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A study on the machining-parameters optimization of wire electrical discharge machining

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Abstract

A suitable selection of machining parameters for the wire electrical discharge machining (WEDM) process relies heavily on the operators' technologies and experience because of their numerous and diverse range. Machining-parameters tables provided by the machine-tool builder can not meet the operators' requirements, since for an arbitrary desired roughness of the machining surface, they do not provide the optimal machining conditions. An approach to determine parameters setting is proposed. Based on the Taguchi quality design method and the analysis of variance, the significant factors affecting the machining performance such as metal removal rate, gap width, surface roughness, sparking frequency, average gap voltage and normal ratio (ratio of normal sparks to total sparks) are determined. By means of regression analysis, mathematical models relating the machining performance and various machining parameters are established. Based on the mathematical models developed, an objective function under the multi-constraint conditions is formulated. The optimization problem is solved by the feasible direction method, and the optimal machining parameters are obtained. Experimental results demonstrate that the machining models are appropriate and the derived machining parameters satisfy the real requirements in practice. © 1997 Elsevier Science S.A.

Keywords: Wire electrical discharge machining; Machining-parameters setting; Taguchi quality design; Optimization

1. Introduction

Wire electrical discharge machining (WEDM) involves a series of complex physical process including heating and cooling. The electrical discharge energy, affected by the spark plasma intensity and the discharging time, will determine the crater size, which in turn will influence the machining efficiency and surface quality [1–4]. Hence, the machining parameters, including pulse-on time, pulse-off time, table feed rate, flushing pressure, wire tension, wire velocity, etc. should be chosen properly so that a better performance can be obtained. However, the selection of appropriate machining parameters for WEDM is difficult and relies heavily on the operators' experience and machining-parameters tables provided by the machine-tool builder.

Scott, Boyina and Rajurkar [5] used a factorial-design method to determine the optimal combination of control parameters in WEDM, the measures of machining performance being the metal removal rate and the surface finish. Based on the analysis of variance, it was found that discharge current, pulse duration and pulse frequency are significant control factors for both the metal removal rate and the surface roughness. A total number of 729 experiments was conducted. 32 machining settings which resulted in a better metal removal rate and surface roughness were determined by two distinct techniques: Explicit enumeration of all possible combinations and the dynamic programming approach. However, this approach requires too many experiments to be carried out. Further, it can not provide the optimal machining parameters for an arbitrary desired surface roughness or gap width.

Although the effect of improper machining-parameters settings in WEDM could be alleviated by an on-line control technique, the control reference values, which vary with different machining conditions, are difficult to determine. Moreover, the control effect will be significant only under appropriate off-line machining-parameters setting. The optimal machining-parameters setting based on the operators' experience

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completely does not satisfy the requirements of both high efficiency and good quality. Machining-parameters tables, provided by machine-tool builders, could be a better choice for operators in factory, but still can not be applied to a wide range of machining conditions. Hence, research incorporating physical principles, experimental techniques, mathematical analysis, optimization and computers, is the trend of WEDM optimal machining-parameters setting studies.

Optimal machining-parameters setting for WEDM still has some difficulty from the view of integrity and practice [6,7]. To be more specific, the experiments are too costly and time consuming to meet the requirement of full factorial designs. There are many machining parameters affecting the WEDM machine performance and the real mathematical models between machining performance and machining parameters are not easy to be derived because of the complex machining mechanism. The purpose of this paper is to present an efficient method by means of which to determine appropriate machining parameters so as to be able to achieve the objective of the shortest machining time whilst at the same time satisfying the requirements of accuracy and surface roughness. The cause-effect relationship of machining parameters and machining performance in WEDM is discussed and the significant parameters affecting machining performance are found. Also, the mathematical models relating the machining performance and machining parameters are established by regression and correlation analysis. Finally, the optimal machining parameters by the non-linear approaching method under the constraints and requirements are obtained.

2. Experimental equipment and design

A WEDM machine, developed by ITRI (Industrial Technology Research Institute) and CHMER company, Taiwan, was used as the experimental machine. The work material, electrode and the other machining conditions were as follows: (1) workpiece (anode); SKD11 alloy steels; (2) electrode (cathode), ∅0.25 mm brass wire; (3) workpiece height, 30 mm; (4) cutting length, 20 mm; (5) open voltage, 95 V; (6) servo reference voltage, 10 V; and (7) specific resistance of fluid, 1-3 mA.

