On Productivity of WSEM Process for Manufacturing Meso-Sized Helical and Bevel Gears

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Abstract. This paper reports on productivity of wire spark-erosion-machining (WSEM) process for manufacturing meso-sized helical gear (MHG) and meso-sized bevel gear (MBG). Productivity of WSEM process is measured by volumetric gear cutting rate (\(VGCR\)). Variation in \(VGCR\) with four WSEM parameters such as servo voltage \(S_v\), pulse-on time \(T_{on}\), pulse-off time \(T_{off}\), and feed rate of wire \(W_f\) is also studied. Box-Behnken design approach of Response Surface Methodology (RSM) was used to design and conduct 29 experimental runs with replicates twice for analysis of \(VGCR\). Analysis of variance (ANOVA) was used to determine the significant parameters and their interactions. It was observed that all considered WSEM parameters are significant and considerably affect \(VGCR\). Desirability function analysis was used to find the optimum WSEM parameters so as to enhance the productivity of WSEM process to manufacture the better quality of MHG and MBG. Confirmation experiments were performed to validate the optimized values of \(VGCR\) corresponding to MHG and MBG and achieved much closer to it. Scanning electron micrographs (SEM) of MHG and MBG revealed uniform and burr-free tooth profile, bore and smoother cracks-free flank surfaces.

1. Introduction

Globally, demands of miniaturized parts and components growing continuously due to rapid development and application of MEMS and microsystems devices. Meso-sized gears (i.e. tip diameter ranging from 1 to 10 mm) are core constituents of these devices and commonly used for actuating and driving purposes. Meso-sized motors, pumps, gearboxes and actuators are some typical applications of these gears which are extensively used in chemical industries, dental and surgical instruments, precision instruments, prototype models, and domestic appliances [1, 2]. These gears are become more popular due to their light weight and small volume, stable superior performance, longer service life, minimum materials and manufacturing cost. Operating performance and service life of these gears are governed by its overall quality (i.e. aspects of gear quality and surface quality) [2]. Manufacturing processes and materials considerably affect the overall quality, manufacturing time and cost of meso-sized gears. Therefore, their proper selection is necessary to manufacture the high quality meso-sized gears with higher productivity and minimum manufacturing cost. Selection of appropriate materials and manufacturing processes of these gears mainly depends on their shape, size and types of applications. Stainless steel, low alloy steel, brass, bronze, copper, aluminium and plastic are
commonly used meso-sized gears materials. Manufacturing processes of meso-sized gears are classified as (i) subtracting processes: hobbing, milling; (ii) formative process: die casting, injection molding; (iii) deformative process: extrusion, rolling; (iv) micro-machining processes: LIGA, hot embossing, micro-injection and compression molding, bio etching; and (v) advanced manufacturing process: abrasive water jet machining; laser ablation, ion-beam machining. Poor gear quality (DIN 9-12), sharp edge definition, burr, microcracks, tool marks, applicable for specific types of gears and materials, requirement of appropriate finishing and hardening processes are some limitations of these processes. These inherent limitations of these manufacturing process and demands of high quality meso-sized gears at reasonable price in global market motivate the researchers to develop and explore another alternative process to manufacture high quality of meso-sized gears with higher productivity and minimum manufacturing cost [3, 4]. Wire spark-erosion machining (WSEM) is emerging advanced machining process to manufacture high quality of meso-sized cylindrical (i.e. spur and helical) and conical (i.e. bevel) gears. Generally, various input parameters govern the productivity of WSEM process to manufacture MHG and MBG. Therefore, selection of optimum WSEM parameters plays important role to manufacture high quality MHG and MBG with higher productivity and minimum manufacturing cost. Its offers several advantages to manufacture meso-sized cylindrical and conical gears (MCCG): (i) ability to manufacture MCCG from any electrically conductive materials of any hardness and thickness; (ii) manufacture different size and shape of gears from same gear plate without changing tool electrode (very thin brass wire) thus minimize total setting time; (iii) higher dimensional accuracy with smooth and burr-free flank surfaces; (iv) achieved gear quality of MCCG up to DIN 6-7 along with higher wear resistance on flank surfaces without using any subsequent finishing and hardening process; and (v) unattended manufacturing of MCCG [2, 3].

