MANUFACTURING OF HIGH QUALITY MINIATURE GEARS BY WIRE ELECTRIC DISCHARGE MACHINING

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Abstract: *This chapter presents the manufacturing of high quality miniature spur gears of brass by Wire Electric Discharge Machining (WEDM). Effects of four WEDM parameters i.e. voltage, pulse-on time, pulse-off time and wire feed rate on five responses namely profile error, pitch error, average roughness, maximum roughness and material removal rate are studied. The experimental research was accomplished in three stages namely pilot, main and confirmation experimentation. The bracketed range of WEDM parameters by pilot experimentation were used in the main experiments designed using Box-Behnken approach of response surface methodology (RSM) and finally the confirmation experiments were conducted to validate the optimum results predicted by desirability anaylsis. The miniature gears manufactured by WEDM had defect-free microstructure, very thin recast layer, good surface finish and having gear quality upto DIN standard 5 for micro-geometry parameters (i.e. profile and pitch) which is much superior than the quality of the miniature gears manufactured by other existing conventional processes.*

Key words: *WEDM, miniature gears, profile, pitch, RSM*

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1. Introduction

In recent years the demand for high-accuracy fine pitch miniature gears has increased and is expected to continue its upward trend in the future also as the emphasis towards the miniaturization continues. The gears having outside diameter less than 10 mm are categorized as miniature gears. Miniature gears can be further subdivided as *micro-gears* (outside diameter < 1 mm) and *meso-gears* (outside diameter in the range of 1-10 mm). Miniature gears are one of the key components of the highly accurate miniaturized devices such as miniature motors and pumps, electronic and home appliances, business machines, automotive parts, timing devices, measuring instruments, MEMS and NEMS, etc. used in the scientific, industrial and domestics areas. Functional characteristics of these miniaturized devices depend on the quality of the miniature gears used. Therefore, highly accurate and advanced manufacturing processes are required for fabrication of high quality miniature gears. The present work is concerned with investigations on manufacturing of high quality meso-gears by WEDM. Brass, bronze, aluminium, stainless steel are the most commonly used materials for these gears (Davis, 2005; Townsend, 2011). Gears made of brass are primarily used as motion transmitting gears which are fine pitched and generally run at very high speed. Therefore, accurate motion transfer, minimum running noise and longer service life are the important desirable characteristics for these gears.

The conventional processes for manufacturing the miniature gears include hobbing, stamping, extrusion, die casting and powder metallurgy. But, these processes suffer from some inherent limitations as mentioned in the Table 1. Moreover, all these processes manufacture gears of low quality i.e. *Deutsche normen* (DIN) quality number is in the range of 9-12 (Bralla, 1998; Davis, 2005; Townsend, 2011). *DIN* and *American gear manufacturers association* (*AGMA*) are the international standards defining the quality of the gears in terms of micro-geometry parameters. Lower DIN number or higher AGMA number indicates better quality of the gear and vice-versa. Table 2 presents the quality requirements of the gears for various applications in terms of DIN and AGMA numbers along with the manufacturing processes used for the miniature gears.

1.1 Micro-Geometry of Miniature Gears

The important micro-geometry parameters of gears affecting their operating performance and service life include errors or deviations in the profile, lead, pitch, runout and surface roughness. Fig. 1 depicts the effects of these micro-geometry parameters on the performance characteristics of the gears. The profile error affects the noise behaviour, lead error governs the load carrying capacity while, pitch error and runout affect the motion transfer characteristics (Fig. 1) (Goch, 2003; Townsend, 2011). Profile error and lead error are the *form errors* while, pitch error and runout are the *position or location errors*. Form errors are the deviations from the intended nominal shape of the gear tooth surface, whereas location errors are related to the accuracy of location of teeth on a gear. *Profile errors* or deviations include form and angle (slope) deviation of the gear tooth profile from the nominal (intended) involute tooth profile, and are measured perpendicular to the functional profile.

Miniature gear manufacturing process	**Limitations**	**DIN quality number**
Hobbing	• Replicates tool marks on gear teeth • Needs subsequent polishing operation for high quality gears • Requires long set-up time.	9
Stamping	• Necessitates shaving operation for final finishing of gears • Cannot manufacture gears with higher tooth thickness • Wear & Tear of die and punch is a problem in stamping.	10
Die-Casting	• Cannot be used where extreme accuracy is needed • Subsequent trimming operations are necessary after the gear has been removed from the die.	11
Extrusion	• Requires secondary drawing operation for improving accuracy of gears • Wear of die is a major problem.	12
Powder Metallurgy	• De-binding of part from mould is difficult • Arrangement of fine metal powder of all types is difficult • Not suitable for gears other than spur type.	10

Tab. 1. Limitations of conventional processes for manufacturing of miniature gears with corresponding DIN quality

Application type	**Typical examples**	**AGMA quality number**	**DIN quality number**	**Corresponding manufacturing or finishing process**
Commercial applications	Hand tools, Pumps, Clocks, Slow speed machineries, Various appliances	3		Plaster-mold casting, Permanent-mold casting
		4	12	Investment casting, *Injection molding*[*], *Extrusion*[*]
		5	11	*Die casting*[*]
		6	10	Milling, Cold drawing, *Stamping*[*], *Powder metallurgy*[*]
		7		Rolling, Broaching
Precision applications	Aircraft engines, Turbines, Cameras, Automatic transmission systems, Instruments, High speed machineries	8	9-10	Rolling, Shaping, *Hobbing*[*]
		9	8-9	Rolling, Shaving, Honing, Lapping, Grinding
		10	7-8	Shaving, Honing, Lapping, Grinding
		11	6-7	Shaving, Grinding
		12-13	4-6	Grinding
Ultra-precision applications	Precision instruments, Military navigations	14	3-4	Grinding
		15	1-2	Grinding with extra care

[*] *used for manufacturing of the miniature gears*

Tab. 2. Quality requirements of the gears for various applications in terms of DIN and AGMA standards (Bralla, 1998; Davis, 2005; Townsend, 2011)

Lead errors or deviations include lead form deviation and lead angle (slope) deviation of the gear tooth flank along the face width and are measured at the middle of the tooth height. *Pitch error* is the difference between the nominal angular locations of the gear flanks to the actual measured locations. *Runout* is the maximum difference of the nominal radial position of all the teeth to the actual measured position. Both *pitch errors* and *runout* are measured at the middle of the tooth height. The geometric inaccuracy of a gear is caused due to the above said errors.

