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ORIGINAL ARTICLE

Process modeling of hybrid machining system consisted of electro discharge machining and end milling

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Abstract This paper presents a novel hybrid machining process (HMP) that combines cutting action with machining using discharge pulses. Working conditions for a machine tool capable of combining micro-electro discharge machining (EDM) with milling is still an ill-defined problem relying on heuristics because there is insufficient knowledge of the discharge mechanism and the effects of machining parameters. The proposed HMP that combines micro-EDM and milling processes was applied to a steel alloy (AISI 1045) as the workpiece and end mill tungsten carbide as the tool electrode. Test results obtained from a number of experiments showed that the developed HMP yields reasonable machining time and surface roughness. Significant controlling variables for the machining response were identified and ranked using the Taguchi method. Furthermore, the response surface method was used to develop an empirical model based on the correlation between input variables and output responses.

Keywords EDM · Hybrid machining process · Milling · Surface response method · Taguchi method

1 Introduction

Recently, advanced technologies in manufacturing industries have demanded the efficient production of much more precise parts. However, traditional or nontraditional machining involving a single process cannot satisfy the present demand for simultaneous high quality and high efficiency.

Thus, a hybrid machining system that integrates several processes to meet the demand represents the current trend in manufacturing. A hybrid machine should make use of the combined or mutually enhanced advantages of the technologies used, and avoid or reduce any adverse effects that the constituent processes produce when they are applied individually. The performance improvement of the hybrid may be considerable and valuable [1].

Nontraditional machining technologies include ultrasonic machining, laser machining, electrochemical machining, and electro discharge machining (EDM) [1–3]. These technologies all involve various working mechanisms and yield various results. In view of the differences in the energy source, operation modes, and process characteristics, they have different applications and limitations.

Among these nontraditional methods of material removal, EDM has attracted much research attention because of its broad industrial applications. EDM is widely used in machining microstructures [3–5]. Despite its benefits, EDM suffers the drawbacks of being very slow and yielding poor surface quality because of the recast layer formed on the machined surface. This would affect the cost of production and the precision of the geometric shape.

A combination of machining processes can be considered as either a ‘hybrid machining process (HMP)’ approach, i.e., two or more processes utilized independently on a single machine, or an ‘assisted machining approach’, in which the two processes are used simultaneously [1]. Furthermore, many researchers have pointed out that EDM is more user-friendly because the gap between the electrode and the workpiece, which is called the gap state, is often used as an indicator of the state of the EDM process [2–5].

As opposed to conventional ED milling, which relies on the high rotation speed of the spindle [2], in the HMP (EDM

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together with milling process), an end mill tungsten carbide tool with two teeth was used on steel alloys (AISI 1045). The discharge pulses were carefully investigated to indicate the gap state during hybrid machining operations. The working conditions of a machine tool capable of combining EDM and milling is still an ill-defined problem relying on heuristics because of the lack of adequate knowledge of the discharge mechanism and the effects of machining parameters [4].

The effect ranks of the most significant controlling variables have been determined by using the Taguchi method in this research. The response surface method (RSM) was used to develop an empirical model that could exploit the correlation between the controlling factors, i.e., energy (E), spindle speed (S_s), feed rate per tooth ($F_{r/t}$), and aspect ratio (A_r) and the output responses, i.e., machining time (M_t) and surface roughness (Ra).

2 Experimental work

2.1 Experimental setup

Figure 1 demonstrates the structure of the developed hybrid machine. All experimental work was conducted on the same machine. The setup consists of an RC-type power supply for the EDM, a CNC miller, an electric flushing pump, and a high-frequency oscilloscope (200 MHz). In this process, EDM uses the RC-based circuit to generate a spark. The end mill tungsten carbide tool is rigidly fixed in the spindle, ensuring that it is straight and can rotate at a very high speed without wobbling. Kerosene was used as dielectric fluid in the experiments. The work materials used in the experimental work were steel alloys with dimensions 10×10×5 mm as shown in Table 1.