Review of past works revealed that WSEM is very emerging and promising advanced manufacturing process to manufacture closed to net-shape meso-sized gears from hard and difficult-to-machine materials. Regrettably, very limited work has been stated on spark-erosion based processes to manufacture meso-sized gears, improving gear quality and productivity. Most of the past work dedicated on fabrication of meso-sized spur gears (MSG), dimensional accuracy, surface roughness, and microstructural studies of meso-sized spur gears [5, 6, 7]. Productivity of WSEM process was improved to manufacture closed to net-shape MSG made of brass [8]. Extensive review of relevant past works revealed that no works have been conducted on manufacturing of MHG and MBG by WSEM process and improving its productivity. Therefore, the major objectives of this study are summarized as follow: (i) improve the productivity of WSEM process for manufacturing MHG and MBG; (ii) study variation in VGCR with WSEM parameters; (iii) identify significant WSEM parameters and their interaction on VGCR; (iv) optimize WSEM parameters with an objective to maximize VGCR to manufacture MHG and MBG; and (v) validate the optimized values of VGCR through confirmation experiments using optimum combination of WSEM parameters.

2. Experimental details

2.1. Details of Materials and Meso-sized Gears
In this study, austenitic stainless steel (grade SS 304) was chosen as gear materials to manufacture MHG and MBG due to their non-magnetic nature, higher resistance to corrosive atmosphere, very good wear resistance and perform satisfactorily for longer duration. It consists 8.3% Ni; 18% Cr; 0.05% C; 1.08% Mn; 0.48% Si; 0.017% S; 0.038% P; and balance Fe (iron) by weight. MHG and MBG made from SS 304 are commonly used in chemical, bio-chemical, pharmaceuticals, food processing industries and domestic appliances. The detailed design specifications of these gears are as follow: (i) for MHG: involute profile, 8.35 mm as tip diameter, 0.66 mm as module, 5 mm as face width, 10 teeth, 20° as helix angle (right hand) and pressure angle; and (ii) for MBG: involute profile, 9.8 mm as major diameter, 7.0 mm as minor diameter, 0.7 mm as module, 5 mm as face width, 12 teeth, 32° as cone angle, 20° as pressure angle.
2.2. Details of Manufacturing Process

Computerized Numerical Control (CNC) four axes (X, Y and U, V) Sprincut win WSEM machine from Electronica Machine Tools Ltd. Pune, India was used to manufacture MHG and MBG. A very fine brass wire of 250 µm diameter was used as tool electrode to cut the MHG and MBG from gear plate (having dimensions of 100 mm as length; 50 mm as width and 5 mm as thickness). Following is the sequences of manufacturing steps used to manufacture MHG and MBG by WSEM and measurement of volumetric gear cutting rate as shown in Figure 1: (i) workpiece preparation followed by grinding and buffing process to make top and bottom surface perfectly flat and edges perpendicular to each other; (ii) drilling of microholes on workpiece (i.e. gear plate) by μ-electro-discharge drilling process; (iii) mounting of workpiece on main worktable of WSEM through adjustable clamps and using dial gauge to ensure its proper mounting on worktable with respect to direction of feed rate of wire; (iv) using ELCAM software to prepared part program of MHG and MBG along with bore; (v) trepanning of microhole up to 3 mm diameter which served as bore of MHG and MBG and its center also served as a center of the meso-sized gears; (vi) run the WSEM in dry mode to bring upper and lower guide adjacent microhole which served as wire passage to cut MHG and MBG according to their corresponding part program; and (vii) microstructure studies of flank surfaces and calculating volumetric gear cutting rate using weighing machine and stop watch.

Figure 1. Sequences of different manufacturing steps used to manufacture MHG and MBG by WSEM process and measurement of considered response.

2.3. Methodology

Twenty nine experiments were designed and conducted (for MHG and MBG separately) according to Box–Behnken design (BBD) of response surface methodology (RSM) and each experiments repeated twice thus total 58 MHG and 58 MBG were manufactured by varying four WSEM parameters namely servo voltage (S_v), pulse-on time (T_on), pulse-off time (T_off) and feed rate of wire (W_f) at three levels each. Values of the fixed parameters, coded levels and their corresponding values of the variable WSEM parameters are depicted in Table 1. These values were selected on the basis of preliminary and pilot experiments conducted using one-variable-at-time approach of design of experiment keeping the view of wire breakage, gear cutting rate, gear quality and surface quality of MHG and MBG.