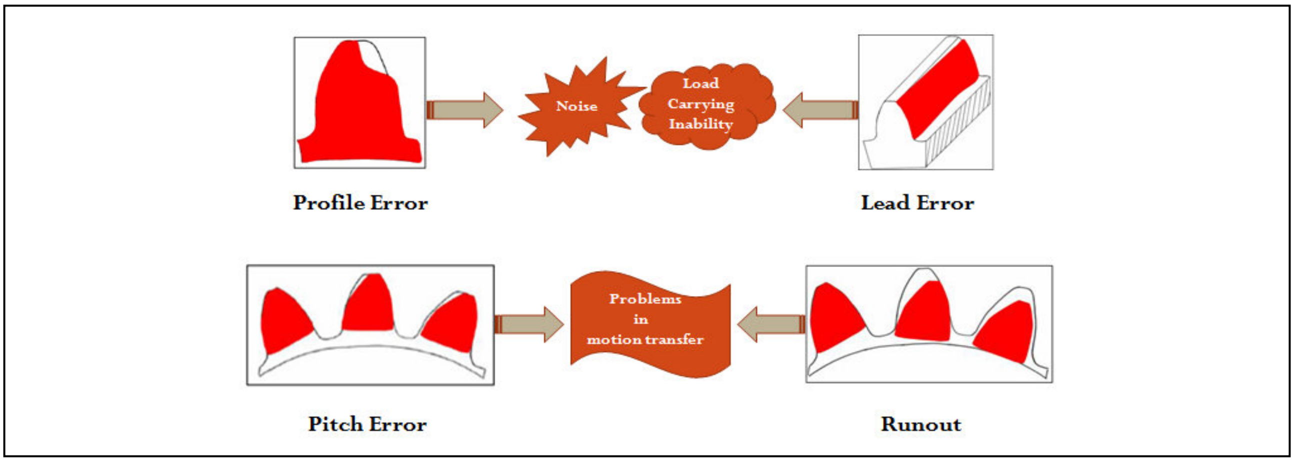


Fig. 1. Effects of micro-geometry errors on performance of miniature gears

Surface roughness refers to short-wavelength and high frequency closely spaced irregularities on the surface which are caused by the nature and the actions of the manufacturing processes (Davim, 2010). Surface roughness affects the fatigue life of the components and this particularly important for the components subjected to dynamic loading such as gears. Two most important surface roughness parameters are average surface roughness 'R_a' and maximum surface roughness 'R_t'. Higher surface roughness (i.e. presence of nicks, burrs, peaks and asperities) leads to early failure by occurrence of wear. Therefore, surface roughness should be minimized to prevent early failure of the gears.

1.2 Introduction to WEDM

High quality finish, better dimensional accuracy, burr-free surfaces and excellent repeatability are some of the important characteristics of WEDM (Benedict, 1987; Ho et al., 2004; Jain, 2008; McGeough, 1988). Therefore, WEDM has been recognized as a potential substitute to the conventional processes for micromachining and miniaturization applications (Gupta and Jain, 2013a-b; Hsu, 2008; Qin, 2010). In WEDM, the material is removed by the thermoelectric erosion process involving melting and vaporization caused due to the electric spark occurring between the wire and the workpiece material. For spark generation, the series of electrical pulses generated by the pulse generator is applied across the inter-electrode gap (IEG) between wire and workpiece in the presence of a dielectric. In the event of spark discharge, there is a flow of current across the IEG. Energy contained in a tiny spark discharge removes a fraction of workpiece material. Large number of such time spaced tiny discharges between the workpiece and wire electrode cause the electro-erosion of the workpiece material. Fig. 2 illustrates the working principle of WEDM.