Table 1 Machining condition during HMP

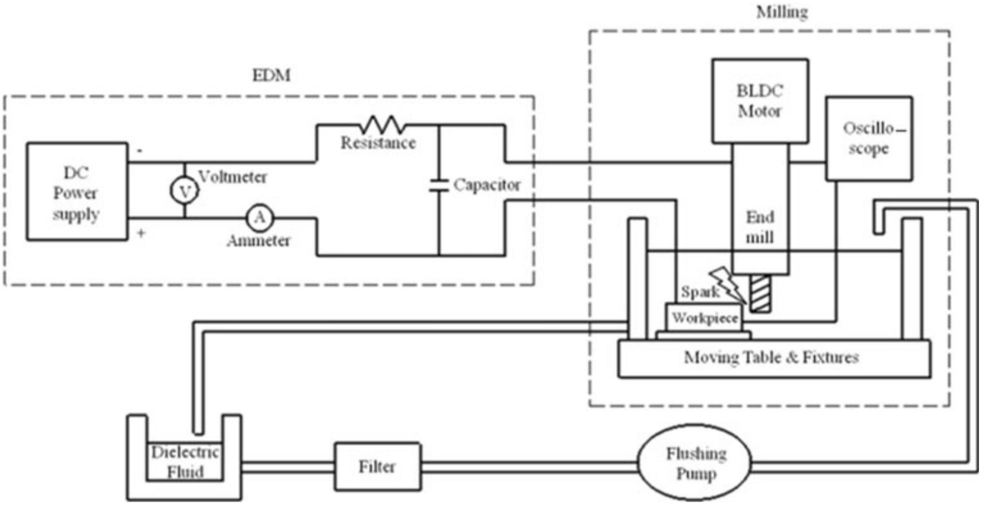
Workpiece material	AISI 1045
Workpiece size	10×10×5 mm
Tool material	Tungsten carbide (WC)
Tool diameter	1 mm
Tool type	End mill (two teeth)
Spindle speed	8,000–18,000 rpm
Depth of cut	500 μm
Width of cut	75–225 μm
Machining length	10 mm
Capacitance	10–1000 pF
Voltage	67.5 V
Feed rate	40–100 μm/s
Coolant fluid	Kerosene

2.2 Experimental procedure

The tool electrode was connected to the negative terminal of an RC-type power supply of direct current, while the workpiece was connected to the positive polarity. During the machining process, the rotating tool electrode was set to the required depth of cut (DOC) and width of cut (WOC), while the workpiece moved with a feed rate (F_r). In this work, the aspect ratio is defined as the ratio between width of cut and depth of cut (WOC/DOC).

This implies that for side cutting or machining, as the spindle rotates at a very high speed (8,000–18,000 rpm), the EDM action occurs when there is no contact between the end mill tool and the workpiece (an EDM gap is created and discharges are produced), in contrast to the milling action that occurs when the end mill tool makes physical contact with the workpiece as shown in Fig. 2. The very high rotation speed of the end mill tool also helps in flushing away the debris from the sparking zone.

Fig. 1 Hybrid machining setup



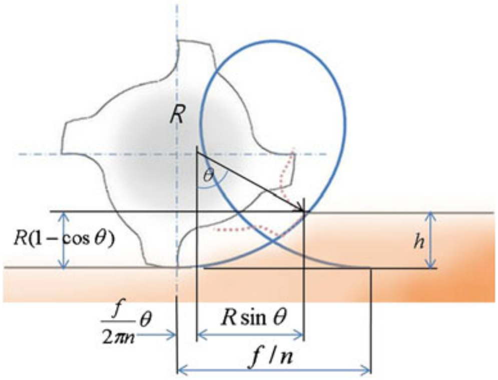


Fig. 2 End mill cutting mechanism

For each test, the gap state (discharge mechanisms) was observed using the oscilloscope. Care was taken to maintain consistent cutting tool and workpiece clamping throughout each machining operation to reduce variability in the dynamics of the machining system. The most significant parameters and correlation between controlling variables and output responses were analyzed using the Taguchi and response surface methods respectively. In the hybrid machining technique, the effects of other machining parameters such as flushing pressure and dielectric properties were kept constant in this study. The cutting conditions for HMP with two or four flutes are shown in Fig. 3, and the relationships between parameters are defined by Eqs. 1, 2, and 3.