Table 1. Identified values of the fixed parameters, code levels and their equivalent values of the variable parameters of WSEM used in the experiments.

| Variable parameters | Code levels | Fixed parameters |
|---------------------|-------------|-----------------|
| Parameters (units)  | -1 0 1      | Peak current (I_p): 12 A; Cutting speed (C_s): 75%; Wire: Soft plain brass; Wire diameter: |
| Pulse-on time ‘T_on’ (µs) | 1.0 1.3 1.6 |                |
### 2.4. Measurement of Responses

Productivity of WSEM process is measured by volumetric gear cutting rate (VGCR). It defines as the amount of the material removed per unit time and expressed by the following equation:

\[
VGCR = \frac{W}{\rho \times t} \left( \frac{\text{mm}^3}{\text{min.}} \right)
\]

Where, \( W \) (i.e. \( W_{\text{before}} - (W_{\text{after}} + W_{\text{gear}}) \)) is total material lost during manufacturing of MHG and MBG obtained by subtracting weight of meso-gear \( W_{\text{gear}} \) and gear plate \( W_{\text{after}} \) after machining from the total weight of gear plate \( W_{\text{before}} \) before machining, \( \rho \) stands for density of gear materials and \( t \) stands for total manufacturing time of MHG and MBG.

Weight of gear plate was measured on precision weighing machine having accuracy up to 0.01g. Manufacturing time of MHG and MBG was directly revealed on the monitor of WSEM or can be calculated by a digital stop watch having a least count of 0.01 seconds. Supra 55 from Carl Zeiss was used for scanning electron microscopic (SEM) images of MHG and MBG.

### 3. Result and discussion

Following tasks were performed for analyses of VGCR of MHG and MBG and their corresponding 29 experimental run with replicates using 10th version of Design Expert software [9]:

(i) Using sequential model sum of squares (SMSS), lack-of-fit and model summary statistics (MSS) to identify the best suitable model for VGCR of MHG and MBG. It was concluded from these tests that the quadratic model is adequate to express the best fit polynomial equations for modelling VGCR of MHG and MBG.

(ii) Modelling equations for the responses using coded values of the variable parameters in the regression analysis. Then identifying significance of these equations along with variable parameters and their interactions involved in these models at 95% confidence interval using analysis of variance (ANOVA). This led to the following modeling equations in which \( S_V \), \( T_{on} \), \( T_{off} \), and \( W_F \) and their squared terms found to be significant parameters and interactions between \( T_{on} \) and \( T_{off} \); \( T_{on} \) and \( S_V \); and \( T_{off} \) and \( S_V \) were found to be significant.

For MHG

\[
VGCR_{\text{MHG}} = 3.86 + 0.97T_{on} - 0.41T_{off} + 0.58S_V + 0.24W_F + 0.25T_{on}^2 + 0.52T_{off}^2 + 0.46S_V^2 \\
+ 0.39W_F^2 - 0.28T_{on}T_{off} - 0.28T_{on}S_V + 0.32T_{off}S_V
\]

For MBG

\[
VGCR_{\text{MBG}} = 3.56 + 1.07T_{on} - 0.42T_{off} + 0.74S_V + 0.24W_F + 0.30T_{on}^2 + 0.38T_{off}^2 + 0.58S_V^2 \\
+ 0.21W_F^2 - 0.4T_{on}T_{off} + 0.32T_{on}S_V + 0.33T_{off}S_V
\]

(iii) Identifying the variation in VGCR with four WSEM parameters. Figures 2(a) and 2(b) shows variation of volumetric gear cutting rate ‘VGCR’ with servo voltage, pulse-on time, pulse-off time, and with feed rate of wire for WSEM manufactured MHG and MBG respectively. Figure 2 depicts main effect plots showing the influences of four WSEM parameters on the VGCR. It can be seen from these figures that (i) VGCR increases with increase in servo voltage and pulse-on time because higher values of these parameters produce violent spark which accelerate the formation of craters on flank surfaces results in higher material removal rate; (ii) VGCR decreases with increase in pulse-off time due to fact that at higher value of pulse-off time decrease frequency of sparks between wire and workpiece results in minimum material removal from workpiece per unit time; (iii) VGCR slightly increases with increase in feed rate of wire because higher feed rate ensure that fresh wire always available for sparking phenomenon in WSEM process. Fresh wire has better dimensional accuracy and ensures stable spark generation.
between inter electrode gap as compare to exposed wire to the spark results in higher material removal at higher feed rate of wire.