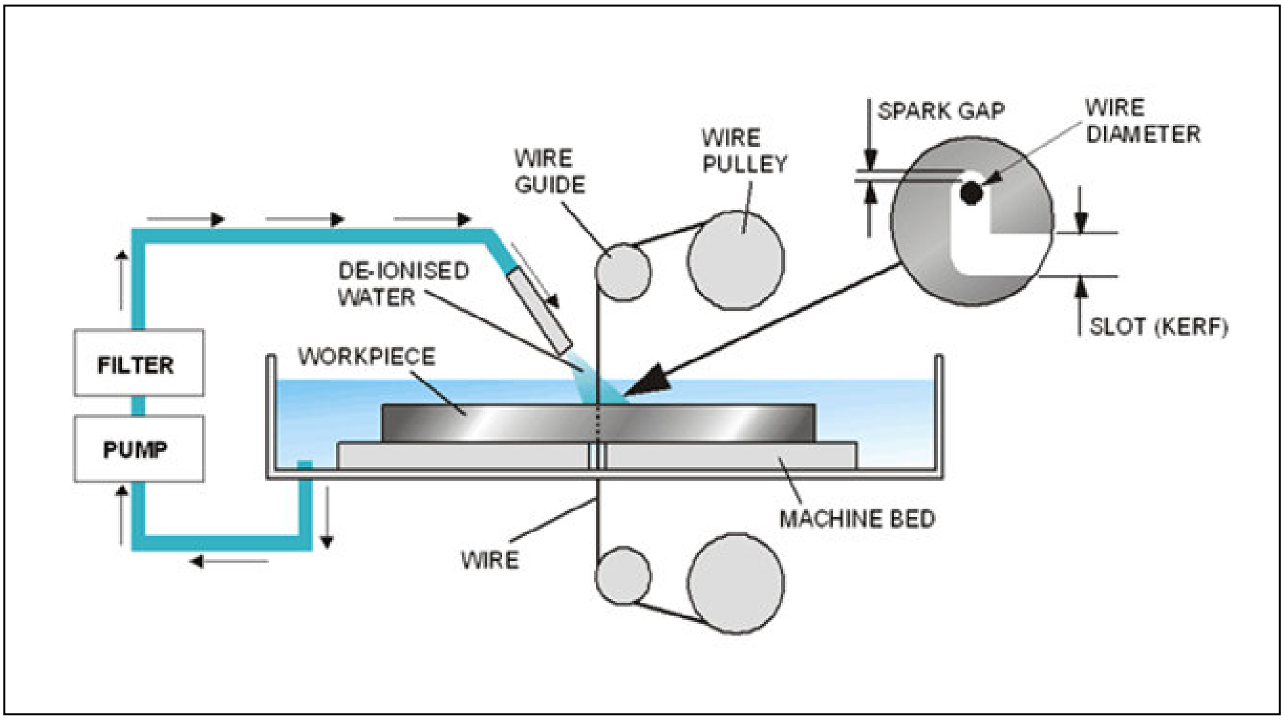


Fig. 2. Working principle of WEDM

The main causes of micro-geometry errors in WEDMed products are irregular shaped craters produced by violent spark at high discharge energy parameter settings, short circuiting, adherence of wire to the workpiece surface, and deflection of wire from its path known as *wire lag* (Arunachalam et al., 2001; Ho et al., 2004; Liao et al., 2004; Mingqi et al., 2005; Puri et al., 2003). The wire lag is caused due to impact of the mechanical forces produced by pressure from the gas bubbles, the axial forces applied to straighten the wire, the hydraulic forces induced by the dielectric flushing, the electro-static forces acting on the wire, and the electro-dynamic forces inherent to the spark generation.

2. Literature Survey

There are very few references available on manufacturing of miniature gears by WEDM or EDM-based processes. Takeuchi et al. (2000) developed a micro-planetary gear system of SKS3 tool steel and WC-Ni-Cr cermets of 0.03 mm module with the help of micro-EDM. The manufactured gears were found good in torque transmission performance. Benavides et al. (2002) manufactured miniature ratchet wheel of different materials (e.g. 304L stainless steel, nitronic 60, austenitic stainless, beryllium copper, and titanium) by micro-WEDM with submicron level surface finish, minimum recast layer and consistent micro-geometry. Di et al. (2006) machined miniature gears of 40 µm module and having seven teeth, from stainless steel plate of 1 mm thickness with an accuracy of ± 0.2 µm. Ali and Mohammad (2008) reported 1.4 µm as R_a and 7 µm as R_t for the miniature copper gear machined at 1 A discharge current, 8 V voltage and 8 μs pulse-on time by WEDM. Thereafter, Ali et al. (2010) obtained average surface roughness (R_a), peak-to-valley height (R_t) and dimensional accuracy of 1.8 μm, 7 μm and 2-3 μm respectively for WEDMed external spur gear of beryllium-copper having 3.58 mm diameter with seventeen teeth and 6 mm face width. Many attempts have been made in the recent past on improving the quality of WEDMed components by using various optimization methodologies (Kanlayasiri et al., 2013; Kuruvila et al., 2011; Tzeng et al., 2011; Yusup et al., 2012).

The review of past work reveals that no work has been reported on studying the behaviour of micro-geometry parameters (i.e. profile and pitch) of miniature gears with WEDM parameters. It can also be concluded that no literature seems to be available on optimization of parameters of WEDM for improving the manufacturing quality in terms of minimization of micro-geometry errors (errors in profile and pitch, and surface roughness of miniature gears). Also, productivity concept has not been taken care of in the previous work on WEDM of miniature gears. The present work bridges this gap by analyzing the behaviour of pitch, profile, surface roughness and material removal rate with the WEDM parameters and optimizing them for manufacturing high quality miniature gears.

3. Objectives of the Research Work

The prime objectives of the present research work were:

1. To explore the capability of WEDM for manufacturing high quality miniature gears.
2. To analyze the effect of WEDM parameters on micro-geometry, surface finish and material removal rate of the miniature gears.
3. To optimize the WEDM parameters to minimize the profile error, pitch error, average roughness, maximum roughness and maximize the MRR.
4. To establish WEDM as a superior alternative process for manufacturing the high quality miniature gears.

4. Research Methodology

The experimental research was accomplished in three stages namely pilot, main and confirmation experimentations. Table 3 presents the objectives, the input parameters, responses, design of experiments (DOE) approach and number of experiments conducted during each stage along with the specification of miniature gears manufactured. Pilot experiments were aimed to bracket the range of WEDM parameters and to fix the level of cutting speed for further research. Total twenty three experiments were designed based on one factor-at-a-time approach varying voltage, pulse-on time, pulse-off time and wire feed rate at five levels and cutting speed at three levels. The results of the pilot experiments gave a brief idea about the micro-geometry and surface integrity of WEDMed miniature gears.

Experimentation stage	**Objectives**	**Input parameters with levels**	**Responses**	**DOE approach (No. of experiments)**
Pilot Experiments	➢ To analyse the behaviour of micro-geometry parameters with WEDM parameters. ➢ To bracket the range of WEDM parameters for further investigations. ➢ To fix the cutting speed for further experimentation. ➢ To analyse the surface integrity of miniature gears.	1. Voltage (V): 5-10-15-20-25	Profile error (µm)	One factor at-a- time (23)
		2.Pulse-on time (µs): 0.6-0.8-1-1.2-1.4	Pitch error (µm)	
		3.Pulse-off time (µs) 90-130-170-210-250	Avg. roughness (µm)	
		4.Wire feed rate: 3-6-9-12-15 (m/min)	Max. roughness (µm)	
		5. Cutting speed (%)*: 50-75-100	Microstructure	
			Micro-hardness	
Main Experiments	➢ To analyse the effect of WEDM parameters and interactions between them on the responses. ➢ To further facilitate the optimization	1. Voltage (V): 5-10-15	Profile error (µm)	Box-Behnken of RSM (29)
		2. Pulse-on time (µs): 0.6-0.8-1	Pitch rrror (µm)	
		3. Pulse-off time (µs): 90-130-170	Avg. roughness (µm)	
		4. Wire feed rate: 9-12-15 (m/min)	Max. roughness (µm)	
			MRR (mm^3/min)	
Confirmation Experiments	➢ To validate the optimum results predicted by desirability analysis.	Optimized WEDM parameters	Profile Error (µm)	(5)
			Pitch Error (µm)	
			Avg. roughness (µm)	
			Max. roughness (µm)	
			MRR (mm^3/min)	
Fixed parameters: Wire material: brass; Wire diameter: 0.25 mm; Wire tension: 1200 grams, Dielectric: de-ionized water; Dielectric conductivity: 20 µS/cm; Dielectric pressure: 7 kg/cm^2 **Miniature gear specifications:** Material: brass; Profile: involute; Type: external spur gear; Pressure angle: 20^0; Module: 0.7 mm; Outside diameter: 9.8 mm; Number of teeth: 12; Face width: 5 mm. *Cutting speed was fixed during main and confirmation experiments.				

