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Optimization of Kerf Width, MRR and Surface Roughness of H-11 Material Machined with Wire Cut EDM Process Using Grey Relation Analysis

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***Abstract*—**In this study, the effects of cutting parameters on kerf width, MRR and surface roughness were experimentally investigated in WEDM. H-11 hot die tool steel was selected as the work material to conduct experiments. The factors selected for the optimization are the pulse on time, pulse off time, flushing pressure, wire tension, servo voltage and wire feed rate each of the factors in three different levels. An optimal parameter combination of the WEDM process was obtained by applying the grey relational analysis (GRA). Also, the analysis of variance (ANOVA) was carried out for finding out the contribution and the effects of machining parameters on the multiple performance characteristics (MPC).

A Taguchi design of experiment (DOE) approach with L27 Orthogonal Array employed to conduct this experiment. Design Expert 8.0.6.1 software was used to perform the ANOVA (analysis of Variance) and confirmation test conducted to verify as well as compare the results from the theoretical prediction using software. And this research work develops new software tools in Visual basic-6.0. a. Develop scalar measurement software tool for measurement of kerf width b. ANOVA Analyzer software tool for analysis of variance.

Keywords- *WEDM, ANOVA, MRR, KW, Grey relational analysis.*

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I. INTRODUCTION *(HEADING 1)*

The selection of cutting parameters for obtaining higher cutting efficiency or accuracy in WEDM is still not fully solved, even with the most up-to-date CNC WEDM machine. This is mainly due to the nature of the complicated stochastic process mechanisms in wire-EDM. As a result, the relationships between the cutting parameters and the process performance are hard to achieve accurately [1]. There is still lack of research on WEDming of material such as chromium based tool steel which include H-11. The hot die steel H-11 is extensively used for Hot-work forging, Extrusion, Manufacturing punching tools, Mandrels, Mechanical press forging die, Plastic mould, Die-casting dies, Aircraft landing gears and Helicopter rotor blades and shafts, etc. applications which are classified as difficult to machine material by conventional method due to high cutting temperature and rapid tool wear [2].

In this study, grey-based Taguchi method for minimizing the kerf width, MRR and surface roughness were used. Experiments were performed under different cutting condition, such as pulse on time, pulse off time, flushing pressure, wire tension, servo voltage and wire feed rate. The kerf width of the machined workpiece are measured and analyzed through Taguchi and GRA to determine the optimal parameters in WEDM process.

II. EXPERIMENTAL PROCEDURE

A. *Material specification*

Wire-cut EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. H-11 is a Die tool steel. This can be used in the toughened condition. H-11 offers high corrosion resistance, wear strength and high hardness. The chemical composition tested at Malguru Trading co, Kadi of the selected work material is shown in Table I.

TABLE I. MATERIAL SPECIFICATION: H11

Chemical	Obtained Value	Required Value
Carbon	0.39	0.32 - 0.45
Chromium	5.12	4.75 - 5.5
Manganese	0.35	0.2 - 0.5
Molybdenum	1.7	1.1 - 1.75
Phosphorus	0.03	0.03 max
Silicon	1.1	0.8 - 1.2
Sulphur	0.02	0.03 max
Vanadium	0.95	0.8 - 1.2

H-11 Material generally used in Hot-work forging, Extrusion, Manufacturing punching tools, Mandrels, Mechanical press forging die, Plastic mould, Die-casting dies, Aircraft landing gears, Helicopter rotor blades and shafts, etc

B. *Number of reading optimization based on Taguchi method*

Control factors along with their levels are listed in Table 2. Full factorial design of experiments would require a large no. of runs; Hence Taguchi based design of experiment method was implemented. In Taguchi method Orthogonal Array provides a set of well balanced experiments, and Taguchi's signal-to-noise. (S/N) ratios, which are logarithmic functions of the desired output, serve as objective functions for optimization. It helps to learn the whole parameter space with a minimum experimental runs. Taguchi replaces the full factorial experiments with a lean, less expensive, faster partial factorial

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experiment. L27 Orthogonal array obtain based on the control factors.