(iv) Identifying the optimum values of the WSEM parameters to maximize the VGCR.

![Image](a) MHG; and (b) MBG.

**4. Optimization**

Desirability functional analysis (DFA) was used for optimization of chosen WSEM parameters to maximize the VGCR of MHG and MBG. Considered response \( y_i \) is transformed into an individual desirability function ‘\( d_i \)’ \( (0 \leq d_i \leq 1) \). This study consist single response VGCR with overall objective to maximize it for value of desirability to 1. Therefore, the overall desirability function analysis of considered response of MHG and MBG for \( i^{th} \) data set can be expressed by following equation:

\[
D_i = \left( \prod_{i=1}^{m} d_i \right)^{\frac{1}{m}} \\
D_i = \left[ \left( d_{VGCR} \right) \right]^{\frac{1}{1}}
\]

Where, \( w_i \) represents the importance of each variable relative to the others; \( d_i \) represents discrete desirability of each response \( y_i \) and \( (0 \leq d_i \leq 1) \). Table 2 presents the optimum WSEM parameters and their corresponding values of VGCR for MHG and MBG obtained from desirability analysis.

**4.1. Validation of optimized results**

Confirmation experiments were performed to validate the optimized values of VGCR of MHG and MBG using optimum WSEM parameters closed to their available values in the machine. It was concluded from Table 2 that values of VGCR of MHG and MBG obtained from confirmation is much closer to their optimized values.

| Results | Optimum values of WSEM parameters | Optimized ‘VGCR’ (mm^3/min.) |
|---------|----------------------------------|-----------------------------|
| For MHG | \( T_{on} \) (\( \mu s \)) | \( T_{off} \) (\( \mu s \)) | \( S_V \) (Volts) | \( W_F \) (m/min.) |
| By DFA  | 1.5                              | 44.6                        | 10.3                 | 14.8         | 6.8         |
| By confirmation | 1.5                              | 44.5                        | 10                    | 15           | 6.7         |
| For MBG | By DFA  | 1.58                          | 46.03                    | 19.12               | 12.17        | 6.5         |
| By confirmation | 1.6                              | 45.5                        | 20                    | 12           | 6.3         |

**4.1.1. SEM images of optimized MHG and MBG.** Figure 3 depicts the SEM micrographs of tooth profile, flank surfaces and bore of MHG and MBG respectively. Figure 3(a) and Figure 3(b) showing the tooth profile, bore, and flank surfaces of MHG and MBG at 50X and 31X magnifications respectively. It can be seen from these micrographs that MHG and MBG have accurate involute tooth
profile and bore free from burr and sharp edge definition without undercut at root. While, flank surfaces of MHG and MBG are smooth, uniform and cracks free.

**Figure 3.** SEM micrographs of bore, tooth profile, and flank surfaces of WSEM manufactured meso-sized gears: (a) MHG at 50X magnification; and (b) MBG at 31X magnification.

5. Conclusions

This paper aimed to maximize the productivity of WSEM process for manufacturing MHG and MBG by WSEM process. Following are the major conclusions of this study:

- Enhanced productivity of the WSEM by achieving optimum parametric combination by DFA.
- $S_v$, $T_{on}$, $T_{off}$, and $W_f$ found as the significant parameters for both MHG and MBG which significantly affect the volumetric gear cutting rate. The significant interaction between $T_{on}$ and $T_{off}$; $T_{on}$ and $S_v$; and $T_{off}$ and $S_v$ on VGCR have been observed.
- VGCR of MHG and MBG increase with longer pulse-on time and higher servo voltage and decrease with longer pulse-off time. While slightly increase with feed rate of wire.
- Validate the optimized values of VGCR through confirmation experiments.
- SEM micrographs of MHG and MBG obtained by confirmation experiments revealed smoother and accurate tooth profile, bore, and flank surfaces free from burr and cracks.

Therefore, the results of the present study will be very useful for the industry users and researchers to manufacture the high quality of meso-sized cylindrical and conical gears with higher productivity.

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