Tab. 3. Details of different stages of the experimentation

The main experiments were aimed to optimize the quality of the miniature gears by minimizing the geometric inaccuracy (i.e. profile and pitch errors), maximizing the surface finish (by minimizing average and maximum roughness), and the material removal rate (MRR). The main Experiments were designed using *Box-Behnken* approach of *response surface methodology* (Montgomery, 2009) by varying voltage, pulse-on time, pulse-off time and wire feed rate at three levels each. The 'Design Expert 8.0' software was used for regression and graphical analysis of the data obtained. Total 29 experiments were conducted with two replicates for the each experiment. Therefore, total 58 gears were manufactured. The values and ranges of fixed parameters were chosen based on the preliminary experiments (Gupta and Jain 2013) and the machine constraints. Analysis of variance (ANOVA) study based regression analysis was done to analyze the experimental data, to develop the relation between responses and WEDM parameters and to find the relative importance of the machining parameters with respect to the measures of performance (i.e. responses). The optimum values of the selected variables were obtained by solving the regression equations and by analyzing, the response surface contour plots. Finally, the confirmation experiments were conducted to validate the optimized results predicted by desirability analysis.

5. Manufacturing of Miniature Gears by WEDM

The miniature gears for the present research work were manufactured on *Ecocut* WEDM machine from *Electronica* India. This machine is based on closed-loop control system and having tolerance of ±15 µm. The machine tool comprises of a main work table (called as X-Y table) and a wire drive mechanism. The gear blank (5 mm thick copper plate) is mounted and clamped on the main work table. It moves along X and Y axes, in steps of 1 micron, by means of stepper motor. A traveling wire which is continuously fed from wire feed spool is caused to travel through the plate and goes finally to the waste-wire box. Along its traveling path, the wire is supported under tension, between a pair of wire guides which are disposed on both (lower and upper) sides of the gear blank. As the material removal or machining proceeds, the work table carrying the gear blank is displaced transversely along a predetermined path (based on the geometry of the miniature gear) which is stored in terms of linear and circular elements in the controller via numeric control program and tries to maintain constant machining gap. While the machining is continued, the machining zone is continuously flushed with de-ionized water as dielectric passing through the nozzles on both sides of the gear blank. An ion exchange resin is used in dielectric distribution system, in order to prevent the increase in conductivity and to maintain the conductivity of the water constant.

Part programs for manufacturing of miniature gears on WEDM were prepared by *Elcam* software which has a separate segment for gear profile creation. The gear profile geometry is defined in terms of various geometrical definitions (lines and arcs) as the wire-tool path elements on graphical screen. The wire compensation (off-set) for wire diameter and machining overcuts was specified. After the profile is fed to the computer, all the numerical information about the path is calculated automatically in terms of geometric and miscellaneous codes (G and M codes). The entered gear profile was verified on the graphic display screen with simulation facility. The numeric control program for gear profile was then transferred to the machine tool by RS 232 cable. The miniature gears were manufactured from a 5 mm thick rectangular brass plate using brass wire of 0.25 mm diameter and de-ionized water as dielectric. The process sequence for manufacturing of miniature gears is depicted by Fig 3.

Profile error (F_a) and pitch error (F_p) were measured on the *SmartGEAR* CNC gear metrology machine. The measurements were taken on the left and right flanks of four gear teeth for profile error and on both the flanks of all the twelve teeth for the pitch error. Profile error (F_a) was calculated by taking average of the mean values of the deviations in left flank (LF) and right flank (RF) of four gear teeth. While pitch error (F_p) was calculated by taking average of the maximum differences in angular positions of RF and LF for all twelve teeth. The surface roughness parameters i.e. average roughness (R_a) and maximum roughness (R_t) were evaluated using *Surfcom* roughness profiler from *Accretech, Japan* on an evaluation length of 0.75 mm on gear tooth flank surface along root to tip using 0.25 mm as cut-off length. For evaluation of the *MRR*, a weighing scale having resolution of 10 milligrams is used for taking the weights of the gear blank (plate of brass) before and after machining, and the machining time is recorded by a stop watch having least count of 0.01 second. The following equation was used to determine the MRR value:

$$MRR = \frac{M_1 - M_2}{\rho \times t} \quad (mm^3/min) \tag{1}$$

Where, M_1 and M_2 are the weights of the gear blank in grams before and after gear manufacturing by WEDM respectively; ρ is the density of the gear material in g/mm^3 (for brass it is 0.0084 g/mm^3); and t is the machining time in minutes.

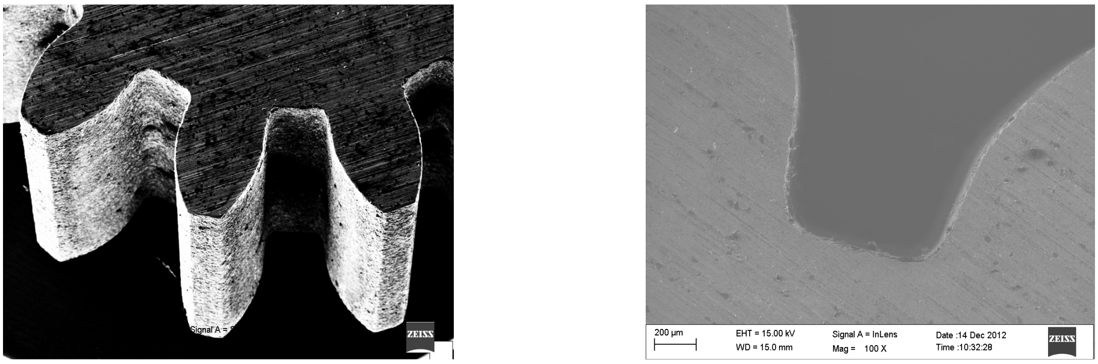
Fig. 3. Process sequence for manufacturing of miniature gears by WEDM

