Some studies into Slicing of Titanium alloy using Wire Electro-Discharge Machining Process

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Abstract

Wire EDM has evolved as one of the promising method for the processing of advanced materials like ceramics, composites and super alloys. Titanium alloy are demanding material because they have properties like high strength to weight ratio and also have exceptional corrosion resistance.

Photovoltaic and chemical industries has demand of sliced parts and wafers as an important component and existing ingot cutting methods adopt contact forces in slicing that easily causes larger variation in the thickness of the sliced piece and higher surface roughness. Wire-EDM is potential process for slicing of advanced and brittle material.

The proposed work aims to demonstrate slicing capability of wire EDM of hard material Titanium (grade 2) using Taguchi's L_9 (3^4) orthogonal array. The optimising technique used is Taguchi based Grey Relational Analysis (TGRA). The influence of process parameters namely pulse on time, pulse off time, wire tension and wire feed rate on the performance characteristics like material removal rate and surface roughness has been studied in the present work.

Slicing of Titanium can be effectively done with the use of Wire EDM. It is found that pulse on time is highest significant factor for MRR and Surface roughness. As pulse on time increases MRR increases and surface roughness also increases. With the help of TGRA the best combination for optimization found are pulse on time 5 µs, pulse off time 7 µs, wire tension 10 kg and wire feed rate is 2 m/min.

***Keywords*:-**Titanium super alloy, WEDM, Slicing, process parameters, TGRA, Multi-objective optimization

1. INTRODUCTION

Advanced material such as hast-alloy, titanium, Inconel, ceramics, carbides and heavy metals are promising material for the modern industrial sector. Such material possesses difficulty by conventional machining. There is high demand of machining of such brittle material in industries like aerospace, medical and chemical industries. Slicing is a technique to slice the material into small thickness. Requirements of slicing technology are necessary for maximum productivity and minimum manufacturing cost. The desired properties which are required by above industries are the minimum surface roughness with crack- and damage-free surface and higher material removal rate.

Conventionally, inner diameter (ID) saws and wire saws have been used for slicing in manufacturing, as these methods are based on mechanical abrasive cutting, the contact forces adversely affect the newly generated surface. The damage may involve generation of surface micro cracks or other machining-related damage to the surface. Dongre et al (2013) [1] used brass wire for slicing of silicon wafers and analysed the performance parameters like current, pulse off time, pulse on time and servo voltage to control the kerf width, slicing speed and surface machine. They show that as current increases energy of spark increases and hence slicing speed increases more the pulse on time more the duration of discharge energy more the craters and hence more slicing speed lower servo voltage gives lower delay time and higher slicing speed also the conventional methods cause high surface roughness and low slicing speed.

Dongre et al (2015**)** [2] used molybdenum wire for slicing and optimise the parameter and found that the wire vibrations could have been minimized due to use of stronger molybdenum wire. The WEDM process does not apply any cutting force on ingots unlike ID saw and wire saw and gives highly finished, crack-free surface, irrespective of the size of the ingot. Joshi et al (2014) [3] used brass wire for slicing silicon wafers and they concluded that increase in open voltage and decrease in servo voltage increases the slicing rate. Bisaria et al (2019) [4] investigated process parameter wire tension, spark off time, and spark on time spark gap voltage, wire speed and response measure the cutting efficiency and surface roughness of $Ni_{50.89}Ti_{49.11}$ and observed that surface roughness and cutting efficiency are mainly influenced by spark on time, spark off time and spark gap voltage while wire speed and wire tension have the inconsequential effects. Sarkar et al (2006) [5] studied the behaviour of γ titanium during wire EDM machining and observed that the surface quality is lower for higher the cutting speed and the variation is approximately linear up to a surface roughness value of 2.44 μm.

Form the above literature review it is found that Wire-EDM is a potential process for slicing of brittle material. This work therefor demonstrates capability of wire EDM for slicing of hard material like Titanium through a multi-objective optimization. The wire–electrical discharge machining technology is adopted as a new candidate for slicing. The main focus of this work is to understand the effect of processing parameters like pulse on time, pulse off time, wire tension and wire feed rate on the cutting process, so the parametric conditions delivering high slicing rate and low surface roughness can be achieved.

2. EXPERIMENTAL PROCEDURE

The experiments were performed on EXCETEK EX 40 Wire-cut EDM machine of EXCETEK TECHNOLOGIES CO., LTD. and S&T Engineers Private Limited.

