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Research Article

Multi-objective Optimization of Wire Electric Discharge Machining of EN31 Tool Steel using Orthogonal array with Principal Component Analysis

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Abstract

Recently mechanical industries, the demands for alloy steel materials having high hardness, toughness and wear resistance are increasing, having wide application in automobile products like bearing shafts, spindles etc is important for quality of cut. Keeping this view, a hybrid approach of Taguchi's methodology (TM) and principle component analysis (PCA) has been applied for multi-objective optimization (MOO) of wire-cut EDM of EN31 steel. To achieve the better qualities using existing resources, the two quality characteristics, cutting speed and surface roughness have been considered for simultaneous optimization. The input parameter considered are Peak current (A), pulse-on time(B), pulse off time(C) and wire tension(D).Initially single-objective optimization has been performed using Taguchi's methodology and then the S/N ratio obtained from TM have been further used in PCA for multi-objective optimization(MOO). The results of MOO include the prediction of optimum input parameter levels and their relative significance on multi quality characteristics. The resources at the predicted optimum parameter levels are in good agreement with the result of confirmation experiments for verification test..

Keywords: *Wire Electric Discharge Machining, Process parameters, Multi-objective optimization, Taguchi Methodology, En-31 tool steel*

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1. Introduction

Wire Electrical discharge machining (WEDM) is a nontraditional, thermoelectric process which erodes material from the work piece by a series of discrete sparks between a work and tool electrode immersed in a liquid dielectric medium. Melting and vaporization due to electrical discharge removes minute amounts of the work material, which are then ejected and flushed away by the dielectric. The schematic representation of the WEDM cutting process is shown in Figure 1.Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of producing accurately machined parts with different hardness or complex shapes, which have sharp edges that are very difficult to be machined by conventional machining processes. At present, WEDM is a widely used technique in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite, or even some ceramic materials, of any hardness (Kalpakjian S. ,1995)**.** Many Wire-EDM machines have adopted the pulse generating circuit using low power for ignition and high power for machining.

Due to its broad capabilities, machining of conducting materials pertaining to almost all areas like production, aerospace and automobiles. That is why the wire-EDM proves the best alternatives or sometimes the only alternative for cutting conductive, exotic and high strength temperature resistive alloys (HSTR), conductive engineering ceramics in order to generate complex shapes and profiles (Lok, Y.K *et al.*, 1997and Kozak, J et al., 2004).

WEDM is considered as variants of the conventional EDM process, which uses an electrode to initialize the sparking process. However, WEDM utilizes a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.30 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tension providing device reducing the tendency of producing inaccurate parts.

Earlier researchers have optimized single quality characteristics at a time using TM for their experimental studies. However there are many manufacturing processes whose performance characteristics depends on various quality characteristics and it is always desired to have an optimum level that improves multiple quality characteristics (MQC) at the same time. In the study of MQC, pure judgment is employed for process

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optimization which is very subjective that brings uncertainty to the decision making process.

PCA has been proved to be the useful tool for dealing with such kind of uncertainty. In PCA, set of correlated variables (quality characteristics) are transformed into a set of uncorrelated principal components (PC). A weighting factor for PC is determined based on its contribution percentage to the total variance. (Fung C-P *et al.*, 2005) have applied the TM and PCA sequentially to optimize the MQC at a time during injection molding process. They were found that this hybrid approach is suitable for optimizing the MQC in manufacturing processes.

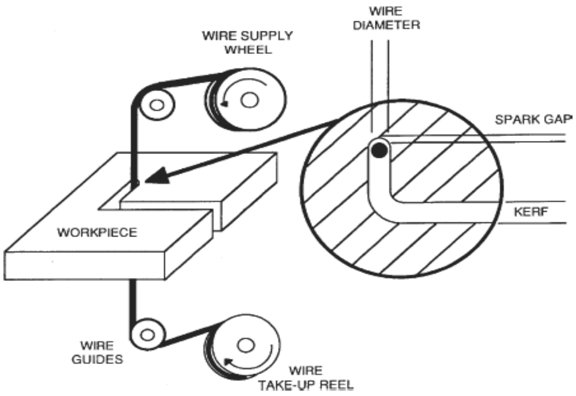


Fig 1 Schematic representation of WEDM cutting process

2. Experimental

The experiment was performed on wire-cut machine (ELECTRONICA SPINT CUT 732), Electronica Machine Tools. The diameter of wire was 0.25mm and the different process parameters (or control factors) taken are: peak current, pulse-on time, pulse-off time wire tension and other parameters were kept Constant . EN31 tool steel was used as a work-piece material in the present experiment having dimension 15mm×20mm×8mm. The chemical composition of EN31 tool steel is given in the table (1). Three levels of each control factors have been selected without considering the interaction effect.