TABLE II. MACHINING PROCESS LEVEL MACHINING PROCESS

Machining process Parameter		Level		
		1	2	3
A	Pulse On Time (µs)	110	120	130
B	Pulse Off Time (µs)	40	50	60
C	Flushing Pressure (kgf/cm2)	10	12	14
D	Wire Tension (gms)	660	900	1140
E	Servo Voltage (volts)	20	30	40
F	Wire Feed Rate(m/min)	4	8	12

C. Experimental setup

In this Experiment carried out by varying six control factors on Ultracut f1 machine of Electronica Pvt. Limited. Molybdenum coated brass wire of 0.25 mm diameter was used.

D. Specimen detail

Total 27 nos. of experiments has been carried out by slit on rectangle plate 30cm x 6cm x 1.2 cm of H-11 material. Peak current selected as constant. Specimen after machining for each thickness level shown in fig 1. Mass of material removal is calculated based on mass difference and theoretically based on kerf width. MRR is calculated based on it in mm3 /min. Surface roughness measured precisely with help of roughness tester Mitutoyo SJ-201P.

Figure 1. Work piece

Figure 2. Work piece photograph after machining

E. Machining characteristic

This study investigates the machining characteristics such as kerf width, surface roughness and material removal rate. These are the most common key indicators used by many manufacturers.

1) Kerf width

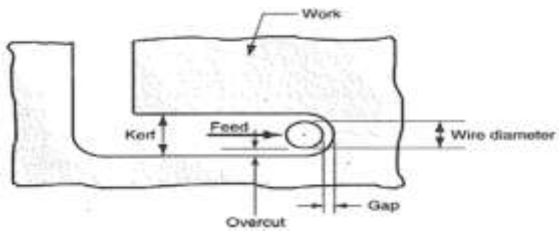

Figure 3. (a) Definition of kerf and over cut in WEDM [1]

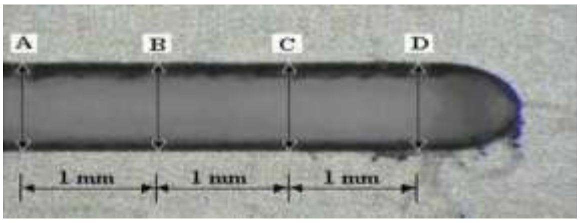

Figure 3. (b) Kerf width measurement positions A, B, C and D

Spark gaps in WEDM make the kerf larger than the wire diameter as shown in Fig. 3.

The kerf width measurements were taken at four positions A, B, C and D, as shown in figure below and the average value of these measurements was recorded as the kerf width of this cut. The kerf width varied over the length of the cut and measurements were taken at the leading (end of cut) and trailing (start of cut) positions on the cut. Both the top and bottom surfaces kerf width were measured. Kerf width which is measured by varies method.

A. Profile projector

B. Digital computer rise microscope

C. The kerf width measurement are taken from the cut kerf photographs using the UTHSCSA Image Tool Version 3.0 program

In all three methods some constrained is there. So in this research work develop a new software tool named ―Scalar Measurement‖ for measurement for kerf width. And this software developed by VB 6.0 languages. And this GUI screenshot is shown in fig. 4.

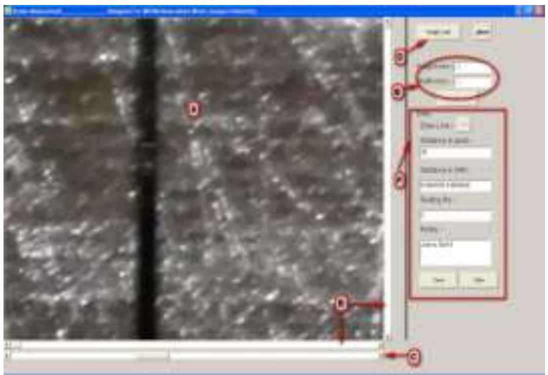

Figure 4. GUI of Scalar measurement software

Where,

A is picture load screen (picture box)
B is vertical and horizontal scrollbar
C is zoom in-zoom out bar
D is image load button
E is picture size (addable)
F is reading display (with saving button)

2) Material removal rate

MRR measured by two varies method such as on weight base and kerf width base.

a) Based on kerf width method b) Based on Wight method

Precision balance was used to measure the weight of the work piece before and after the machining process. In this Research part, choose a kerf width base method.