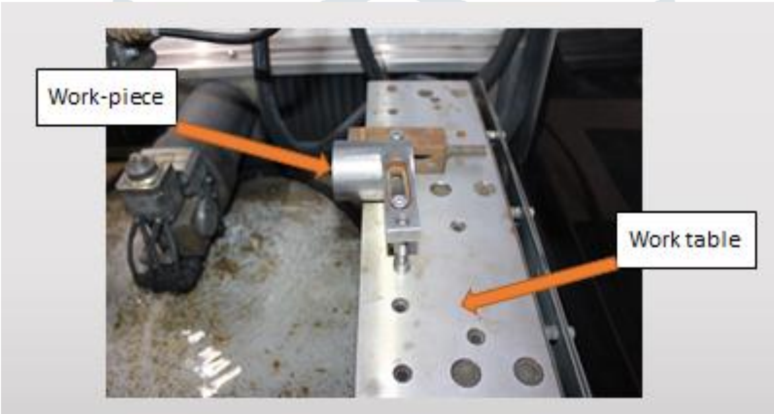

Figure 1: Mounted and clamped work-piece on work-table

2.1 Work material

Titanium (grade 2) ingot with dimension of ϕ 50 mm and length of 160 mm has been used as work material for this study.). Composition of work material as per spectroscopy report is shown in table 1. The sliced wafers has the thickness of 1.125 mm and a diameter of 50 mm circular. The tensile strength of material is 345 MPa and yield strength is 275 MPa. The density of Titanium grade 2 is 4512 kg/m^3 approximately half of steel density. Titanium is the light material with high strength also it is Brittle in nature. Due to its light weight and high strength it is widely used in aerospace and automotive industries

Table 1: Composition of Titanium (grade 2)

	N	C	O	Fe	H	Ti	Other
Min	-	-	-	-	-	-	-
Max	.03	.10	.25	.30	.0155	Balance	0.4

2.2 Wire material

The wire material used in this study is made of Brass whose diameter is 0.25 mm. The range of alloying element in the Brass material are 63-65.5% for Cu and 35-56.5%Zn. Composition of Brass wire is shown in the Table 2. For dielectric the De-ionised water is used for experiments.

Table 2: Composition of Brass wire [6]

Components	Coper (C)	Zinc (Zn)	Iron (Fe)	Lead (Pb)
Wt. %	63-67	balance	0.05 max	0.05 max

2.3 Process parameters

In this study the four process factors are included to see their effects on the responses and are described in Table 3 with their levels. The levels were decided on the basis of pilot run. Some of the parameters are kept constant during machining which are shown in table 4.

Table 3: Process parameters and their level

Factor	Name	Symbol	Unit	Levels		
				1	2	3
A	Pulse on time	T_{on}	Microsecond (μs)	5	10	15
B	Pulse off time	T_{off}	Microsecond (μs)	10	4	7
C	Wire Tension	WT	Gram (gm)	800	1000	1200
D	Wire Feed Rate	WFR	Meter/minute (m/min)	1	2	3

Table 4: Parameters kept constant during experimentation

Parameters	Symbol	Unit	Value
Open circuit voltage	OV	Volt	1
Servo voltage	SV	Volt	40
Arc on time	A_{on}	ns	7
Arc off time	A_{off}	μs	16
Dielectric fluid pressure	WP	Kgf/cm^2	5
Workpiece diameter	50 mm		
Sliced sample thickness	1.250 mm		
Wire diameter	.25 mm		

2.4 Performance measure

Material removal rate is calculated by the formula given in the equation 1. A surface roughness tester Surtronic 25 (Taylor Hobson) was taken into account for the measurement of surface roughness in this study.

$$\mathbf{MRR} = \frac{w_i - w_f}{\rho t}\ (\mathbf{mm^3/min}) \qquad (1)$$

Where W_i is the weight before the machining (gm), W_f is weight after the machining (gm), ρ is density of the workpiece, t is the time taken for the machining (min).

3. RESULTS AND DISCUSSION

3.1 Optimizing the data using TGRA

3.1.1 Data Normalization

Step by step procedure for the analysis of the data are given below for the experimental results for obtaining the linear normalization pre-processing is done which is known as grey relational generation [7].

Higher the better value [8]:

$$x_i(k) = \frac{y_i(k) - min\, y_i(k)}{max\, y_i(k) - min\, y_i(k)} \quad (2)$$

Lower the better value [9]:

$$x_i(k) = \frac{max\, y_i(k) - y_i(k)}{max\, y_i(k) - min\, y_i(k)} \quad (3)$$

$x_i(k)$ is the grey relational generation value after calculation; $min\, y_i(k)$ is lowest value of $y_i(k)$ and $max\, y_i(k)$ is the highest value of $y_i(k)$.