According to the Taguchi quality design concept [8], a L18 mixed orthogonal arrays table was chosen for the experiments. A total of six machining parameters (pulse-on time, pulse-off time, table feed, wire tension, wire speed and flushing pressure) were chosen for the controlling factors and each parameter was designed to have three levels, namely small, medium, and large, denoted by 1, 2 and 3, as shown in Table 1. In order to obtain better mathematical fitting models, another L18 experiments, as given in Table 2, were conducted.

Table 1
Experimental design I

Control factor	Level 1	Level 2	Level 3	Unit
Table feed	0.4	2.5	—	mm min^{-1}
Pulse-on time	3	7	10	0.1 μs
Pulse-off time	6	9	13	1.6 μs
Wire speed	6	9	12	m min^{-1}
Wire tension	800	1000	1200	gf
Flushing	3	5	7	kg cm^{-2} [a]

[a] 1 kg cm^{-2} = 98.1 kPa.

The machining results after the WEDM process under the designed machining conditions are evaluated in terms of the following measured machining performance: (1) gap width (gap, μm); (2) metal removal rate (MRR, mm^3 min^{-1}); (3) surface roughness (R_a, μm); (4) discharging frequency, (F_q, kHz); (5) gap voltage (V_g, V); (6) normal discharge frequency ratio (F_r).

3. Experimental results and data analysis

The chosen six parameters have different influences on the machining performance. The significant parameters are found by the analysis of variance (ANOVA). By regression analysis, mathematical models relating the machining performance to various machining parameters are established and the optimal machining-parameters setting is obtained using the feasible-direction non-linear programming method.

3.1. *The influence of machining parameters on machining performance*

The characteristic that higher value represents better machining performance, such as MRR, is called 'higher is better, HB'. Inversely, the characteristic that lower value represents better machining performance, such as surface roughness, is called 'lower is better, LB'. In quality engineering [8], the S/N ratio (signal-to-noise ratio) could be an effective representation to find the significant parameter from those controlling machining

Table 2
Experimental design II

Control factor	Level 1	Level 2	Level 3	Unit
Table feed	1.2	2	---	mm min^{-1}
Pulse-on time	5	7	8	0.1 μs
Pulse-off time	8	9	11	1.6 μs
Wire speed	8	9	10	m min^{-1}
Wire tension	900	1000	1100	gf
Flushing	4	5	6	kg cm^{-2}

Table 3
η data for MRR ($mm^3 \, min^{-1}$)

	Factors								MRR			η
	Feed	T_{on}	T_{off}	V_w	F_w	P	E_1	E_2	Y_1	Y_2	Y_3	η (db)
1	1	1	1	1	1	1	1	1	3.85	3.95	3.96	11.864
2	1	1	2	2	2	2	2	2	3.84	3.83	3.9	11.723
3	1	1	3	3	3	3	3	3	3.69	3.61	3.71	11.291
4	1	2	1	1	2	2	3	3	5.12	5.03	5.1	14.122
5	1	2	2	2	3	3	1	1	4.71	4.66	4.64	13.386
6	1	2	3	3	1	1	2	2	5.16	5.05	5.24	14.233
7	1	3	1	2	1	3	2	3	5.7	5.34	5.49	14.814
8	1	3	2	3	2	1	3	1	5.28	5.28	5.4	14.517
9	1	3	3	1	3	2	1	2	6.36	7.28	6.55	16.517
10	2	1	1	3	3	2	2	1	4.75	4.61	4.55	13.32
11	2	1	2	1	1	3	3	2	5.35	5.72	5.47	14.818
12	2	1	3	2	2	1	1	3	4.96	5.17	4.91	13 966
13	2	2	1	2	3	1	3	2	31.02	31.77	31.84	29.976
14	2	2	2	3	1	2	1	3	30.97	31.03	31.99	29.916
15	2	2	3	1	2	3	2	1	32.35	32.39	32.24	30.191
16	2	3	1	3	2	3	1	2	33.92	34.36	34.59	30.702
17	2	3	2	1	3	1	2	3	28.32	28.98	28.94	29.17
18	2	3	3	2	1	2	3	1	30.74	30.01	30.66	29.676

parameters by evaluating the minimum variance. For HB and LB, the definition of the S/N ratio for machining-performance results y_i of n repeated number (in this case $n = 3$, $i = 1, 2, 3$) are:

HB: S/N ratio $= 1/\sigma^2$, $\quad \sigma^2 = \frac{1}{n}\left(\frac{1}{y_1^2} + \frac{1}{y_2^2} + \cdots + \frac{1}{y_n^2}\right)$

LB: S/N ratio $= 1/\sigma^2$, $\quad \sigma^2 = \frac{1}{n}(y_1^2 + y_2^2 + \cdots + y_n^2)$

In Taguchi quality engineering [8], the η value is a better representation than the S/N ratio. Larger η (or a larger S/N ratio equivalently) is better for both HB and LB.

$\eta = 10 * \log(S/N \text{ ratio})$

By applying the equation above, the η values of machining performance for each experiment of L18 can be calculated. Taking the metal removal rate (MRR) as an example, the η values are computed and given in Table 3.

In order to obtain the effects of machining parameters on machining performance for each different level, the η values of each fixed parameter and level for each machining performance are summed up. From Table 3, taking T_{on} on MRR as an example, the η values of three levels can be summarized as follows:

Level 1:

$$\eta_{on1} = 11.864 + 11.723 + 11.291 + 13.320 + 14.818 + 13.996 = 77.012$$

Level 2:

$$\eta_{on2} = 14.122 + 13.386 + 14.233 + 29.976 + 29.916 + 30.191 = 131.824$$

Level 3:

$$\eta_{on3} = 14.814 + 14.517 + 16.517 + 30.702 + 29.170 + 29.676 = 135.396$$

Similarly, those η values of the other parameters on other machining performance could be evaluated. Table 4 shows the total η values of the levels of six parameters on MRR.

3.2. Analysis of variance

From Table 4, the combination of machining parameters $(\text{Feed})_2 T_{on3} T_{off3} V_{w1} F_{w1} P_2$ would result in maximum MRR because of larger η values. However, it is hard to assure that only this setting will result in maximum MRR because of the small difference of the η value between different levels and experimental error. Hence, analysis of variance (ANOVA) and the F test are used to analyze the experimental data as follows:

$$S_m = \frac{\left(\sum \eta_i\right)^2}{18}, \quad S_T = \sum \eta_i^2 - S_m$$

$$S_A = \frac{\sum \eta_{Ai}^2}{N} - S_m, \quad S_E = S_T - \sum S_A$$

Table 4
Total η values of each level on MRR

Level	Feed	T_{on}	T_{off}	V_w	F_w	P
1	122.467	77.012	114.798	116.682	115.321	113.756
2	221.765	131.824	113.53	113.571	115.251	115.274
3		135.396	115.904	113.979	113.66	115.202
Sum	344.232	344.232	344.232	344.232	344.232	344.232

$$V_A = \frac{S_A}{f_A}, \quad F_{A0} = \frac{V_A}{V_E}$$

where S_T is the sum of squares due to total variation; S_m is the sum of squares due to mean; S_A is the sum of squares due to factor A (A = Feed, T_{on}, T_{off}, V_w, F_w and P); S_E is the sum of squares due to error; η_i is the η value of each experiment ($i = 1-18$); η_{Ai} is the sum of i level of factor A ($i = 1, 2$ or $i = 1, 2, 3$); N is the repeating number of each level of factor A; f_A is the degree of freedom of factor A; V_A is the variance of factor A; and F_{A0} is the F test value of factor A.

The square sum, variance and F test value of machining parameters on the MRR in Table 5 were obtained by substituting those data in Tables 3 and 4 into the above equations. The bold type in Table 5 indicates the significant factors on MRR being Feed and T_{on} for the reason that both of the F_{A0} values are bigger than $F_{0.05,n1,n2}$. Similarly, the significant parameters for each machining performance are shown in Table 6.

In order that the effects of machining parameters on machining performance can be seen more clearly, the data in Table 4 were plotted as shown in Figs. 1-3. It is found from Fig. 1 that larger Feed and T_{on} results in larger MRR (HB) and from Fig. 2 larger T_{on} results in larger gap width (LB). For surface roughness (LB), larger T_{on} result in a bigger crater on the surface (Fig. 3). No significant parameter was found on normal discharge frequency ratio (Y_r), one of the reasons being that all parameters have little effect on Y_r, whilst another more likely reason is that the effects of the error factor on the experimental results exceed those of all of these machining parameters. The trends of the influence of significant parameters on machining performance are summarized in Table 7.