$$\text{Noncontact period per revolution :} \quad r = 1 - \frac{n_t}{2\pi}\theta \tag{1}$$

$$\text{Contact angle :} \quad \theta = \cos^{-1}\left(1 - \frac{h}{R}\right) \tag{2}$$

$$\text{Immersion ratio :} \quad i_r = \frac{h}{R} \tag{3}$$

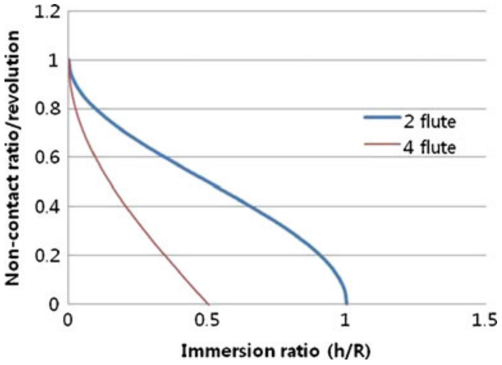


Fig. 3 Noncontact ratio according to the immersion ratio

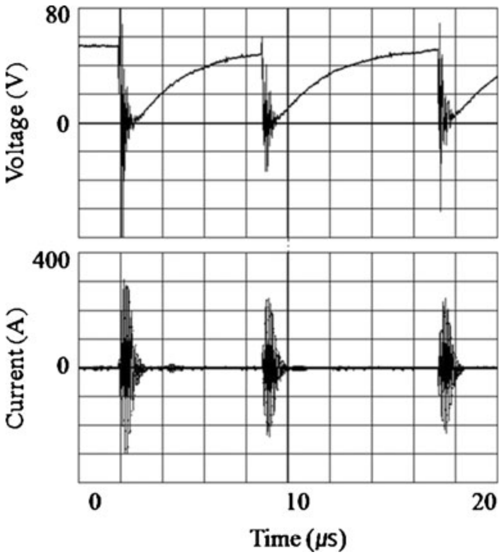


Fig. 4 Discharge pulses for the HMP

The gap state as an indicator of the HMP condition was investigated through measurement of the discharge pulses, and the results of the gap condition are shown in Fig. 4. The discharge pulses displayed by the oscilloscope were compared with those from previous studies that used RC-type and transistor isopulse power supplies for the EDM process [3, 4]. In this work, the gap state was more stable with the HMP and the process was thus more promising for improving machining time.

2.3 Design of experiment

The Taguchi approach and RSM via the MINITAB program have been used for the design of the experiment (DoE). An L9 (3^4) orthogonal array (four input variables with three levels as shown in Table 2) dictated 18 tests. The approach was very efficient because instead of doing the 162 (2×3^4) tests required for the factorial method, only 18 tests were required to establish the ranks of the most significant parameters to M_t and Ra. Moreover, the central composite approach for RSM dictated 60 tests (four input variables with five levels as illustrated in Table 3) to establish and validate the correlation between input factors (E, S_s, $F_{r/t}$, and A_r) and output responses (M_t and Ra).

Table 2 Level for L9 array

Factors	Low (−1)	Medium (0)	High (1)
Energy (μJ)	0.24	0.71	1.11
Spindle speed (rpm)	8,000	12,000	16,000
Feed rate/tooth (μm/min tooth)	2,500	3,500	4,500
Aspect ratio	0.15	0.3	0.45

Table 3 Level for RSM

Factors	−α (−1.41)	Low (−1)	Medium (0)	High (1)	α (1.41)
Energy	0.024	0.24	0.71	1.11	2.37
Spindle speed	11,000	12,000	14,000	16,000	18,000
Feed rate per tooth	1,500	2,500	3,500	4,500	5,000
Aspect ratio	0.12	0.15	0.3	0.45	0.5

3 Result and discussions

During each experiment, M_t was recorded accurately by the use of a digitizer recorder stop watch. A noncontact 3D micro surface profiler was used to measure Ra. From the experimental results in Table 4, the Taguchi method was used to establish the ranks of the most significant machining input factors for the HMP. Tables 5, 6, 7, and 8 illustrate results from the Taguchi method and the effect ranks of the machining factors for the output responses. Their ranks through analysis of the means and the signal-to-noise (SN) ratios are plotted in Figs. 5, 6, 7, and 8.