3) Surface roughness

Surface topography or surface roughness, also known as surface texture are terms used to express the general quality of a machined surface, which is concerned with the geometric irregularities and the quality of a surface [2]. Surface Roughness measure as the arithmetic average, Ra (μm). The Ra value, also known as centre line average (CLA) and arithmetic average (AA) is obtained by averaging the height of the surface above and below the centre line. The Ra will be measured using a surface roughness HOMMEL TESTER T500. The Ra values of the WEDMed surface were obtained by averaging the surface roughness values of 5 mm measurement length.

III. GREY RELATIONAL ANALYSIS

A. Optimization terminology

Optimization is the process of finding the minimum or maximum of a function by systematically choosing the values of the variables from within an allowed set. The function which has to be optimized is called the objective function and the variables on which the objective function depends are called the parameters. The possible set of values of the parameters forms the search space. In addition if there are any constraints then they must also be satisfied by the optimum solution.

Optimization can be considered to be a search process wherein we are interested in finding that particular solution (out of the entire search space) which makes the objective function minimum or maximum. Classical optimization methods are primarily of two types: direct and gradient based search methods. In direct search methods, only objective function and constraint values are used to guide the search strategy, where as gradient-based methods use the first and/or second-order derivatives of the objective function and/or constraints to guide the search process [3].

Optimization of machining parameters not only increases the utility for machining economics, but also improves the product quality to a great extent. Taguchi method is a systematic application of design and analysis of experiments to improve product quality and process. In recent years, the Taguchi method has also become a powerful tool for improving productivity during research and development [4-9]. Taguchi method has a limitation that it can be used to optimize a single performance characteristic.

The usual recommendation for the optimization of a process with multiple performance characteristics is left to engineering judgment and verified by confirmation experiments [10-15].

In Wire electrical discharge machining (WEDM) process, material removal rate is a higher-the-better (HB) performance characteristic. However, surface roughness is a lower-the-better (LB) performance characteristic and kerf width is a lower-the-better (LB) performance characteristic. The use of Taguchi method with the grey relational analysis can simplify the optimization of process parameters for multiple performance characteristics [11]. In this work, the orthogonal array with the grey relational analysis is used to investigate the multiple performance characteristics in the EDM process.

In grey relational analysis, grey relational coefficient for different process characteristics is calculated and average of these coefficients is called grey relational grade which is used as a single response for the Taguchi‘s experimental plan. The procedure of multiple performance characteristics optimization using grey relational analysis has been illustrated in Fig. 5.