3.3. Mathematical model of machining performance

By regression and correlation analysis, the mathematical models are obtained as follows:

$$Y_{mr} = 18.5953x_1^2x_2 - 3.5215x_1^2x_2^2 - 17.7297x_1x_2 - 5.4441x_1 + 5.7634x_2 + 3.2558$$

$$Y_{gap} = 0.5097x_2 + 0.4406$$

$$Y_{SR} = 0.6831x_2^2 - 0.2698x_2 + 0.5725$$

$$Y_{fq} = -0.0148x_1x_2^2 + 9.4631x_1^2x_2 - 18.3852x_1x_2 + 3.0855x_1 + 7.8901x_2 - 1.7051$$

$$Y_{vg} = -6.3851x_2^2 + 7.1263x_1x_2^2 - 10.5043x_1^2x_2 + 10.5767x_1x_2 - 0.0287$$

where x_1 and x_2 are calculated by the following equations:

$$x_1 = \log(\text{Feed})/\max(\log(\text{Feed}))$$

$$x_2 = \log(T_{on})/\max(\log(T_{on}))$$

Because:

$$400 \le \text{Feed} \le 2500, \qquad 3 \le T_{on} \le 10$$

then:

$$0.7657 \le x_1 \le 1, \qquad 0.4771 \le x_2 \le 1$$

Evidence shows that the mathematical models derived by the regression analysis above are sufficiently precise to represent the real machining performance. Presented are the correlation coefficients of experimental data (Y_i) and data (Y'_i) calculated by the regression mathematical model.

$$\text{coef}(Y_{mr}, Y'_{mr}) = 0.9883$$

$$\text{coef}(Y_{gap}, Y'_{gap}) = 0.9054$$

$$\text{coef}(Y_{sr}, Y'_{sr}) = 0.9652$$

$$\text{coef}(Y_{fq}, Y'_{fq}) = 0.9598$$

$$\text{coef}(Y_{vg}, Y'_{vg}) = 0.9601$$

Another correlation-coefficient analysis between various machining performances was evaluated as given in Table 8, which table shows that a larger MRR will be accompanied by a bigger R_a. A larger gap width will accompany a bigger R_a and gap voltage and the total discharge frequency will increase whilst the gap voltage decreases. It is impossible to achieve a higher MRR and good surface phenomena simultaneously. Therefore, the optimum machining parameters setting will be presented in the next section.

3.4. The optimization of machining parameters settings

The feasible-direction method of non-linear programming was applied to find the optimum machining set-

Table 5
ANOVA for MRR

Factor (A)	Degree (f_A)	Square sum (S_A)	Variance (V_A)	F_{A0}	$F_{0.05,n1,n2}$
Feed	1	547.7829	547.7829	**19.0955**	5.99
T_{on}	2	356.9892	178.4946	**6.2223**	5.14
T_{off}	2	0.4704	0.2352	0.0082	5.14
V_w	2	0.9528	0.4764	0.0166	5.14
F_w	2	0.2941	0.1471	0.0051	5.14
P	2	0.2444	0.1222	0.0043	5.14
E_{e1+e2}	6	172.1185	28.6864		
T	17	1078.852			

Bold type indicates significant factors.

ting by seeking the maximum value of the objective function under some constraints [9]. A programmed software was adopted to solve above problem.

Referring to Fig. 4, first an initial set of design variable X^0 is required to be specified as the starting point in the design space. Beginning from this starting point, the variable vector is updated iteratively by using the iterative form given by:

$$X^q = X^{q-1} + \alpha^* \cdot S^q$$

where X^q is the optimal variable solution and S^q is a usable-feasible search direction vector in the design space in no. q iteration. The scalar quantity α^* defines the distance that is desired to be moved in the direction S. The task is to find a search direction S which will reduce the objective function without violating the active constraint for some finite move. Any S vector which reduces the objective function is called the usable direction. Therefore, if the objective function is denoted by $F(X)$, then the dot product of the gradient of $F(X^0)$, $\nabla F(X^0)$ and S should be negative because the angle between them exceeds 90°. Mathematically, the usability requirement becomes:

$$\nabla F(X^0) \cdot S \leq 0$$

and a direction is called feasible if, for some small move in that direction, the active constraint will not be violated, i.e. the dot product of the gradient of $g_1(X^0)$, $\nabla g_1(X^0)$ and S must be non-positive. Here $g_1(X)$ is the constraint function. Thus:

$$\nabla g_1(X^0) \cdot S \leq 0$$

In this paper, the feasible-direction non-linear programming method is applied to show how the optimal machining parameters setting which will result in the maximum metal removal rate under constraints (surface roughness and gap limitations for examples) can be obtained.