The experimental investigations ranked the spindle speed as the most effective factor in surface quality, as shown in Tables 5 and 6 and Figs. 5 and 6, while the feed rate per tooth is highest ranked for the machining time, as illustrated in Tables 7 and 8 and Figs. 7 and 8. The larger-is-better methodology was selected in the DoE for the machining variables against process responses because this characteristic involves continuously measurable results.

3.1 Effect of feed rate and spindle speed

It has been noted that the selected machining factors did not influence the HMP at the same level. According to the theories and experimental observations of the machining process, the feed rate and spindle speed effects remain fully valid in the HMP using end mill tools for side cutting/machining on steel alloys. The HMP demonstrated significant difference in the machining time and surface quality with changes in feed rate per tooth and spindle speed respectively. This results mainly from the effective tool geometry (Fig. 2) and corresponding cutting force variations.

Table 4 Taguchi method for M_t and Ra

Run no.	E (μJ)	S_s (rpm)	$F_{r/t}$ (μm/min t)	A_r	M_t (s)	Ra (μm)
1	0.24	8,000	2,500	0.15	126	1.38
2	0.24	12,000	3,500	0.30	96	0.83
3	0.24	16,000	4,500	0.45	71	0.57
4	0.71	8,000	3,500	0.45	92	4.66
5	0.71	12,000	4,500	0.15	69	0.93
6	0.71	8,000	2,500	0.30	130	1.67
7	1.11	16,000	4,500	0.30	71	2.50
8	1.11	12,000	2,500	0.45	128	0.56
9	1.11	16,000	3,500	0.15	92	0.72

3.2 Regression analysis for M_t and Ra

A mathematical and statistical technique (RSM) was used to model the relationship between the controlling factors and output responses. Quadratic polynomial regression equations, in terms of factors (Table 9), were derived to fit the experimental data.

Analysis of variance and the coefficient approach were used in the regression analysis. The models of M_t and Ra are shown in Eqs. 4 and 5. This technique was preferred because with other techniques such as the factorial method many tests are required, and a separate set of tests is required for each combination of machining variables. It is obvious that increasing the total number of tests increases the experimental cost and process time. Some of the test results are illustrated in Table 9.

$$\begin{aligned} M_t = {} & 293.484076 - 1.39425\,E + 7.75312 \times 10^{-3} S_S \\ & - 0.123416\,F_{r/t} + 59.3979\,A_r + 2.72675 \\ & \times 10^{-7}\,S_S^2 + 1.29972 \times 10^{-5}\,{F_{r/t}}^2 \\ & - 115.883\,A_r^2 + 6.2272 \times 10^3 \left(F_{r/t} \times A_r\right) \end{aligned} \tag{4}$$

$$\begin{aligned} Ra = {} & 12.425188 - 4.75097\,E + 4.62436 \times 10^{-4}\,S_s \\ & - 8.21727 \times 10^{-3}\,F_{r/t} - 1.67809\,A_r + 1.5761 \\ & \times 10^{-6}\,{F_{r/t}}^2 + 7.04093 \times 10^{-4}(E \times S_s) \\ & - 1.19515 \times 10^{-3}\left(E \times F_{r/t}\right) - 2.08 \\ & \times 10^{-7}\left(S_s \times F_{r/t}\right) \end{aligned} \tag{5}$$

Table 5 Response for Ra (SN ratios)