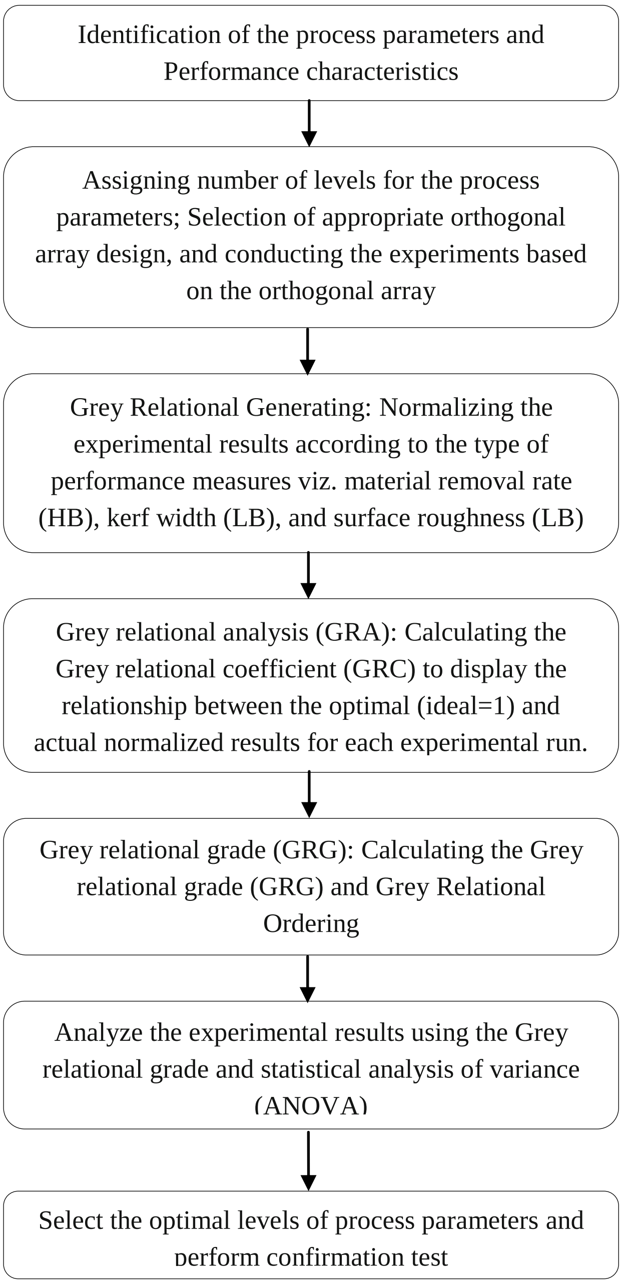

Figure 5. Flow chart for the experimental analysis [14]

B. Analysis of method:

1) Signal-to-noise ratio

Taguchi method is one of the simplest and effective approaches for parameter design and experimental planning [15]. In this method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value (S.D.) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the S.D.

There are three types of S/N ratio depending on the type of characteristics — the lower the better, the higher the better, and the nominal the better.

The S/N ratio with a “the lower the better” characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} y^2{}_{ij}\right) \tag{1}$$

The S/N ratio with a “the nominal the better” characteristic can be expressed as :

$$\eta_{ij} = -10\log\left(\frac{1}{ns}\sum_{j=1}^{n} y^2{}_{ij}\right) \tag{2}$$

The S/N ratio with a “the higher the better” characteristic can be expressed as [72]:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y^2{}_{ij}}\right) \tag{3}$$

where y_{ij} is the i^{th} experiment at the j^{th} test, n is the total number of the tests and s is the standard deviation. Regardless of category of the performance characteristics, a greater η value corresponds to a better performance.

2) Data pre-processing

In grey relational analysis, the function of factors is neglected in situations where the range of the sequence is large or the standard value is enormous. However, this analysis might produce incorrect results if the factors, goals and directions are different. Therefore, one has to pre-process the data which are related to a group of sequences, which is called “Grey relational generation” [6]. Data preprocessing is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range between zero and one. The normalization can be done from three different approaches [7].

If the target value of original sequence is infinite, then it has a characteristic of “the larger the better”.

The original sequence can be normalized as follows:

$$x_i^*(k) = \frac{x_i^*(k) - \min x_i^o(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{4}$$

If the expectancy is “the smaller the better”, then the original sequence should be normalized as follows:

$$x_i^*(k) = \frac{\max_i^0(k) - x_i^o(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{5}$$

However, if there is a definite target value to be achieved, the original sequence will be normalized in the form:

$$x_i^*(k) = 1 - \frac{\left|x_i^0(k) - x^0\right|}{\max x_i^0(k) - x^0} \tag{6}$$

or the original sequence can be simply normalized by the most basic methodology, i.e. let the values of original sequence be divided by the first value of sequence:

$$x_i^*(k) = \frac{x_i^0(k)}{x_i^0(1)} \tag{7}$$

Where $x_i^*(k)$ is the value after grey relation generation (data pre-processing), max $x_i^0(k)$ is the largest value of $x_i^*(k)$, min $x_i^0(k)$ is the smallest value of $x_i^*(k)$ and x^0 is the desired value.

