Parametric optimization of laser micro milling process parameters of Hastelloy C276 using TOPSIS method

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Abstract: Laser micro machining is well recognized non – conventional machining process among various advanced machining processes. For advanced engineering applications micromachining of engineering materials has an extensive demand in the fields of automotive, electronics, biomedicine, aerospace. In the present research, a multi response optimization technique TOPSIS method was adopted to analyze the process variables of Laser micro-milling of Hastelloy C276. In the current study Scanning speed (v), Pulse intensity (PI), Pulse frequency (PF) and Pulse duration (PD) were considered as process parameters to achieve the output characteristics such as surface roughness (Ra) and milling depth (MD). Based on the machining conditions, Taguchi's L27 orthogonal array of designed experiments were used in order to optimize the process variables in laser micro-milling.

Keywords — ***Laser Micro-Milling, Optimization, Hastelloy C276, surface roughness, milling depth, TOPSIS .***

I. INTRODUCTION

The micro-manufacturing processes are a growing area and have found widespread use in a variety of applications, such as biomedical devices, which represent a niche market, thereby creating a need to find alternative processes to manufacture these components with low cost, high accuracy and high quality surface finishing.

Laser-energy beam processing is widely used for cutting, drilling, scribing, marking, welding, sintering and heat treatment applications. Computer numerically controlled machining systems based on laser beams, also called laser milling systems, have become commercially available in recent years. Further developments in pulsed laser techniques and systems have increased the applicability of laser milling technology in production systems. Hence, it has become a viable alternative to conventional methods for producing complex and micro-features on difficult-to-process materials and is being employed increasingly in industry because of its known advantages. Productivity enhancement can be possible by running the experiments at optimum process parameters. In the literature, researchers put efforts and discovered few optimization techniques with simple steps such as Taguchi method[1, 2], Gray relational analysis [3-8] and **TOPSIS** [9-10]. Recently, a few attempts were done in mahining operation using optimization methods as follows.

Nayak and Mahapatra [11] carried out experimental work on wire electrical discharge machining and multi – response optimization is done using the AHP and TOPSIS method. In their investigation discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow rate each at three levels are considered as process variables whereas material removal rate, surface roughness and kerf were recorded as performance characteristics. Temucin et al. [12] used fuzzy based decision model for nontraditional machining process selection. In their study ELECTRE I, TOPSIS, PROMETHEE II, as well as Fuzzy ELECTRE I and Fuzzy TOPSIS based on the hybrid DSS were used to rank alternative machining technologies for the cutting process of carbon structural steel with the width of plate of 10mm. Yuvaraj and Pradeep Kumar [13] carried out experiments on aluminum alloy AA5083-H32 based on L_{27} orthogonal array and Optimized Abrasive Water Jet Cutting Process Parameters using TOPSIS Method. At the end of their investigation optimized results were obtained with the combination of input process variables such as water jet pressure of 300MPa, traverse rate of 120mm/min, abrasive flow rate of 360 g/min, and standoff distance of 1mm. Marzban and Ghaseminejad [14] carried out experiments on