Level	E	S_s	$F_{r/t}$	A_r
1	−1.23	6.87	0.74	1.01
2	5.73	−2.43	2.97	1.67
3	0.02	0.07	0.82	1.93
Delta	6.97	9.30	2.23	0.92
Rank	2	1	4	3

Table 6 Response for Ra (Means)

Level	E	S_s	$F_{r/t}$	A_r
1	−1.23	6.87	0.74	1.01
2	5.73	−2.43	2.97	1.67
3	0.02	0.07	0.82	1.93
Delta	6.97	9.30	2.23	0.92
Rank	2	1	4	3

Table 7 Response for M_t (SN ratios)

Level	E	S_s	$F_{r/t}$	A_r
1	39.56	41.19	42.14	39.48
2	39.44	39.52	39.40	39.65
3	39.48	37.78	36.94	39.48
Delta	0.12	3.41	5.20	0.30
Rank	4	2	1	3

Table 8 Response for M_t (means)

Level	E	S_s	$F_{r/t}$	A_r
1	97.67	116	128	95.67
2	97	97.67	93	99
3	97	78	70.33	97
Delta	0.67	38	57.67	3.33
Rank	4	2	1	3

From Eqs. 4 and 5, M_t and Ra depend strongly on the selected input parameters (E, S_s, $F_{r/t}$, and A_r). To validate the developed models, the same procedure as was used to determine input data in Table 9 was used, but of course with different data. Experimental test results were compared with data generated (from the already established empirical models) through computer simulation using the MAPPLE program. Both results were plotted for comparison of the experimental and generated data, as illustrated by Figs. 9 and 10.

Both plots (Figs. 9 and 10) demonstrated that the results generated from the empirical models (Ra and M_t) reasonably correlated with those from the validating experiments. The regression statistic R^2 (adj.) was found to be 97.67 % for M_t and 76.32 % for Ra. Both percentage values of Ra and M_t indicated that the models presented in this work fit suitably with the HMP results.

In this paper, the hybrid machining results (Table 9) have been compared to the results reported by other EDM users and the improvement in term of machining time and surface quality is greatly reasonable with the HMP [6–10].

4 Conclusions and remarks

The experimental investigations revealed that the gap state as an indicator of machining conditions is more stable in the developed HMP. The system promises to satisfy demands for both high quality and high efficiency compared with EDM working individually. By using the Taguchi method, the most effective machining parameters have been ranked and may be employed to optimize the HMP. The mathematical and statistical models developed promise the potential to predict both M_t and Ra for various process parameter settings. The

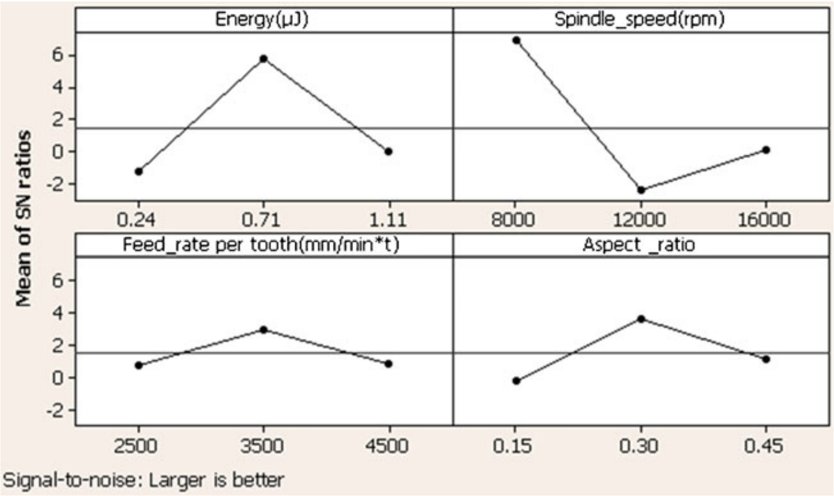


Fig. 5 Main effect for Ra (SN ratios)