Table 1: Chemical composition of EN31 tool steel

Element	C	Cr	Mn	P	S	Si
%	1.07	1.12	0.58	0.04	0.03	0.32

Table 2: Control factors and their levels used in the experiment

Control factor	Symbol	Level 1	Level 2	Level 3
Peak current	A	90	150	230
Pulse on time	B	115	125	130
Pulse off time	C	48	50	56
Wire tension	D	5	8	10

The numerical values of selected control factors at different levels are shown in the table (2). The range of selected parameters was decided by conducting exhaustive pilot experimentation on EN31 tool steel having dimension 100mm ×20mm×15mm.

In this present study, for optimizing MQC simultaneously, both TM and PCA both are applied sequentially. This section gives a brief idea about these two approaches.

2.1 Taguchi Method

It is a widely accepted method of design of experiment (DOE). TM has proved to be an effective methodology for producing high quality components at relatively low cost. This approach has not only used in India but successfully applied in many other countries like Japan and Europe manufacturing industries, especially in electronics. Food processing automobile and medical industries (Phadke MS, 1989 and Ross PJ, 1988).

The objective of Taguchi approach is to find out the optimum setting of process parameters or control factors, in turn making the process insensitive to sources of variation due to uncontrollable or noise factors.

In this present study, the main control factors that have an influence on the performances are taken as input parameters and the experiment is performed using specially designed orthogonal array (OA). The selection of appropriate OA is based on total degree of freedom (d.f) which is calculated as (Phadke MS, 1989 and Ross PJ, 1988).

d.f= (number of levels-1) for each factor +(no. of levels-1)×(number of levels -1) for each interaction+1

The S/N ratio (SNR, dB) represents the quality characteristics for the observed data in the Taguchi DOE and is mathematically calculated as (Phadke MS, 1989 and Ross PJ, 1988).

$$\text{SNR}=-10\log(\text{MSD}) \qquad (1)$$

Where MSD is the mean square deviation and commonly known as quality loss function. Depending upon the experimental objective, the quality loss function are classified into three types: lower the better (LB), higher the better (HB) and nominal the best (NB) . In the case of cutting speed, higher the better and for surface roughness, lower the better are desirable. These quality loss values in TM are called as HB and LB type and are computed as follows (Phadke MS, 1989 and Ross PJ, 1988).

For larger the better: $\text{MSD}=[1/n \sum_{i=1}^{n} \frac{1}{Yi2}]$ (2)

For smaller the better: $\text{MSD}=[1/n \sum_{i=1}^{n} Yi^2]$ (3)

Where Y_i is the observed data of quality characteristics at the $i^{th.}$ Trial and n is the number of repetitions at the same trial. The S/N ratio represents the desired part/undesired part and aim is always to maximize the S/N ratio whatever be the nature of quality characteristics. Using S/N ratio, influence of effective parameters on process results can be obtained and the optimal combination of process parameters can be determined (Phadke MS, 1989 and Ross PJ, 1988)

2.1 Principal Component Analysis (PCA)

It is a multivariate statistical method. this method selects a number of components to account for the variance of original multi-response (Antony J *et al.*, 2000) Using PCA, the original data-set of MQC are converted into PC which is a linear combination of multi-response obtained in a trial run. The procedure of PCA can be described as follows (Fung C-P *et al*, 2005 and Tzeng Y.F *et al*, 2006)

1.) The S/N ratios of each quality characteristics obtained from Taguchi method (TM) are normalized as

$$X_i{*}(j) = \frac{xi(j) - xi\ (j)^{-}}{x(j+) - x\ (j)^{-}} \tag{4}$$

Where $X_i{*}(j)$ is the normalized S/N ratio for $j^{th.}$ Quality characteristics in the $i^{th.}$ experimental run, $xi(j)$ is the S/N ratio for $j^{th.}$ Quality characteristics in the $i^{th.}$ experimental run $x\,(j)^{-}$ is the minimum and $x(j+)$ is the maximum S/N ratios for jth$^{\cdot}$ Quality characteristics in all runs.