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AISI 1040. L9 taguchi design was used to study effects of process parameters on output characteristics. In their investigation TOPSIS method integrated with principal component analysis was used for multi-responses optimization of laser cladding process. At the end their study they stated that the laser power has greatest influence on laser cladding quality characteristics. Manivannan and Pradeep Kumar [15] investigated the Multi-response optimization of Micro-EDM process parameters on AISI304 steel using TOPSIS. In their investigation L_9 orthogonal experimental design was used. At the end of their study it was observed that the feed rate exerts a greater influence on the hole quality. The identified optimal level of process parameter setting was maintained at a feed rate of 4 µm/s, a current of 10 A, a pulse on time of 10 µs, and a gap voltage of 10 V. Prabhu and Vinayagam [16] investigated the Multiresponse Optimization of EDM Process with Nano fluids using TOPSIS Method And Genetic Algorithm. In their investigation it was observed that the effect of pulse voltage for the combined response is most significant. The optimum process parameters are pulse current 8 A, pulse duration 5 µs and pulse voltage 80 V. Khan and Maity [17] used MCDM-based TOPSIS Method for the Optimization of Multi Quality Characteristics of Modern Manufacturing Processes. At the end their study they stated that it can provide more accurate evaluation of the alternatives. On the other hand, the proposed method is computationally very simple, understandable and robust, which can be used with a large number of input and output parameters. Tripathy and Tripathy [18] carried out experiments on H-11 die steel in order to optimize the powder mixed electro-discharge machining using grey relational analysis and topsis. In their study parameters like powder concentration, peak current, pulse on time, duty cycle and gap voltage were chosen as input parameters and output characteristics i.e MRR, tool wear rate, electrode wear ratio, and surface roughness were recorded. They have found that the TOPSIS approach provides superior results than the grey relational approach. Shivakoti et al. [19] used Fuzzy TOPSIS-Based Selection for optimizing the Laser Beam Micro-Marking Process Parameters. From their investigation it was observed that a small pulse frequency and high current and scanning speed lead to increase in mark intensity. Parthiban et al. [20] used TOPSIS based parametric optimization of laser micro-drilling of TBC coated nickel based superalloy. In their investigation L_8 orthogonal design was used for conducting experiments. At the end of their study it was observed that the holes drilled at an inclination angle of 45^0, laser scan speed of 3 mm/s and 400 number of passes found to be optimum. The optimized parameter combination exhibited a 19% improvement in surface finish and 12% reduction in surface crack density. Ananthakumar et al. [21] investigated the optimization of multi-response characteristics in plasma arc cutting of Monel 400™ using RSM and TOPSIS. In their investigation Material removal rate, kerf taper and heat affected zone were recorded as performance characteristics whereas arc current, cutting speed, stand-off distance and gas pressure were taken as the input process variables. At the end their study, stated that the most influencing parameters on MRR and HAZ, whereas KT primarily affected with cutting speed.

From the existing literature, it was stated that many researchers had attempted to optimize the process parameters of laser micro-machining by using single response optimization such as Taguchi method and Grey relational analysis. Multi-criteria decision making approach like TOPSIS has not yet been implemented to find the optimal setting during Laser micro-machining of nickel based super alloy. Hence, this study intended to focus on the parametric optimization of Laser micro-machining process variables such as Scanning speed, Pulse intensity, Pulse frequency and Pulse duration to enhance the Performance characteristics such as Milling Depth and Surface Roughness on nickel based super alloy.

II. METHODOLOGY

TOPSIS namely Technique for Order Preference by Similarity to an Ideal Solution is a method to solve the problems with multiple responses. Firstly, Hwang and Yoon were introduced this technique in 1981. The concept involved in this technique is that identifying best alternate solution which is at the shortest distance from positive ideal solution and farthest from negative ideal solution. Based on the quality characteristic of the objective function considered either maximization or minimization beneficiary criteria is controlled with help of ideal solution either positive or negative respectively. Any solution that maximizes beneficiary criteria is called as ‘Positive natured ideal solution’ whereas minimizes beneficiary criteria is called ‘Negative ideal solution’. In the present work, maximization of Milling Depth and minimization of surface roughness (SR) are considered as objective functions. The methodology involved in the work is shown below.

The TOPSIS technique solves the problem in a succession of six steps as follows:

Step-1: Calculation of normalized decision matrix.

$$r_{ij} = x_{ij}\sqrt{\sum_{i-1}^{m} x_{ij}^{2}} \quad \text{i =1, 2, ..., m and j = 1, 2, ..., n.} \quad \textbf{(1)}$$

Where, r_{ij} is called normalized value.

Step-2: Evaluation of weighted normalized decision matrix.

$$v_{ij} = r_{ij} \times w_j \qquad \textbf{(2)}$$

Where, i =1, 2,..., m. and j = 1, 2, ..., n.

v_{ij} = weighted normalized value

w_j = weight of the jth attribute

$$\text{and } \sum_{j=1}^{n} w_j = 1$$

Step-3: Determine the the positive ideal solution (V^+) is for the best possible value and the negative ideal solution(V^-) worst value of each and every attribute from the weighted decision matrix which are determined as follows.