6. Results and Discussion

6.1 Results of Pilot Experiments

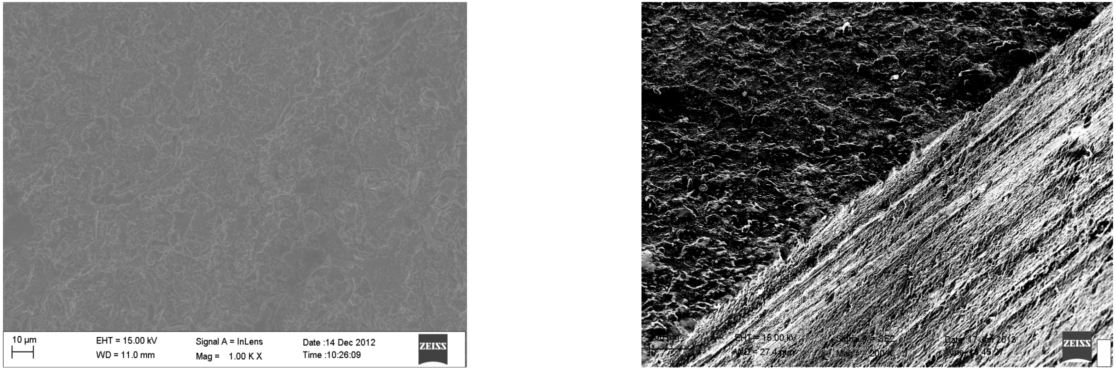
Keeping in view the objectives of minimizing the total profile error, accumulated pitch error and surface roughness simultaneously, 5-15V for voltage, 0.6-1.0 µs for pulse-on time, 90-170 µs for pulse-off time, 9-15 m/min for wire feed rate with 100

% cutting speed have been bracketed for further detailed investigations (Gupta and Jain, 2013a-b). The best quality miniature gear manufactured by WEDM using the combination of 15 V voltage, 1 µs pulse-on time, 170 µs pulse-off time, 9 m/min wire feed rate and 100% cutting speed, had DIN quality number of 6 for pitch (with pitch error of 11.2 µm), and DIN quality number of 8 for profile (with profile error of 13.2 µm). The values of average and maximum roughness for this gear were 1.1 µm and 6.4 µm respectively. The set of parameters for best quality gear generated crack-free, regular shaped shallow cratered teeth surfaces. No dominant pattern of micro-hardness variation, in case of the best quality gear, with respect to the depth was noticed. This indicates either the absence or very small thickness of recast layer and heat affected zone. This gear also had very low macro-geometry deviations i.e. deviation in span (4 µm), deviation in chordal tooth thickness (5 µm), deviation in the dimension over two balls (10 µm). Fig. 4 depicts the SEM images of the this gear showing (a-b) the uniform burr-free tooth profile (c) defect-free surface of the gear tooth (d) arrangements of craters on the WEDMed surface of the tooth of the best gear.



(a) at 50X

(b) at 100X



(c) at 1000X

(d) at 300X

Fig. 4. SEM images (a) and (b) proturbance-free gear teeth profile; (c) smooth crack-free texture of the best tooth surface; (d) uniform distribution of regular craters on tooth surface

Results of the experiments proved the capability of WEDM for manufacturing high quality miniature gears. Main experiments were conducted for analysing the behaviour of micro-geometry with WEDM parameters and to improve the quality of the miniature gears.