3) Grey relational coefficient and grey relational grade

Following data pre-processing, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The Grey relational coefficient can be expressed as follows [7]:

$$\xi_i(k) = \frac{\Delta_{\min} + \varsigma.\Delta_{\max}}{\Delta_{oi}(k) + \varsigma.\Delta_{\max}} \tag{8}$$

Where $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$, namely,

$$\Delta_{0i}(k) = \left\|x_0^*(k) - x_i^*(k)\right\|,$$

$$\Delta_{\max} = \max_{\forall j\varepsilon i}\max_{\forall k}\left\|x_0^*(k) - x_i^*(k)\right\|,$$

$$\Delta_{\min} = \min_{\forall j\varepsilon i}\min_{\forall k}\left\|x_0^*(k) - x_i^*(k)\right\|,$$

ς is distinguishing or identification coefficient: $\varsigma \in [0,1]$, $\varsigma = 0.5$ is generally used.

After obtaining the grey relational coefficient, its average is calculated to obtain the grey relational grade.

The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{9}$$

However, since in real application the effect of each factor on the system is not exactly same, Eq. 9 can be modified as:

$$\gamma_i = \sum_{k=1}^{n} w_k . \xi_i(k) \qquad \sum_{k=1}^{n} w_k = 1 \qquad (10)$$

Where w_k represents the normalized weighting value of factor k. Given the same weights, Eqs. 9 and 10 are equal.

In grey relational analysis, the grey relational grade is used to show the relationship among the sequences. If the two sequences are identical, then the value of grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequence to the reference sequence, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades [11]. In this study, the importance of both the comparability sequence and reference sequence is treated as equal.

IV. ANALYSIS AND DISCUSSION

Optimal parameter combination the work-piece kerf width, material removal rate and surface roughness for different combinations of WEDM parameters of 27 experimental runs are listed in Table III

As far as SI is concerned, the lower surface roughness, the lower kerf width and the higher material removal rate are indications of better performance. The S/N ratios of the work-piece kerf width, material removal rate and surface roughness for 27 experimental runs calculated using Eq. 1 and Eq. 2 are listed in Table III.

TABLE III. THE S/N RATIO

Exp. No	Signal to Noise Ration		
	Kerf width	Material removal rate	Surface roughness
1	11.83181	12.46540	-10.48351
2	11.85898	14.38215	-9.41615
3	10.64192	14.86361	-8.68595
4	11.92387	11.78044	-10.36580
5	11.15354	10.28591	-9.74277
6	11.45352	8.70510	-8.49763
7	11.63066	6.75477	-9.79439
8	11.33741	5.67913	-8.79139
9	11.27675	4.57314	-7.59227
10	10.85145	18.91203	-10.11195
11	11.93416	16.74596	-10.17194
12	11.60419	16.85106	-10.42721
13	11.52198	13.56345	-10.17517
14	10.65376	13.27628	-10.39210
15	10.99502	12.38291	-9.79439
16	11.70722	9.03542	-10.27766
17	11.54820	7.86940	-10.71424
18	11.00735	8.36536	-9.88309
19	11.16924	15.79472	-11.97581
20	11.82164	14.32073	-10.60835
21	11.66386	14.30770	-8.56820
22	10.73110	13.92992	-10.83583
23	11.01352	14.26595	-10.69752
24	10.95507	11.62397	-10.90193
25	10.76103	11.84975	-10.97589
26	9.94600	13.20421	-10.30873
27	9.84019	11.99439	-9.97999

Table IV lists all of the sequences following data pre-processing of kerf width, material removal rate and surface roughness by using Eq. 4 and Eq. 5.