$V^+ = (V_1^+ \ldots\ldots\ldots V_m^+)$ Maximum values.

$V^- = (V_1^- \ldots\ldots\ldots. V_m^-)$ Minimum values.

Step-4: Calculate Euclidean distance separation measures i,e. separation measures of each alternative from the positive ideal solution and the negative ideal solution using the following formulae.

$$S_i^* = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^*)^2},\ j = 1,2,\ldots,m \qquad (3)$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^-)^2},\ j = 1,2,\ldots,m \qquad (4)$$

Step-5: Calculation of relative Closeness Co-efficient to the ideal solution using the following formula.

$$CC_i^* = \frac{S_i^-}{S_i^* + S_i^-},\ i = 1,2,\ldots,m \qquad (5)$$

Step-6: Rank the preference order and segregate either ascending or descending according to requirement.

III. EXPERIMENTAL WORK

Hastelloy C276 have attractive mechanical and chemical properties, was selected as workpiece in the present due to their extensive usage in the fields of aerospace and chemical processing industries. Table 1 depicts chemical composition of the workpiece material. In this work, laser micro machining process such as 'v', 'PI', 'PF' and 'PD' were considered as inputs. A top layers of 1 mm material have been removed from the purchased workpiece and applied etchant on it to minimize the flaws, dirt, etc. Experiments were carried on this material using Femtosecond laser micromachining process according to the Taguchi L27 OA design. Each experiment is run for 10 mm length. Figure 1 depicts the experimental equipment and machining operation. Taguchi design assists in controlling the experimental cost and efforts required to perform experiments. In this work, machinability indices such as 'Ra' and 'MD' were taken. After conducting experiments, machined product is kept under the confocal microscope and measured the 'Ra' and 'MD' outputs. Both 'Ra' and 'MD' measured three times at three different locations on the machined product and average is considered as final value. Table 2 list the obtained results.

Table 1 The Chemical Composition of Hastelloy C276.

Element	%weight
Ni	57
Co	2.5
Cr	16
Mo	16
Fe	5
W	4
Mn	1
V	0.35
Si	0.08
C	0.01
Cu	0.5

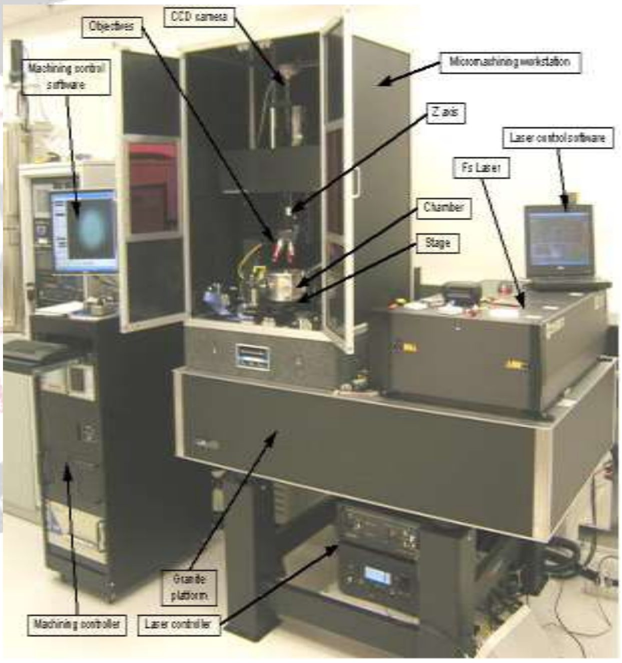

Figure 1 Femtosecond laser micromachining equipment.

Table 2 L_{27} Orthogonal array with experimental responses.