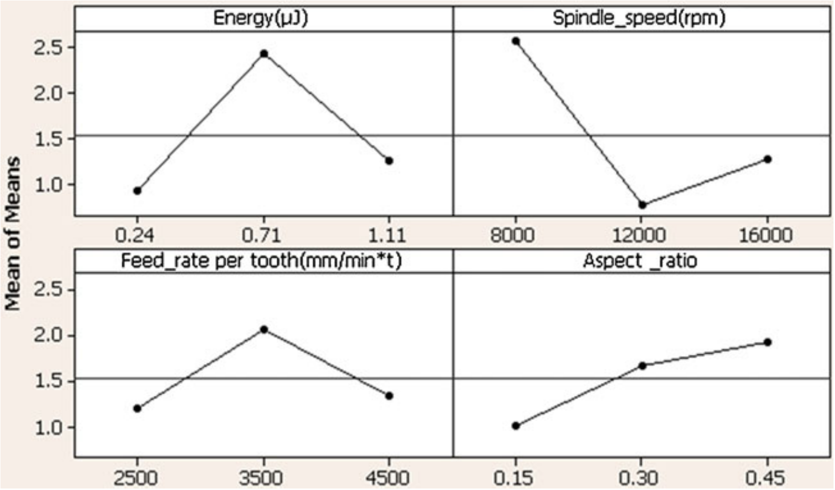


Fig. 6 Main effect for Ra (means)

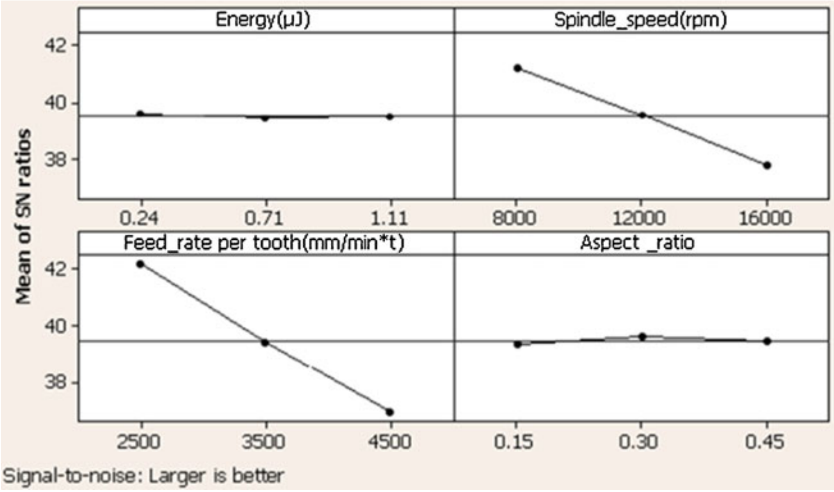


Fig. 7 Main effect for M_t (SN ratios)

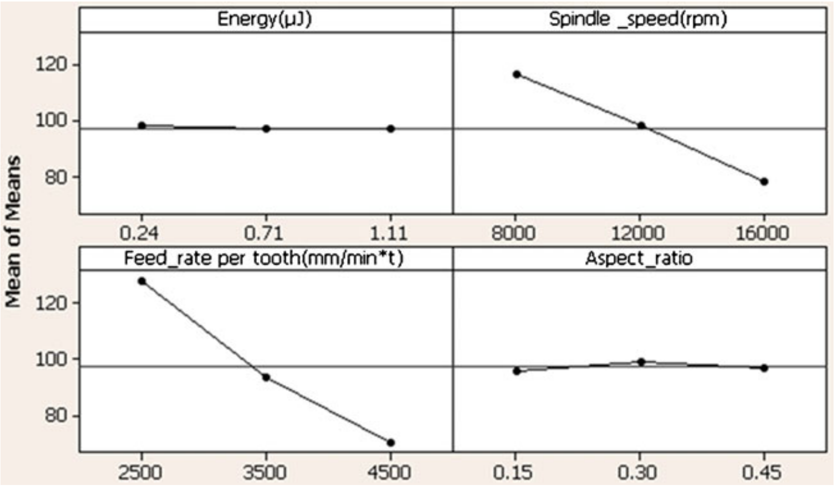


Fig. 8 Main effect for M_t (means)