Table 5: Normalization of the experimental results for performance measures

Run	Data Normalization					
	Material Removal Rate (MRR)			Surface Roughness (SR)		
Ideal value	**1**	**1**	**1**	**1**	**1**	**1**
1	1.0000	1.0000	1.0000	0.722669	0.722673	0.722677
2	0.91246	0.91254	0.91262	1.00000	1.00000	1.00000
3	0.75960	0.75962	0.75964	0.941778	0.941787	0.941796
4	0.510081	0.510099	0.510118	0.668521	0.668525	0.668529
5	0.553748	0.553744	0.553740	0.795789	0.795796	0.795803
6	0.708869	0.708873	0.708877	0.692145	0.692147	0.692149
7	0.500000	0.500010	0.500020	0.500011	0.500000	0.499989
8	0.504833	0.504831	0.504829	0.568847	0.568838	0.568829
9	0.635969	0.635975	0.635981	0.603053	0.603048	0.603043

3.1.2 Grey Relational Coefficient

The relationship between the ideal and actual normalized values are established by the grey relational coefficient. A new matrix is formed after normalization of the output. It can be calculated by following expression [10]:

$$\xi = \frac{\underbrace{min}_{i}\underbrace{min}_{j}\left|x_j^0 - x_{ij}\right| + \zeta \underbrace{max}_{i}\underbrace{max}_{j}\left|x_j^0 - x_{ij}\right|}{\left|x_j^0 - x_{ij}\right| + \zeta \underbrace{max}_{i}\underbrace{max}_{j}\left|x_j^0 - x_{ij}\right|} \quad (4)$$

Where

x_j^0 is normalized result which is obtained by j^{th} response measures where x_j^0 value is considered 1 for the reference value. For computing the GRC the value of distinguishing coefficient ζ is taken as 1.

3.1.3 Determination of Grey Relational Grade (GRG)

Grey relational grade for each performance measures is obtained by taking an average of each grey relational coefficient of each performance measure [11].

The expression for the GRG is:

$$r_i = \frac{1}{m}\sum_{j=1}^{m} \xi_{ij} \quad (5)$$

GRG grade are calculated by the above equation which also provide the alternative ranking. The high value of GRG gives the Better ranking. The value of higher GRG shows that the S/N ratio of respective grade is much closer to normalized value. The GRG value for each experiment and their respective ranking is shown in the Table 8. From the table it is clear that run 2 having the 1 ranking gives the best multiple performance characteristics, followed by the run 1 and 3.

Table 6: GRG for each experimental run

Run	Grey relational grade	Rank
1	0.861336	2
2	0.956270	1
3	0.850703	3
4	0.589312	7
5	0.674770	5
6	0.700510	4
7	0.500000	9
8	0.536835	8
9	0.619511	6

3.1.4 Response Table for Grey Relational Grade (GRG)

Response table for GRG is shown below, the average value of GRG for the process parameter at different level is calculated. Then difference between maximum and minimum average value is calculated to obtain the ranking of the factors. The ranking decides the significance of different factors. It can be seen that highest significant factor is pulse on time following by pulse off time, wire feed rate and wire tension.

Table 7: Response Table for Grey Relational Grade (GRG) Larger the Better

Level	T_{on}	T_{off}	WT	WFR
1	0.8894*	0.7236*	0.6996	0.7185
2	0.6549	0.7226	0.7217*	0.7189*
3	0.5521	0.6502	0.6752	0.6590
Delta	0.3373	0.0734	0.0465	0.0600
Rank	**1**	**2**	**4**	**3**

***Optimum setting are A1B1C2D2**

3.1.5 Main effect plot for Grey Relational Grade (GRG)

In the given figure main effect plot is shown where the mid line represent the mean of GRG value. It is included from the figure that the optimum values for the maximum multiple performance are pulse on time of 5 µs, pulse of time of 4 µs, wire tension of 1000 gm and wire feed rate of 2 m/min. it is observed that the pulse on time is highest significant factor for higher MRR and lower Surface roughness. The combination of pulse on time and pulse off time having the value 5 µs and 4 µs gives the optimum output because high energy is released per spark because spark timing is increased viz. the energy will discharge for more time [12]. Low value of pulse off time gives low MRR because it causes increase in debris in spark gap which leads to abnormal cracking [13] also dielectric strength is not able to recover [14]. As the pulse on time increases the higher amount of energy is liberated which causes larger crater that leads to higher surface roughness [15]. Low pulse off time leads to poor time for reionization and high pulse off time indicates that sparking is off for long duration thus sufficient pulse off time leads to lower surface roughness [13]. The value of wire feed rate 2m/min gives the optimum condition as wire feed rate increases the MRR increases as the wire feed rate is increased more new wire comes in contact with the workpiece but further increase in wire feed rate causes wastage of wire [16]. 1000 gm wire tension is optimum for higher MRR and lower surface roughness as increased in wire tension ceases to lower the vibration in wire which leads to lower surface roughness and also the gap between electrode and work material becomes small thus rising in more energy release and higher MRR [17].