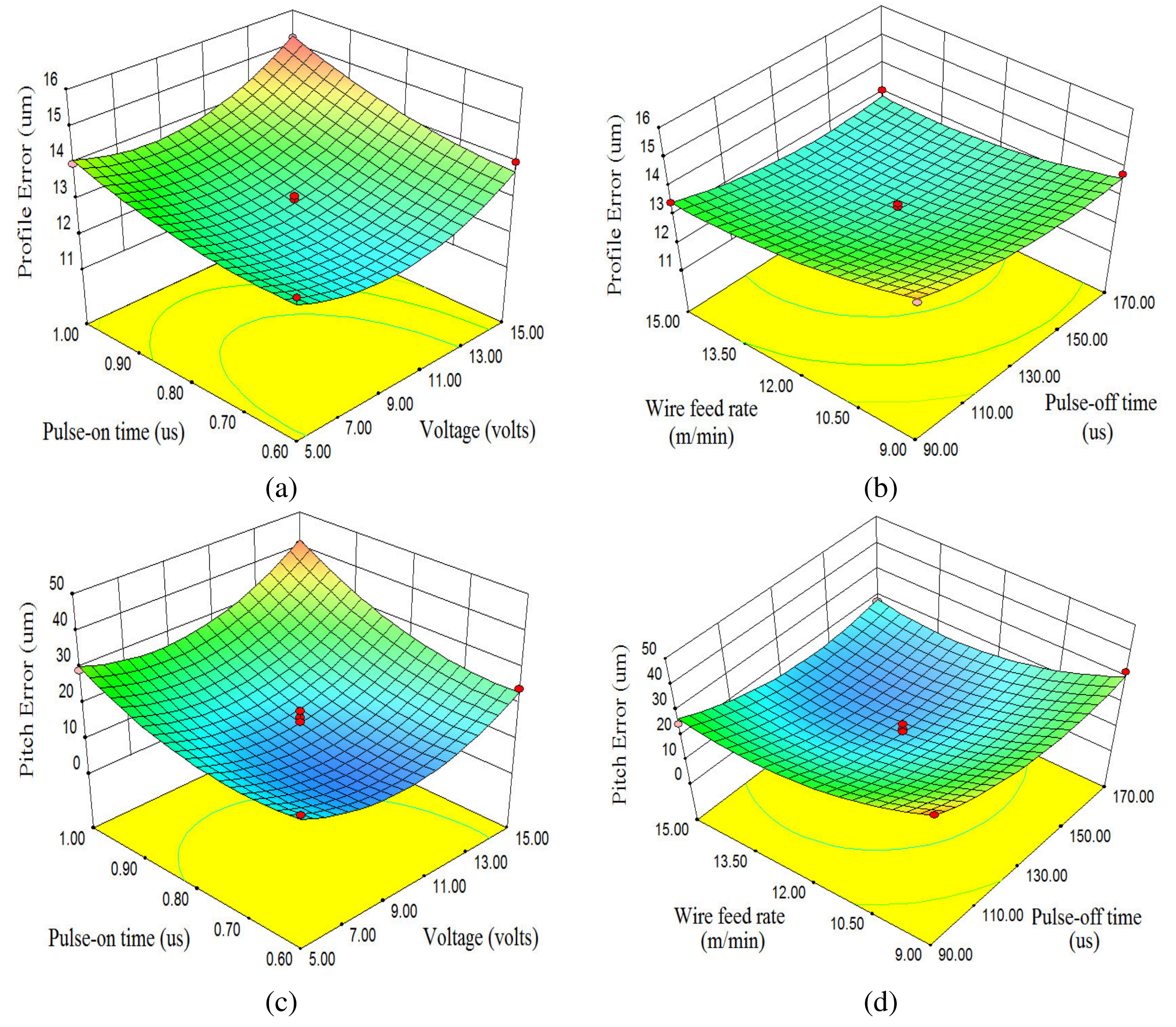
6.2 Results of Main Experimentation

Twenty nine main experiments were conducted according to *Box-Behnken* approach of RSM. Table 4 presents the parametric combinations and corresponding responses for the different experimental runs. ANOVA has been used to study the significant WEDM parameters.

Expt. No.	**Input Parameters**				**Responses**				
	V (Volts)	**T_{on} (µs)**	**T_{off} (µs)**	**W (m/min)**	**'F_a' (µm)**	**'F_p' (µm)**	**'R_a' (µm)**	**'R_t' (µm)**	**MRR (mm^3/min)**
1	15	0.8	130	15	14.20	30.20	1.70	7.40	38
2	10	0.8	90	9	14.50	41.00	2.00	9.20	42.5
3	5	1.0	130	12	14.00	29.40	1.80	8.72	25.68
4	10	0.8	130	12	13.10	12.40	1.40	7.23	28
5	15	0.6	130	12	14.00	24.20	1.44	7.14	25.46
6	5	0.8	130	9	14.40	32.10	1.70	8.00	31.4
7	5	0.8	170	12	13.00	19.20	1.35	6.87	17.8
8	10	1.0	130	9	14.60	44.50	1.82	8.85	35.58
9	15	0.8	130	9	14.80	38.60	1.76	8.55	38
10	10	0.8	170	15	13.10	18.10	1.28	7.01	27.6
11	15	0.8	170	12	14.40	35.00	1.71	7.30	28.2
12	15	1.0	130	12	15.20	40.80	1.92	8.90	42.42
13	10	0.8	130	12	12.80	16.25	1.65	7.00	30.5
14	10	0.8	130	12	12.50	11.80	1.70	6.78	34
15	10	0.8	130	12	13.10	15.00	1.60	6.90	27.8
16	15	0.8	90	12	14.80	35.70	1.87	8.70	36.4
17	10	0.8	170	9	13.80	32.40	1.68	7.80	25.54
18	10	1.0	90	12	13.90	38.00	1.97	9.80	40.73
19	5	0.8	90	12	14.30	34.00	1.61	8.20	28
20	10	0.8	130	12	13.00	18.20	1.76	7.11	32
21	10	0.6	90	12	14.20	28.35	1.63	7.30	28.16
22	10	0.6	170	12	11.70	8.30	1.40	7.00	24
23	10	0.8	90	15	13.50	25.10	1.55	8.23	32.45
24	10	1.0	130	15	14.00	27.00	1.74	8.70	37.17
25	5	0.6	130	12	13.30	20.65	1.14	6.72	16.08
26	10	0.6	130	9	13.50	25.00	1.49	7.45	30.64
27	10	1.0	170	12	14.60	32.80	1.65	7.90	28.8
28	5	0.8	130	15	13.00	22.40	1.25	6.75	22
29	10	0.6	130	15	12.00	16.00	1.18	6.90	20.26

Tab. 4. Experimental runs and corresponding responses for main experimentation

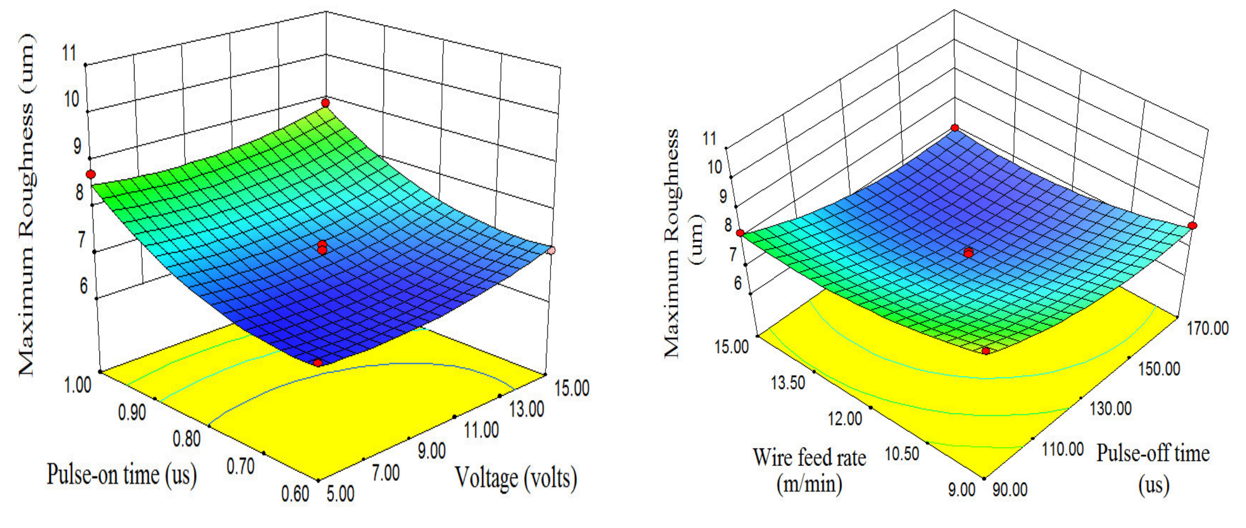
ANOVA study found that all four WEDM parameters significantly affect the profile error, pitch error, average roughness, maximum roughness and MRR. Figures 5 and 6 illustrates the variation of the response surfaces for F_a (Fig. 5a and 5b), F_p (Fig. 5c and 5d) and R_t (Fig. 6a and 6b) with the WEDM parameters. It can be observed that the minimum values of F_a and F_p are obtained in the range of 8-9 volts (Fig. 5a and 5c). This is due to fact that at very low voltage, high amount of wire lag is caused by high electrostatic force while, higher values of voltage and pulse-on-time lead to generation of larger forces caused by violent spark and pressure of the gas bubbles. It can be seen from Fig. 5b and 5d that there exists an optimum range for pulse-off time (140-160 µs) and wire feed rate (12.5-14 m/min). It can be explained by the fact that lower pulse-off time and wire feed rate causes wire vibrations due to short circuiting while, their higher values cause excessive hydraulic forces resulting in wire lag and again increasing errors in profile and pitch.