TABLE IV. THE SEQUENCES OF EACH PERFORMANCE CHARACTERISTIC AFTER DATA PRE-PROCESSING

Exp. No.	data pre-processing (pre-Normalization)		
	Kerf width	Material removal rate	Surface roughness
1	0.0489	0.5504	0.6596
2	0.0359	0.6841	0.4161
3	0.6171	0.7177	0.2495
4	0.0049	0.5026	0.6327
5	0.3728	0.3984	0.4906
6	0.2295	0.2882	0.2065
7	0.1449	0.1521	0.5024
8	0.2850	0.0771	0.2736
9	0.3140	0.0000	0.0000
10	0.5171	1.0000	0.5748
11	0.0000	0.8489	0.5885
12	0.1576	0.8563	0.6467
13	0.1968	0.6270	0.5892
14	0.6115	0.6070	0.6387
15	0.4485	0.5447	0.5024
16	0.1084	0.3112	0.6126
17	0.1843	0.2299	0.7122
18	0.4426	0.2645	0.5226
19	0.3653	0.7826	1.0000
20	0.0537	0.6798	0.6880
21	0.1291	0.6789	0.2226
22	0.5745	0.6525	0.7399
23	0.4397	0.6760	0.7084
24	0.4676	0.4917	0.7550
25	0.5602	0.5075	0.7719
26	0.9495	0.6019	0.6197
27	1.0000	0.5176	0.5447

Also, the deviation sequences Δ_{0i}, $\Delta_{max}(k)$ and $\Delta_{min}(k)$ for i=1–27 and k=1–3 can be calculated as follows:

$$\Delta_{01}(1) = \left| x_0^*(1) - x_1^*(1) \right| = \left| 1.0000 - 0.0635 \right| = 0.9365$$

$$\Delta_{01}(2) = \left| x_0^*(2) - x_1^*(2) \right| = \left| 1.0000 - 0.5237 \right| = 0.4763$$

$$\Delta_{01}(3) = \left| x_0^*(3) - x_1^*(3) \right| = \left| 1.0000 - 0.6596 \right| = 0.3404$$

So, $\Delta_{01}(i) = (0.9365, 0.4763, 0.3404)$

The results of all Δ_{0i} for i=1 to 27 are given in Table IV.

TABLE V. THE DEVIATION SEQUENCES

Experiment No.	Δ0i(1)	Δ0i(2)	Δ0i(3)
1	0.9511	0.4496	0.3404
2	0.9641	0.3159	0.5839
3	0.3829	0.2823	0.7505
4	0.9951	0.4974	0.3673
5	0.6272	0.6016	0.5094
6	0.7705	0.7118	0.7935
7	0.8551	0.8479	0.4976
8	0.7150	0.9229	0.7264
9	0.6860	1.0000	1.0000
10	0.4829	0.0000	0.4252
11	1.0000	0.1511	0.4115
12	0.8424	0.1437	0.3533
13	0.8032	0.3730	0.4108
14	0.3885	0.3930	0.3613
15	0.5515	0.4553	0.4976
16	0.8916	0.6888	0.3874
17	0.8157	0.7701	0.2878
18	0.5574	0.7355	0.4774
19	0.6347	0.2174	0.0000
20	0.9463	0.3202	0.3120
21	0.8709	0.3211	0.7774
22	0.4255	0.3475	0.2601
23	0.5603	0.3240	0.2916
24	0.5324	0.5083	0.2450
25	0.4398	0.4925	0.2281
26	0.0505	0.3981	0.3803
27	0.0000	0.4824	0.4553

Using Table V, Δ_{max} and Δ_{min} can be found as follows:

$$\Delta_{max} = \Delta_{21}(1) = \Delta_{09}(2) = \Delta_{09}(3) = 1.0000$$

$$\Delta_{min} = \Delta_{27}(1) = \Delta_{10}(2) = \Delta_{19}(3) = 0.0000$$

The distinguishing coefficient ζ can be substituted for the Grey relational coefficient in Eq. 8. If all the process parameters have equal weighting, ζ is 0.5. Table VI lists the Grey relational coefficient and grade for each experiment of the L_{27} orthogonal array by applying Eqs. 8 and 10.