2.) The normalized multi-response array for m quality characteristics and n experimental runs can be represented by matrix X^* as

$$X^* = \begin{bmatrix} xi*(1) & \cdots & xi*(m) \\ \vdots & & \vdots \\ xn*(1) & \cdots & xn*(m) \end{bmatrix} \tag{5}$$

3.) The correlation coefficient array (R_{ji}) of matrix X^* is evaluated as follows:

$$R_{ji} = \frac{\mathrm{cov}(xi{*}(j), xi{*}(l))}{\sigma xi{*}(j) \times \sigma xi{*}(l)} \tag{6}$$

Where, $\mathrm{cov}(xi*(j), xi*(l))$ is the covariance of sequences X_i*(j) and X_i*(l); σ_i*(l) is the standard deviation of sequence X_i*(j).

4.) The Eigen values and eigenvectors of matrix R_{ji} are calculated.

5.) The PC are computed as follows:

$$P_i\,(k) = \sum_{j=i}^{m} (xi(j) \times vk(j)) \tag{7}$$

Where P_i (k) is the kth PC corresponding to ith experimental run, $vk(j)$ is jth element of kth eigenvector.

6.)The total principal component index (TPCI) corresponding to ith experimental run (Pi) is computed as follows:

$$P_i = \sum_{j=i}^{m} Pi(k) \times e(k) \tag{8}$$

Where eig (k) is the kth eigen value.

$$e(k) = \frac{eig(k)}{\sum_{j=i}^{m} eig(k)} \tag{9}$$

2.2. Wire cut EDM Process

Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of producing accurately machined parts with different hardness or complex shapes, which have sharp edges that are very difficult to be machined by conventional machining processes. At present, WEDM is a widely used technique in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite, or even some ceramic materials, of any hardness (Kalpakjian S., 1995, Luxon JT, Parker DE 1985, and Chryssolouris G., 1991) Many Wire-EDM machines have adopted the pulse generating circuit using low power for ignition and high power for machining. However, it is not suitable for finishing process since the energy generated by the high-voltage sub-circuit is too high to obtain a desired fine surface, no matter how short the pulse-on time is assigned (Lok, Y.K *et al*, 1997) WEDM is considered as variants of the conventional EDM process, which uses an electrode to initialize the sparking process. However, WEDM utilizes a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.30 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tension providing device reducing the tendency of producing inaccurate parts. Selection of appropriate input parameters and their levels are very much important as far as these quality characteristics (cutting speed and surface roughness) concerned.

3. Results and Discussion

3.1 Wire-Cut EDM Performance evaluation

In the present study the quality characteristics analyzed are cutting speed and surface roughness. Two such cuts each of 10 mm cube were obtained in each experimental run and for ach quality characteristics an average quality value of two cuts has been taken. For WEDM, cutting rate is a desirable characteristic and it should be as high as possible to give least machine cycle time leading to increased productivity. In the present study cutting rate is a measure of job cutting which is digitally displayed on the screen of the machine and is given quantitatively in mm/min.

Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion. Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if small, the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface.

In this work the surface roughness was measured by Mitutoyo Surftest SJ-201P. The Surftest is a shop–floor type surface-roughness measuring instrument, which

Table 3 Experimental layout using L_9 orthogonal array

Expt. Run	**PC**	**T_{on}**	**T_{off}**	**WT**	**Trial 1**	**Trial 2**	**Mean of (CS1 & CS2)**	**Trial 1**	**Trial 2**	**Mean of (Ra1 & Ra2)**
	(A)	(B)	(C)	(D)	CS1	CS2		**Trial 1**	**Trial 2**	
1	1	1	1	1	1.12	1.1	1.11	Ra 1	Ra 2	1.56
2	1	2	2	2	1.16	1.14	1.15	1.58	1.54	1.755
3	1	3	3	3	2.21	2.19	2.2	1.76	1.75	3.425
4	2	1	2	3	1.83	1.78	1.805	3.43	3.42	1.51
5	2	2	3	1	3.36	3.36	3.36	1.51	1.51	3.68
6	2	3	1	2	2.83	2.8	2.815	3.69	3.67	3.015
7	3	1	3	2	2.2	2.19	2.195	3.02	3.01	4.445
8	3	2	1	3	2.61	2.58	2.595	4.48	4.41	4.74
9	3	3	2	1	3.64	3.61	3.625	5.00	4.48	3.825
							Avg. of Cutting Speed=2.317			Avg. of Surface Roughness=3.106

traces the surface of various machine parts and calculates the surface roughness based on roughness standards, and displays the results in μm.