For illustration purposes, if it is required to maximize the metal removal rate under the constraints of a gap width smaller or equal to 0.42 mm, and the surface roughness should be less or equal to 3.0 μm, then mathematically, this problem is expressed as:

Maximize: Y_{mr}

Subject to:

$$Y_{gap} \leq 0.42 \text{ mm}$$

$$Y_{sr} \leq 3.0 \ \mu\text{m}$$

$$(x_1 - 1)(x_1 - 0.7675) \leq 0$$

$$(x_2 - 1)(x_2 - 0.4771) \leq 0$$

The non-linear optimization yields:

Feed = 2.48 (mm min^{-1}) T_{on} = 8.13 (0.1 μs)

Table 6
The influence of machining parameters on machining performance

	Y_{mr}	Y_{gap}	Y_{sr}	Y_{tq}	Y_{vg}	Y_r
Feed	✱			✱	✱	
T_{on}	✱	✱	✱	✱	✱	☆
T_{off}			☆	☆	☆	
V_w	☆	☆				
F_w						
P						

✱, Significant parameter; ☆, sub-significant parameter.

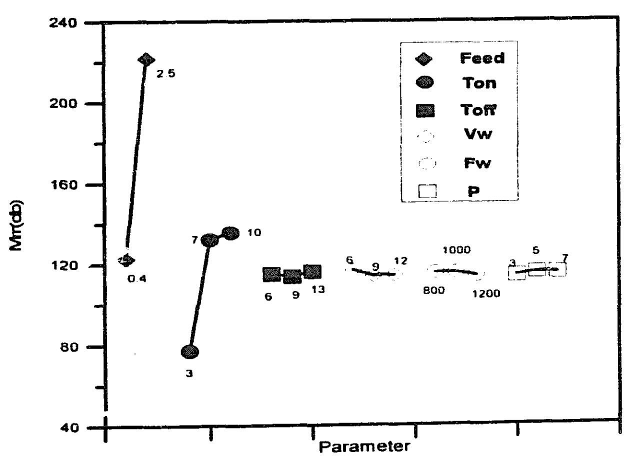

Fig. 1. The influence of machining parameters on the MRR.

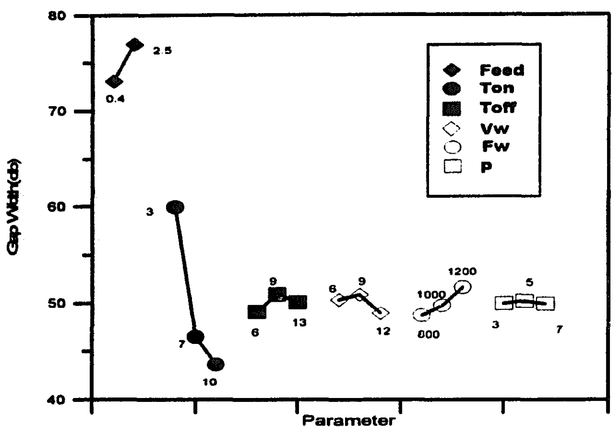

Fig. 2. The influence of machining parameters on the gap width.

In practice, if the following are chosen: Feed = 2.5 (mm $\min^{-1}$), $T_{on} = 8$ (0.1 μs), $T_{off} = 9$ (1.6 μs), $V_w = 9$ m $\min^{-1}$, $F_w = 1000$ gf, $P = 5$ kg cm^{-2}; then the actual experiments result in:

$Y_{mr} = 34.577\ (mm^3\ min^{-1})$ $\quad Y_{gap} = 0.403\ (mm)$

$Y_{sr} = 2.94\ (\mu m)$ $\quad Y_{fq} = 25.833\ (kHz)$

$Y_{vg} = 61.235\ (V)$

The metal removal rate is maximized whilst the gap width and surface roughness constraints are satisfied for a table feed of between 0.4 and 2.5 mm $\min^{-1}$ and T_{on} between 3 and 10 (0.1 μs).