	Input Process parameters				**Quality Characteristics (avg.)**	
Exp. No	**Scanning speed(mm/sec)**	**Pulse intensity (%)**	**Pulse frequency (KHz)**	**Pulse duration (µs)**	**Surface Roughness (µm)**	**Milling Depth (µm)**
1	300	80	30	2	4.258	91.08

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2	300	80	35	4	3.169	85.32
3	300	80	40	6	2.426	85.75
4	300	85	30	4	3.547	67.47
5	300	85	35	6	3.646	73.76
6	300	85	40	2	2.353	82.73
7	300	90	30	6	3.413	64.78
8	300	90	35	2	3.457	74.25
9	300	90	40	4	1.885	74.91
10	350	80	30	2	3.589	60.49
11	350	80	35	4	3.505	58.51
12	350	80	40	6	2.099	62.76
13	350	85	30	4	3.196	54.49
14	350	85	35	6	2.396	65.57
15	350	85	40	2	2.304	65.97
16	350	90	30	6	2.503	52.54
17	350	90	35	2	2.484	56.49
18	350	90	40	4	1.869	70.59
19	400	80	30	2	2.549	39.42
20	400	80	35	4	2.825	48.51
21	400	80	40	6	2.154	54.52
22	400	85	30	4	2.292	35.79
23	400	85	35	6	1.878	49.96
24	400	85	40	2	1.71	61.05
25	400	90	30	6	2.019	44.51
26	400	90	35	2	2.466	58.79
27	400	90	40	4	1.15	62.68

IV. RESULTS AND DISCUSSIONS

The two major output responses Surface roughness (R_a) and Milling depth (MD) are normalized and shown in Table 3. For present work weightages for both the responses surface roughness and milling depth is taken as 0.5 that is, W_{Ra} = 0.5 and W_{MD} = 0.5. With respect to weight criteria the relative normalized weight matrix is evaluated. These weightages multiplied to obtain the normalized weighted matrix and it is shown in Table 4. The positive ideal and negative ideal solutions are evaluated based on normalized weighted matrix. The obtained positive, negative ideal solutions are shown in Table 5.

Table 3 Normalized Matrix.

Exp. No	Surface roughness	Milling depth
1	0.2998	0.2716
2	0.2231	0.2544
3	0.1708	0.2557
4	0.2497	0.2012
5	0.2567	0.2199
6	0.1656	0.2467
7	0.2403	0.1932
8	0.2434	0.2214
9	0.1327	0.2234
10	0.2527	0.1804
11	0.2468	0.1745
12	0.1477	0.1871
13	0.2250	0.1625
14	0.1687	0.1955
15	0.1622	0.1967
16	0.1762	0.1567
17	0.1749	0.1684
18	0.1316	0.2105
19	0.1794	0.1175
20	0.1989	0.1446
21	0.1516	0.1626
22	0.1613	0.1067
23	0.1322	0.1490
24	0.1204	0.1820
25	0.1421	0.1327
26	0.1736	0.1753
27	0.0809	0.1869

Table 4 Weighted Normalized Matrix.

Exp. No	Surface roughness	Milling depth
1	0.1499	0.1358
2	0.1115	0.1272
3	0.0854	0.1278
4	0.1248	0.1006
5	0.1283	0.1099
6	0.0828	0.1233
7	0.1201	0.0966
8	0.1217	0.1107
9	0.0663	0.1117
10	0.1263	0.0902
11	0.1234	0.0872
12	0.0738	0.0935
13	0.1125	0.0812
14	0.0843	0.0977
15	0.0811	0.0983
16	0.0881	0.0783
17	0.0874	0.0842
18	0.0658	0.1052
19	0.0897	0.0587
20	0.0994	0.0723
21	0.0758	0.0813
22	0.0806	0.0533
23	0.0661	0.0745
24	0.0602	0.0910
25	0.0710	0.0663
26	0.0868	0.0876
27	0.0404	0.0934

Table 5 Ideal Best and Ideal worst solutions.