The work piece is attached to the detector unit of the SJ-201 which traces the minute irregularities of the work piece surface. The vertical stylus displacement during the trace is processed and digitally displayed on the liquid crystal display of the SJ-201.

The surf test has a resolution varying from .01 μm to 0.4 μm depending on the measurement range

3.2 Determination of optimal cutting parameters

This section has discussed about the results of single-objective optimization using TM and multi-objective optimization (MOO) by using a hybrid approach of TM and PCA. This section has also reported the verification results obtained on suggested optimum parameters.

3.2.1 Orthogonal array experiments

The total degree of freedom (d.f) has been calculated without considering an interaction effect among different control factors. At three different levels, the total d.f for four control factors is (3-1)×4+1=9. That is why an L_9 orthogonal array (OA) has been selected for conducting experiments. Table (3) shows observed values for each quality characteristics cutting speed, surface roughness in different trials.

3.2.2 Single-objective optimization using TM

The S/N ratios (η values) for CS and SR have been calculated from experimental values of each quality characteristics (3).

The S/N ratio corresponding to each experimental run is shown in table (4).The factor effect of a parameter at any level is computed by taking the average of all S/N ratios at the same level.

The effect of various factors at different levels for response CS and SR are shown in table (5).

In addition to this, the graphical representations of factors effect at different levels are shown in fig.(2). The optimum parameter level is the level corresponding to maximum average S/N ratio for a control factor. Therefore, the optimum parameter level for minimum value of SR is A1B1C2D1and for maximum value of CS is A3B3C3D1respectively.

Table 4: S/N ratios (in dB) for CS and SR

S.No.	CS	SR
1	0.9065	-3.8625
2	1.2140	-4.8608
3	6.8485	-10.6805
4	5.1055	-3.5795
5	10.5268	-11.3170
6	8.9741	-9.5713
7	6.8089	-12.9477
8	8.2660	-13.5156
9	11.1742	-11.6413
Overall Mean $(\bar{\eta})$	6.6472	-9.1085

Table 5: Response table for CS and SR

S.No.	Factors	Mean S/N ratios		
		Level 1	Level 2	Level 3
For Cutting Speed (CS)				
1	Peak Current	2.990	8.202	8.750
2	Ton	4.274	6.669	8.999
3	Toff	6.049	5.831	8.061
4	Wire Tension	7.536	5.666	6.740
For Surface Roughness				
1	Peak Current	6.468	8.156	12.701
2	Ton	6.797	9.898	10.631
3	Toff	8.983	6.694	11.648
4	Wire Tension	8.940	9.127	9.259

A better feel for the relative effect of the different parameters/factors can be obtained by the decomposition of the variance, which is commonly called ANOVA. It is a statistical method to estimate quantitatively the relative contribution that each factor of parameter makes an overall measured response. F-ratio represents a relative significance of factors or percentage contribution. Greater the F-ratio more significant will be the parameter. The results of ANOVA for CS and SR are given in the table (6a & 6b).

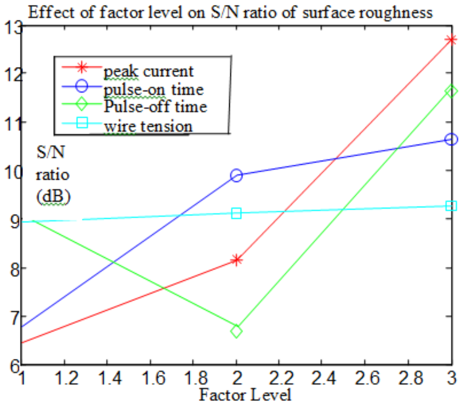
Table 6 Results of ANOVA for CS and SR (a) For CS