(a) (b) (c) (d)

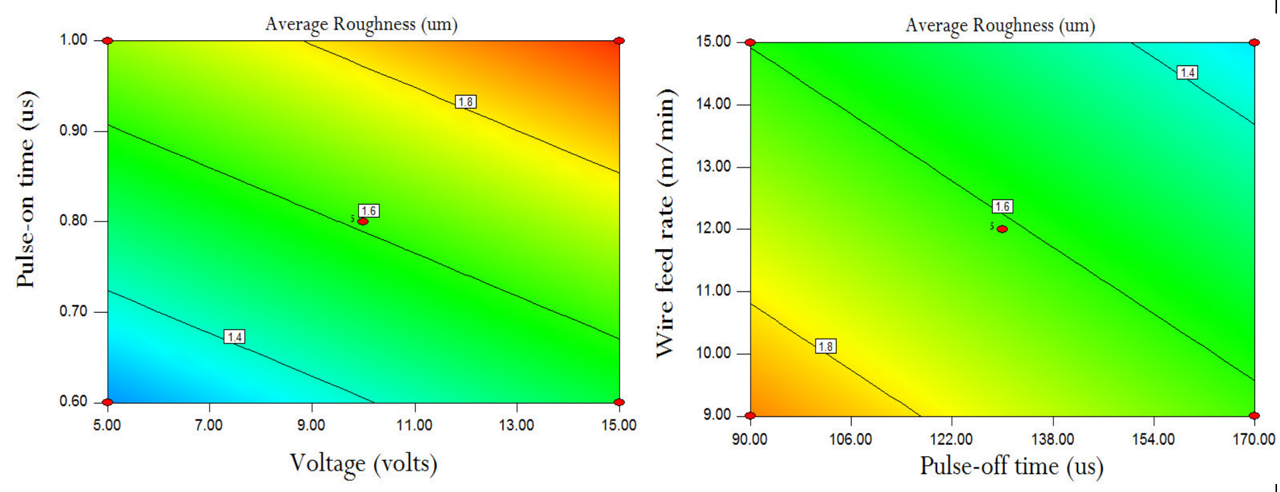
Fig. 5. Variation of F_a and F_p with WEDM parameters

It is evident from the Figures 6a and 6b that the optimum ranges of voltage (6-8 V), pulse-on time (0.6-0.7 µs), pulse-off time (150-160) and wire feed rate (12.5-14.5 m/min) exist for minimum R_t. While, variation of R_a is linear with WEDM parameters i.e. lowest voltage and pulse-on time (Fig. 7a) and highest pulse-off time and wire feed rate (Fig. 7b) should be used to minimize R_a. It can be explained by as follows. Use of higher voltage, longer pulse-on time and shorter pulse-off time increases the discharge energy at the plasma channel, availability of time for transfer of this energy to the gear tooth surface and decreases the flushing time. While, lower wire feed rate increases frequency of wire breakage. All these factors lead to formation of deeper and irregular craters on the gear tooth surface increasing the surface roughness value.



(a) (b)

Fig. 6. Variation of R_t with WEDM parameters



(a) (b)

Fig. 7. Variation of R_a with WEDM parameters

Fig. 8 shows the effects of WEDM parameters on MRR. It can be seen that higher MRR can be achieved using higher voltage, longer pulse-on time, shorter pulse-off time and lower wire feed rate. Increase in voltage and pulse-on time leads to increase in MRR because strong electric field at higher voltage facilitates the ionization of dielectric and thereby increase in discharge and increase in the period of transferring of discharge energy to the electrodes which results in rapid melting and evaporation of large amount of material.

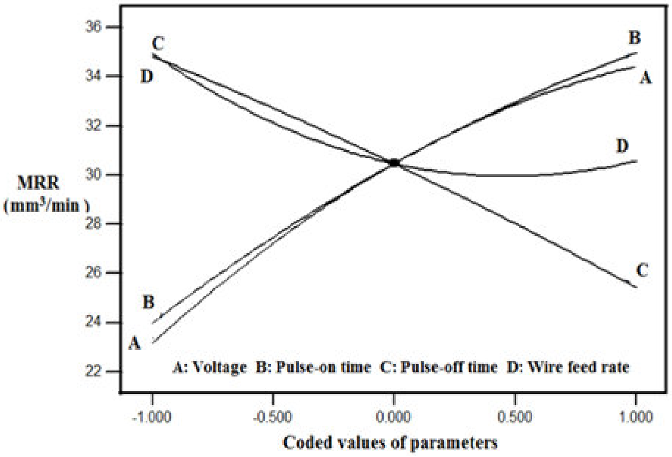


Fig. 8. Effect of WEDM parameters on *MRR*

6.3 Optimization

In order to get precise quality and productivity, the understanding and control of any process are the prerequisites and can only be achieved by accurate modelling and optimization of the process and its parameters. The single-objective optimization of WEDM parameters was done for minimum values of F_a, F_p, R_a, R_t and for maximum value of *MRR*.

6.3.1 Desirability analysis

Desirability analysis uses desirability function which is the geometric mean of the individual desirabilities of all the responses and tries to find the optimum values of the process parameters to meet the goal of the desirability function. Each response Y_i is converted into an individual desirability function d_i whose value can range from 0 (when the response is outside the acceptable region) to 1 (when the response is at its goal or target value). The more closely the response approaches the goal or target value, the closer is the desirability to 1. Equation (2) presents the generalized equation of the desirability function for the i^{th} data**:**

$$D_i = \left(\prod_{j=1}^{n} d_{ij} \right)^{\frac{1}{n}} \tag{2}$$

Where, n is number of responses; d_{ij} is the desirability of the j^{th} response for the data with $0 \leq d_{ij} \leq 1$.