4. Conclusions

A methodology to determine the optimal machining parameters setting in WEDM was proposed. This methodology is not only time saving and cost effective but also efficient and precise in determining the machining parameters.

Table 7
The trends of the influence of parameters on machining performance

	Y_{mr}	Y_{gap}	Y_{sr}	Y_{fq}	Y_{vg}	Y_t
Feed	↗			↗	↘	
T_{on}	↗	↗	↗	↘	↗	

↗, Performance increasing as increasing Feed or T_{on}.
↘, Performance decreasing as increasing Feed or T_{on}.

Table 8
Correlation coefficients between machining performance

	Y_{mr}	Y_{gap}	Y_{sr}	Y_{fq}	Y_{vg}
Y_{mr}	1				
Y_{gap}	0.2429	1			
Y_{sr}	0.4689	0.8701	1		
Y_{fq}	0.1594	−0.7945	−0.5898	1	
Y_{vg}	−0.0754	0.8178	0.636	−0.9496	1

It is found the table feed and pulse-on time have a significant influence on the metal removal rate, the gap voltage and the total discharge frequency, whilst the gap width and the surface roughness are mainly influenced by the pulse-on time. Therefore, adjusting the table feed and T_{on} is an appropriate strategy to control the discharging frequency for the prevention of wire breakage. A larger table feed and a smaller T_{on} are recommended for the reason that a longer T_{on} will result in a higher value of R_a. However, this does not take place for a larger Feed, although the table feed cannot be increased without constraints because of the risk of wire breakage.

In the future, the methodology presented in this paper could be applied to different machining condition such as different work material, electrode, etc. so as to build a CAPP expert system of WEDM with the goal of automation.

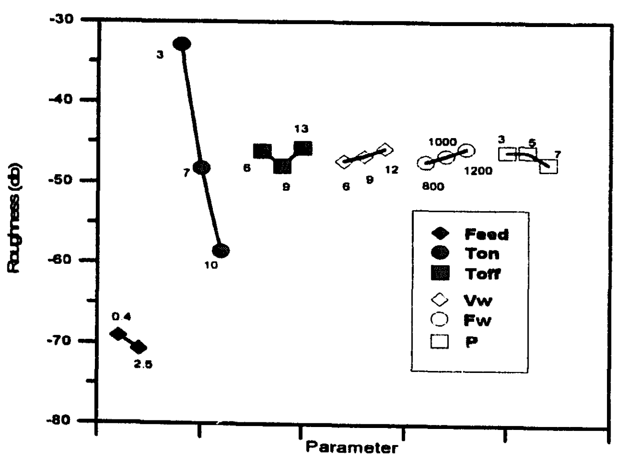

Fig. 3. The influence of machining parameters on the surface roughness.

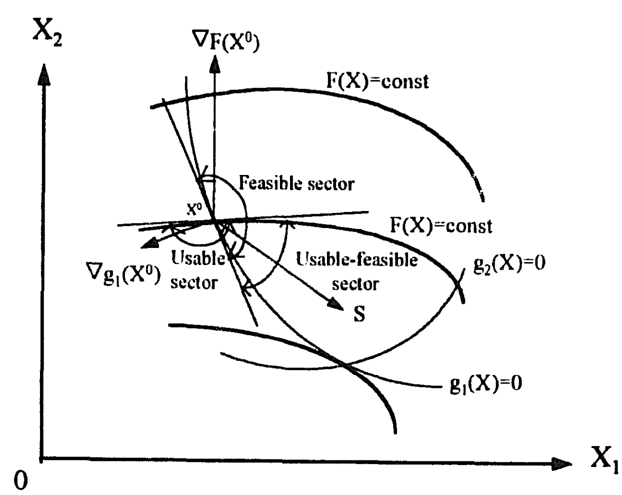

Fig. 4. Usable–feasible search direction [9].

5. Nomenclature

Feed	table feed
T_{on}	pulse-on time
T_{off}	pulse-off time
V_w	wire speed
F_w	wire tension
P	flushing pressure
Y_{gap}	gap width
Y_{mr}	metal removal rate
Y_{sr}	surface roughness
Y_{fq}	discharge frequency
Y_{vg}	gap voltage
Y_r	normal discharge frequency ratio

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