Symbol	Factors	dof	SS	MS	F	Cont. (%)
A	Peak current	2	3.114	1.551	9.555	50.0768
B	Pulse-on time	2	2.089	1.044	6.409	33.5919
C	Pulse-off time	2	0.325	0.162	-	5.24134
D	Wire tension	2	0.689	0.345	2.115	11.0900
Error		0	-	-	-	-
Pulled Error		2	0.32596	0.16298	-	-
Total		8	6.21902			100.0

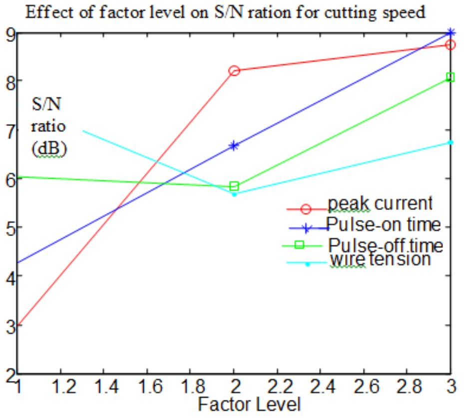
(b) For SR

Symbol	Factors	dof	SS	MS	F	Cont. (%)
A	Peak current	2	7.168	3.584	7.100	58.88
B	Pulse-on time	2	1.621	0.810	23.80	13.32
C	Pulse-off time	2	3.315	1.657	48.68	27.24
D	Wire tension	2	0.068	10.03	1.000	0.560
Error		0				
Pulled Error		2	0.068			
Total		8	12.172			100

The results show that the peak current is the significant for cutting speed and surface roughness under more than 95% confidence level. The contribution of factors in increasing order for CS is peak current(A),pulse-on time (B), wire tension (D) and pulse-off time (C), for surface roughness (SR) is peak current (A), wire tension (C), pulse-on time (B) and pulse-off time (D).



(a)



(b)

Fig 2 : Effect of factor levels on S/N ratio for a) surface roughness b) cutting speed

3.3 Multi-objective optimization using hybrid approach of TM and PCA

The normalized S/N ratios for each performance measures CS and SR against different experimental runs have been calculated using equation (4) and are shown in table7. Table shows a correlation coefficient array using equation (8). The Eigen values and eigenvector computed from correlation coefficient matrix are: 1.7762, 0.2238 and [-0.7071, -0.7071], [-0.7071, 0.7071] respectively. The three principle components PC1, PC2 and their integrated TPCI for each experimental run have been computed using Equations (7)-(9) and tabulated in table 9. The factor effect at each parameter levels have been computed by taking, the average TPCI at that level and given in table 10. The factor effect at different level is shown graphically in figure 2. The optimum parameter level for MQC corresponds to the maximum average TPCI for a control factor which is A1B3C2D1 i.e. peak current at 90A, pulse-on time at 130µs, pulse-off time at 50µs and wire tension at 5N.

Table 7 Normalized S/N ratio for CS and SR

Expt. No.	CS	SR (Ra)
1	0	0.97152
2	0.02995	0.87104
3	0.53176	0.28533
4	0.40895	1.00000
5	0.93695	0.22174
6	0.78573	0.39696
7	0.57485	0.05715
8	0.71676	0.00000
9	1.00000	0.18863

The contribution of each factor in increasing order was calculated using ANOVA and shown in table11. The graphical representation of contribution of different control factors on TPCI of MQC is shown in figure 3. The improvement in predicted TPCI at optimum level is found

Table 8 Correlation Coefficients among the targeted quality characteristics

Correlation Coefficient	CS	SR
K_{cs}	0.7071	0.7071
K_{Ra}	-0.7071	0.7071

Table 9 Principal component scores and their integrated TPCI

Expt. No.	PC1	PC2	TPCI
1	-0.6869	0.6869	0.5663
2	-0.5947	0.6367	0.5268
3	0.1742	0.5776	0.5416
4	-0.4179	0.9963	0.8701
5	0.5057	0.8193	0.7913
6	0.2749	0.8363	0.7862
7	0.3660	0.4468	0.4395
8	0.5068	0.5068	0.5068
9	0.5737	0.8405	0.8167