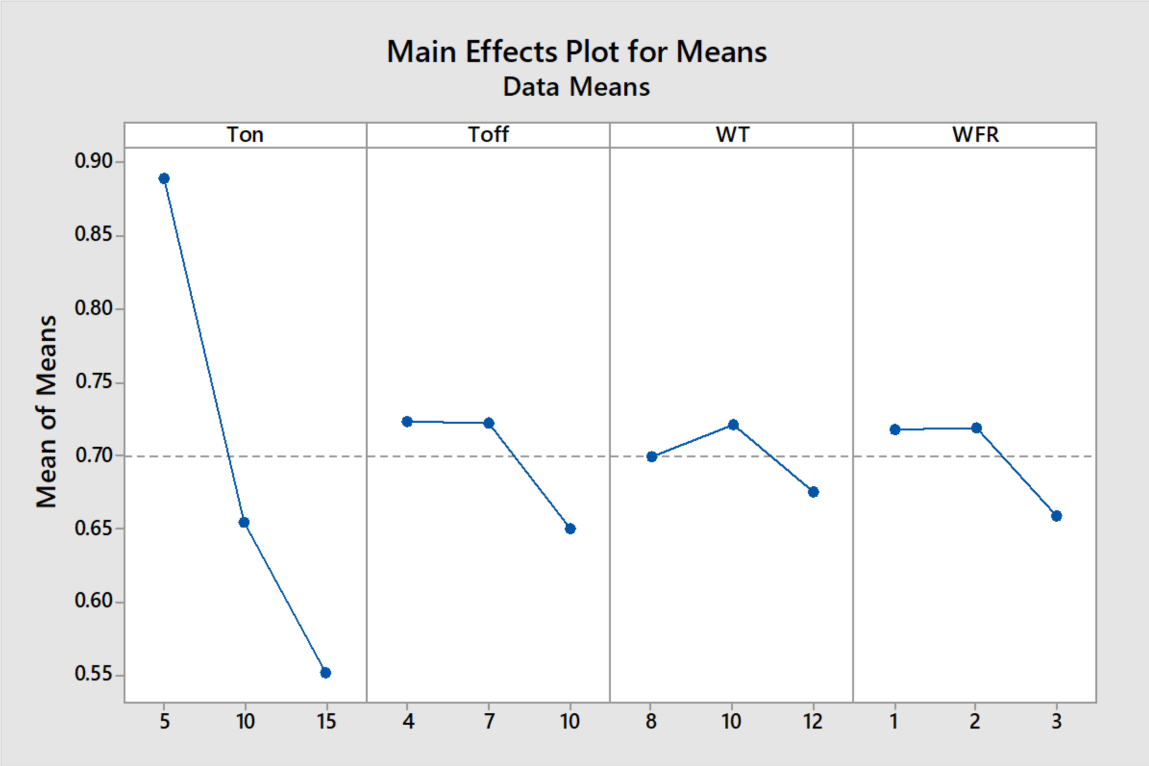

Figure 2: main effects plot based on grey relational grade (GRG)

4. CONCLUSION

In this experimental work, the response characteristics like MRR and Surface Roughness are optimized. Along with optimization of both responses the Taguchi Grey Relational Analysis is adopted for the multi-objective optimization of the responses. It also shows the inter relation between the all the factors without involving any complex mathematics. The various conclusion that are observed from the results are given below:

1. The higher value of GRG gives the optimal settings which are pulse on time, pulse off time, wire tension and wire feed rate and the optimum level are A1B1C2D2 respectively which gives the actual value as 5 µs for pulse on time, 10 µs for pulse off time, 1000 gm wire tension and 2 m/min wire feed rate.
2. The response table for GRG gives the ranking, this helps in determining the significance among the process parameters. The rankings are pulse on time as rank 1, pulse off time rank as 2, wire feed rate rank as 3 and wire tension rank as 4.
3. It was found that the pulse on time has the greatest significance among all other process parameters, followed by pulse off time, wire feed rate and wire tension for multi objective optimization.
4. Pulse on time the higher significant factor for higher material removal rate followed by wire feed rate, pulse off time and wire tension. As the pulse on time increases the material removal also increases but it also causes the higher surfaces roughness.
5. For surface roughness the significant factor are pulse on time followed by wire tension, pulse off time and wire feed rate. Wire tension has significant effect on the surface roughness as wire tension increases the vibration decreases and value of surface roughness decreases.

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