Table 9 Results with the RSM for M_t and Ra

Run no.	E	S_r	$F_{r/t}$	A_r	E (μJ)	S_r (rpm)	$F_{r/t}$ (μm/s)	A_r	M_t (s)	Ra (μm)
1	1	−1	−1	−1	1.11	12,000	2,500	0.15	124	0.82
2	−1	1	−1	−1	0.24	16,000	2,500	0.15	129	0.72
3	−1	−1	1	−1	0.24	12,000	4,500	0.15	71	0.74
4	1	1	1	−1	1.11	16,000	4,500	0.15	67	1.47
5	−1	−1	−1	1	0.24	12,000	2,500	0.45	129	0.76
6	1	1	−1	1	1.11	16,000	2,500	0.45	124	4
7	1	−1	1	1	1.11	12,000	4,500	0.45	73	0.42
8	−1	1	1	1	0.24	16,000	4,500	0.45	76	0.77
9	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3
10	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3
11	−1	−1	−1	−1	0.24	12,000	2,500	0.15	126	0.84
12	1	1	−1	−1	1.11	16,000	2,500	0.15	126	5.66
13	1	−1	1	−1	1.11	12,000	4,500	0.15	65	0.47
14	−1	1	1	−1	0.24	16,000	4,500	0.15	69	0.51
15	1	−1	−1	1	1.11	12,000	2,500	0.45	129	0.52
16	−1	1	−1	1	0.24	16,000	2,500	0.45	129	0.45
17	−1	−1	1	1	0.24	12,000	4,500	0.45	72	0.56
18	1	1	1	1	1.11	16,000	4,500	0.45	72	0.65
19	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3
20	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3
21	−1.41	0	0	0	0.024	14,000	3,500	0.30	92	0.99
22	1.41	0	0	0	2.37	14,000	3,500	0.30	93	2.2
23	0	−1.41	0	0	0.71	11,000	3,500	0.30	92	1.19
24	0	1.41	0	0	0.71	18,000	3,500	0.30	91	1.37
25	0	0	−1.41	0	0.71	14,000	1,500	0.30	216	10.95
26	0	0	1.41	0	0.71	14,000	5,000	0.30	64	1.11
27	0	0	0	−1.41	0.71	14,000	3,500	0.12	90	2.56
28	0	0	0	1.41	0.71	14,000	3,500	0.50	94	1.1
29	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3
30	0	0	0	0	0.71	14,000	3,500	0.30	92	0.3

empirical models have been found to be unique, powerful, and flexible. In future work, an experimental comparative standardized model will be developed by which to evaluate the hybrid machining performance in comparison with the EDM individually. The empirical model will be useful to manufacturing industries and companies when making critical decisions because it is applicable to all three machining approaches: EDM, milling, and HMP.

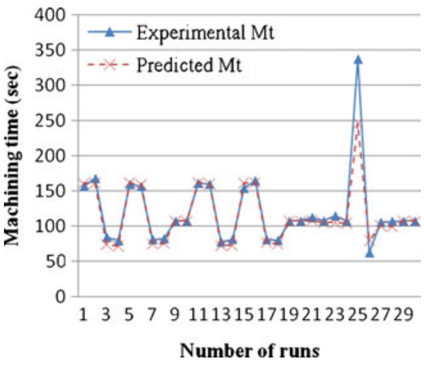


Fig. 9 Plot for validation of the M_t

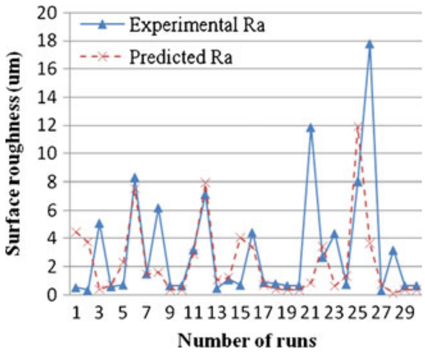


Fig. 10 Plot for validation of the Ra

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