Average (P) =0.153667

Table 10 Response table for TPCI

Symbol	Factors	Level-1	Level-2	Level-3	Max.-Min.	Rank
A	Peak current	0.5449	0.8159	0.5877	0.2710	1
B	Pulse-on time	0.6253	0.6083	0.7148	0.1065	4
C	Pulse-off time	0.5908	0.7379	0.6198	0.1471	2
D	Wire tension	0.7248	0.5842	0.6395	0.1406	3

Table 11 Results of ANOVA for TPCI

Symbol	Factors	DOF	SS	MS	F	Contribution (%)
A	peak current	2	22.3393	11.1697	5.6300	57.400
B	pulse-on time	2	3.9679	1.9840	1.0000	10.190
C	pulse-off time	2	6.3766	3.1883	1.60704	16.380
D	wire-tension	2	6.2342	3.1171	1.5711	16.030
Error		0				
Pooled Error		2	3.9679			
Total		8	38.9181			100.000

Table 12: Result of Confirmation Experiment for multi-objective optimization

Factor Level	Initial	Optimized
	A3B3C3D1	A1B3C2D1
CS (mm/min.)	2.883677	2.987556
Factor Level	A1B1C2D1	A1B3C2D1
SR (Ra)	2.3436	2.356879

to be 0.10 as compared with initial parameter setting. The value of CS and SR at this optimum level are found to be 2.987556 mm/min., and 2.356879 Ra respectively, after conducting the confirmation run to verify the results (Table12). The results of confirmation test show that the quality characteristics cutting speed & surface roughness have been improved considerably. Therefore, overall improvement has been registered.

Conclusions

The concluding remarks of the present research work can be summarized as follows.

1) In single objective optimization using Taguchi method, peak current, pulse-on time and wire tension are the significant factors for cutting speed, while peak current pulse-off time, pulse-on time are the significant for surface roughness.

2) The optimum parameter levels predicted in single-objective optimization for maximum value of cutting speed and minimum value of surface roughness are A3B3C3D1 and A1B1C2D1 respectively.

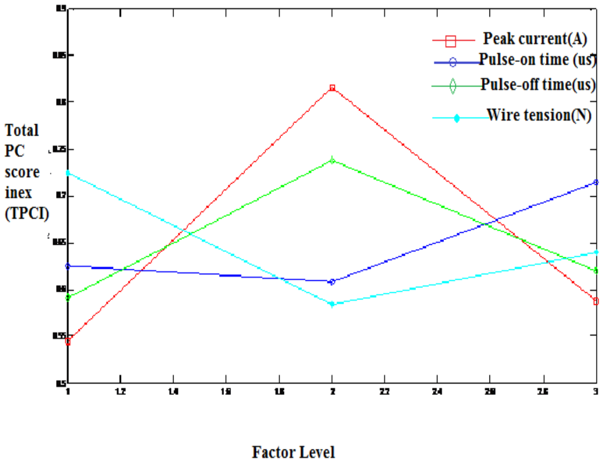


Fig 3: Effect of factor levels on TPCI

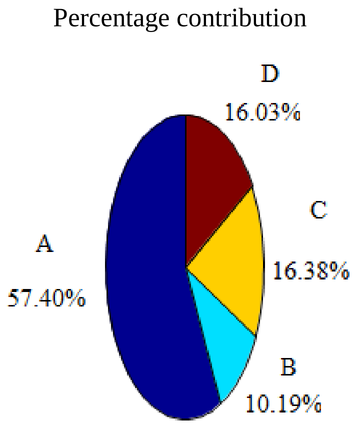


Fig 3: Contribution of different control factors on TPCI multiple quality characteristics

3) Multiple quality characteristics (MQC) has found improved by using hybrid approach of Taguchi(TM) and principle component analysis (PCA) as compared to initial parameter setting. the optimum value of control factors for overall improvement in MQC is peak current=90 ampere, pulse-on time=130us, pulse-off time=50us and wire

tension=5N. The value of cutting speed and surface roughness at optimum parameter level is 2.987556 mm/min. and 2.356879 Ra.

4) The contribution of different control factors on MQC is peak current-57.40%, pulse-on-10%, pulse-off-16.38% and wire tension-16.03% . the peak current found to the significant parameter in this operating range.

5) In Multi-objective optimization, the loss in some quality characteristics is always possible as compared to single-objective optimization but overall quality is improved.

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