	Surface roughness	Milling depth
V^+	0.0404	0.1358
V^-	0.1499	0.0533

From ideal, positive and negative ideal solutions separation measures are evaluated using (3) and (4), shown in Table 6. Finally, step is that evaluation of relative closeness coefficient (CC*i*) values for each combination of factors of machining process using (5). The Evaluated closeness coefficients are shown in Table 7. Whichever contains maximum closeness coefficient that gives the optimized combination of results. From Table 2. it is observed that the milling depth ranges from 44.51 to 91.08 µm. Specifically, for experiment number 9 which represents a set of input process variables Scanning speed 300mm/sec, Pulse intensity 90%, Pulse frequency 40KHz and Pulse duration

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4μs produces milling depth about 74.25μm with good closeness coefficient 0.7423. Separately, Surface quality is 1.15μm which is minimum for last experiment. Surface roughness obtained for optimized combination is 1.885μm.

Table 6 Eucledian Distance from Ideal best and worst.

Exp. No	S^+	S^-
1	0.1094	0.0824
2	0.0716	0.0832
3	0.0456	0.0985
4	0.0914	0.0534
5	0.0915	0.0605
6	0.0441	0.0969
7	0.0888	0.0524
8	0.0850	0.0639
9	0.0353	0.1018
10	0.0972	0.0437
11	0.0960	0.0430
12	0.0538	0.0859
13	0.0903	0.0466
14	0.0580	0.0791
15	0.0552	0.0822
16	0.0746	0.0666
17	0.0697	0.0696
18	0.0396	0.0988
19	0.0914	0.0604
20	0.0866	0.0539
21	0.0649	0.0791
22	0.0917	0.0692
23	0.0664	0.0864
24	0.0489	0.0972
25	0.0758	0.0798
26	0.0668	0.0718
27	0.0423	0.1165

Table 7 Closeness Coefficients and their Ranks.

Exp. No	Closeness Coefficients	Rank
1	0.4297	18
2	0.5375	12
3	0.6835	5
4	0.3689	24
5	0.3981	20
6	0.6871	4
7	0.3714	23
8	0.4291	19
9	0.7423	1
10	0.3101	26
11	0.3092	27
12	0.6149	7
13	0.3404	25
14	0.5769	9
15	0.5980	8
16	0.4716	16
17	0.4996	15
18	0.7135	3
19	0.3978	21
20	0.3834	22
21	0.5492	11
22	0.4300	17
23	0.5652	10
24	0.6653	6
25	0.5128	14
26	0.5179	13
27	0.7334	2

ANOVA is performed to identify the significant level of each input parameter and its effect on the multi-response characteristics of micro machining. ANOVA test is conducted with a confidence level of 95% and a insignificant level of 5%. Table 8 and 9 shows results of ANNOVA for surface roughness and milling depth respectively.

Table 8 Results of ANNOVA for Surface Roughness.

Source of process	DOF	Adj SS	Adj MS	F	P Value
SS	2	4.6206	2.31029	5.34	0.015
PI	2	1.6027	0.80135	1.85	0.185
PF	2	0.2131	0.10653	.25	0.784
PD	2	0.0187	0.00936	0.02	0.979
Error	18	7.7819	0.43233		
Total	16	14.2369			

Table 9 Results of ANNOVA for Milling Depth.

Source of process	DOF	Adj SS	Adj MS	F	P Value
SS	2	3397.52	1698.76	27.91	0.000
PI	2	59.31	29.65	0.49	0.622
PF	2	121.18	60.59	1.00	0.389
PD	2	362.57	181.28	2.98	0.076
Error	18	1095.76	60.88		
Total	16	5036.32			

V. CONCLUSION

The scope for present work was the optimization of process variables in Laser micro milling of nickel based super alloy using TOPSIS. Optimization using TOPSIS methodology was performed successfully in order to control the Laser Micro Milling process. The process variables investigated in this work are Scanning speed, Pulse intensity, Pulse Frequency and Pulse duration. From present work following conclusions are drawn.

- The optimized combination of process variables are Scanning speed 300mm/sec, Pulse intensity 90%, Pulse frequency 40KHz and Pulse duration 4μs.
- The Maximum milling depth 91.08 μm is obtained at 300mm/sec, Pulse intensity 80%, Pulse frequency 30KHz and Pulse duration 2μs.

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- The better surface quality 1.15μm is obtained at 400mm/sec, Pulse intensity 90%, Pulse frequency 40KHz and Pulse duration 4μs.

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