TABLE VI. THE CALCULATED GREY RELATIONAL COEFFICIENT AND GREY RELATIONAL GRADE AND ITS ORDERS FOR 27 COMPARABILITY SEQUENCES

Exp. No.	Grey relational coefficients			Grey relational grade	Orders
	Kerf width	Material removal rate	Surface roughnes s		
1	0.3446	0.5265	0.5949	0.4887	16
2	0.3415	0.6128	0.4613	0.4719	17
3	0.5663	0.6391	0.3998	0.5351	12
4	0.3344	0.5013	0.5765	0.4708	18
5	0.4436	0.4539	0.4953	0.4643	20
6	0.3936	0.4126	0.3866	0.3976	25
7	0.3690	0.3710	0.5012	0.4137	24
8	0.4115	0.3514	0.4077	0.3902	26
9	0.4216	0.3333	0.3333	0.3627	27
10	0.5087	1.0000	0.5404	0.6830	2
11	0.3333	0.7680	0.5485	0.5499	11
12	0.3725	0.7767	0.5860	0.5784	6
13	0.3837	0.5727	0.5490	0.5018	14
14	0.5627	0.5599	0.5805	0.5677	9
15	0.4755	0.5234	0.5012	0.5000	15
16	0.3593	0.4206	0.5634	0.4478	23
17	0.3800	0.3937	0.6347	0.4695	19
18	0.4729	0.4047	0.5116	0.4630	21
19	0.4406	0.6970	1.0000	0.7125	1
20	0.3457	0.6096	0.6158	0.5237	13
21	0.3647	0.6089	0.3914	0.4550	22
22	0.5403	0.5900	0.6578	0.5960	5
23	0.4715	0.6068	0.6316	0.5700	8
24	0.4843	0.4959	0.6712	0.5505	10
25	0.5321	0.5038	0.6867	0.5742	7
26	0.9082	0.5568	0.5680	0.6777	3
27	1.0000	0.5089	0.5234	0.6774	4

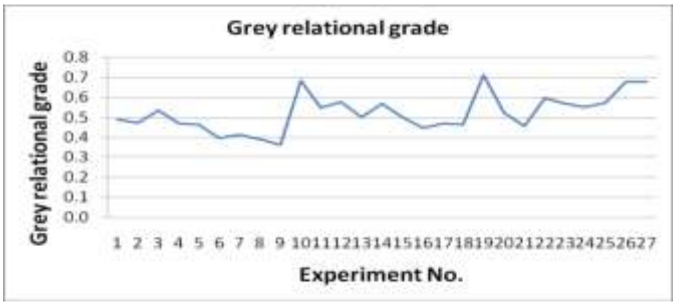

Figure 6. Graph of Grey relational grade

According to performed experimental design, it is clearly observed from Table VI and the grey relational grade graph (Figure 6) which shows the change in the response when the factors go from one level to other that the WEDM parameters setting of experiment no. 19 has the highest grey relation grade. Thus, the tenth experiment gives the best multi-performance characteristics of the WEDM process among the 27 experiments.

V. CONCLUSIONS

A multi-response optimization technique has been adopted in the search for an optimal parametric combination to yield favorable slat geometry during WEDM machining on H11 material. All parameter, which greatly influence the quality and feature characteristics of a machining, are the responses considered for study. The improvement of machining from the initial condition to optimal condition is 130 µs pulse on time, 40 µs pulse off time, 14 kgf/cm2 flushing pressure, 900 gms wire tension, 20 volts servo voltage and 12 m/min wire feed rate, which validates the effectiveness of the optimization method proposed in this study among the 27 experiments.

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