	40.40	6.01	4.44	6.78	2.80	1.55
15	40.41	6.01	4.30	6.85	2.48	1.56
16	40.79	6.04	4.23	6.97	2.20	1.58
17	41.92	6.01	4.17	6.89	1.94	1.59
18	41.62	6.01	4.09	7.02	1.73	1.59
19	42.03	6.03	4.03	7.03	1.54	1.61
20	44.03	6.03	4.03	7.07	1.28	1.64
21	47.27	6.05	4.00	7.09	1.00	1.69

With reference to table 1, if the component with $SR \leq 6.00$µm to be produced, the table suggests appropriate process parameters that would yield the minimum *PC* satisfying the desired surface finish limit. Referring to Table 1, serial number 3 gives optimum values of process parameters (V=43.19 V, I=11.98 A, T_{on}=6.03 µs and T_{on}=7.83 µs). The corresponding value of *SR* and *PC* obtained are 5.97 μm and 1.28 kW respectively. From this table the shop floor engineers are able to select the optimum cutting conditions of desired *SR* value of component produced with minimum *PC*.

5. Conclusion

In this work, sustainable machining of Al7075-B_4C-flyash HMMNC using EDM is done for producing best product quality. The experimental results show that current and pulse-on-time are the main dominating parameter for all sustainability measures (i.e., *SR* and *PC*). The developed full quadratic modeling show good correlations and obtain an average error percentage of 3.76% and 3.97% for *SR* and *PC* respectively. The surface plot shows that increase in current and pulse-on-time, the spark energy and higher material removal causes wider and deeper craters. However, it develops poor surface finish. The prolonged duration of pulse on time (T_{on}) increases electrical load which in turn increases power consumption. The lower values of I and T_{on} provides minimum power consumption and smoother surface finish. GA optimization obtains 21 Pareto optimal fronts that helps shop floor engineers to select optimal combination of cutting conditions for any desired value of *SR* varying from 1.00 to 6.27 at which *PC* are minimum. The approach is found to be an effective tool and developed with minimum effort.

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