In the present case there are five responses F_a, F_p, R_a, R_t and *MRR*. For each response the optimized values of WEDM parameters were predicted by desirability approach. The individual desirabilities for F_a, F_p, R_a, R_t and *MRR* for the i^{th} data were calculated by following equations (Montgomery, 2009):

$$\left(d_{F_a}\right)_i = \left[\frac{F_{a_{max}} - F_{a_i}}{F_{a_{max}} - F_{a_{min}}}\right] \quad (3) \qquad \left(d_{F_P}\right)_i = \left[\frac{F_{P_{max}} - F_{P_i}}{F_{P_{max}} - F_{P_{min}}}\right] \quad (4)$$

$$\left(d_{R_a}\right)_i = \left[\frac{R_{a_{max}} - R_{a_i}}{R_{a_{max}} - R_{a_{min}}}\right] \quad (5) \qquad \left(d_{R_t}\right)_i = \left[\frac{R_{t_{max}} - R_{t_i}}{R_{t_{max}} - R_{t_{min}}}\right] \quad (6)$$

$$(d_{MRR})_i = \left[\frac{MRR_i - MRR_{min}}{MRR_{max} - MRR_{min}}\right] \quad (7)$$

Where, *i* is the value of *i* th response obtained *min* and *max* are the minimum and maximum values of the responses.

6.4 Confirmation Experiments

The optimum values of the WEDM parameters obtained through desirability analysis for each response were standardized based on machine constraints and are given in Table 5. On these standardized optimum values of WEDM parameters, the confirmation experiments were conducted to validate the predicted results.Very close agreement found between the experimental results and those obtained by the desirablity analysis.

Responses	**WEDM parameters**								**Values of response from**	
	Optimized				**Standardized**				**Desirability analysis**	**Confirmation Experiments**
	V	T_{on}	T_{off}	W	V	T_{on}	T_{off}	W		
R_a	6.31	0.61	164.01	14.47	6	0.6	165	15	1.07	1.10
R_t	7.61	0.61	149.86	14.13	8	0.6	150	14	6.48	6.40
F_a	8.14	0.60	165.36	12.99	8	0.60	160	13	11.58	11.10
F_p ***D:0.983**	8.71	0.64	154.15	12.87	9	0.65	150	13	8.91	8.4
MRR	14.8	0.83	97.14	9.18	15	0.85	100	9	42.81	42.97

Tab. 5. Comparison of optimum values with the results of confirmation experiment for F_a, F_p, R_a, R_t and *MRR*

Fig. 9 depicts SEM images of the miniature gears manufactured at optimal parameters. It is clear that miniature gears have burr-free uniform tooth profile.

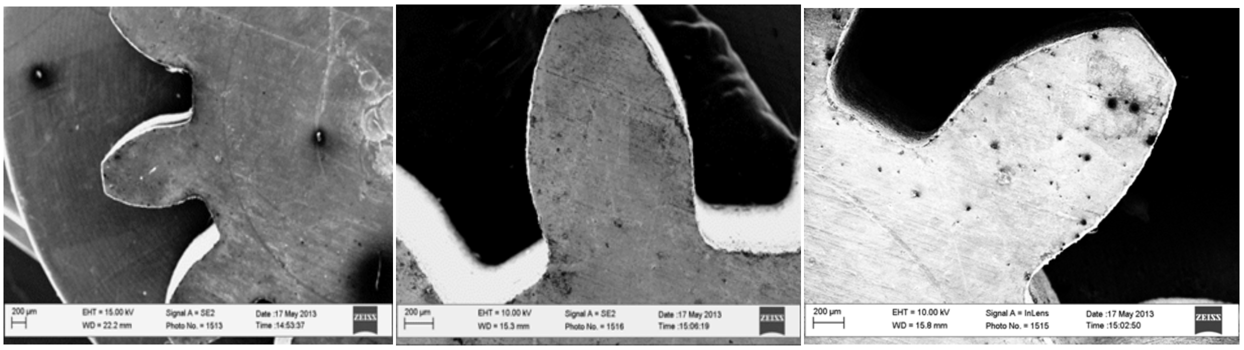


Fig. 9. SEM images of Miniature gear manufactured at optimal parameters

7. Conclusions and Future Scope

As the demand of the miniaturized devices continues to grow, the requirement of high quality miniature gears is ever increasing. The results of the present work would be very useful to engineers and manufacturers for manufacturing of high quality miniature gears by wire electric discharge machining. This chapter reported about the investigations on the effects of WEDM parameters on the profile error, pitch error, average roughness, maximum roughness and material removal rate of miniature gears. This chapter also describes the single objective optimization of WEDM parameters for minimization of profile error, pitch error, average roughness and maximum roughness, and maximization of MRR. Following conclusions can be drawn from the present work:

1. Voltage, pulse-on time, pulse-off time and wire feed rate were found to be highly significant parameters.
2. Main reasons of errors in profile and pitch, and surface roughness are irregular shaped craters created due to violent sparks having high discharge energy, short circuiting and adherence of wire on gear tooth surface, and wire-lag due to various forces generated during machining.
3. It was also found that WEDMed miniature gears had burr-free uniform profile, defect free surfaces and very thin recast layer.
4. Optimization was done to improve the quality and productivity of WEDMed miniature gears. Confirmation experiments revealed very close agreement between predicted and experimental results of optimization.
5. The optimized values of profile (11.1 μm) and pitch (8.4 μm) categorize the gear in high quality i.e. *DIN* quality number *7* and *5* respectively, which are superior than the other existing conventional processes of miniature gear manufacturing.
6. The results of the present work prove the superiority and capability of WEDM to manufacture high quality miniature gears for the miniaturized devices.

Similar work can also be done for miniature gears of different materials such as stainless steel, bronze, aluminium and other metallic materials. Wires of different materials and types can be used to manufacture miniature gears and effect of the same can be analyzed on the quality of miniature gears. High end WEDM machine tool having minimum constraints can be used to analyze the effect of other WEDM parameters such as current, wire tension, flushing pressure etc. on the quality of miniature gears.

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