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Comparative Study of Conventional and Micro WEDM based on Machining of Meso/Micro Sized Spur Gear

Mohammad Yeakub Ali[1,#], A. N. Mustafizul Karim[1], Erry Yulian T. Adesta[1], Ahmad Faris Ismail[2], 'Aisy Anuarin Abdullah[1] and Mohd Nazrol Idris[1]

1 Department of Manufacturing and Materials Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia
2 Department of Mechanical Engineering International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia
Corresponding Author / E-mail: mmyali@iium.edu.my, TEL: +603-6196-4507, FAX: +603-6196-4477

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This paper discusses the comparison of micro machining process using conventional and micro wire electrical discharge machining (WEDM) for fabrication of miniaturized components. Seventeen toothed miniaturized spur gear of 3.5 and 1.2 mm outside diameter were fabricated by conventional and micro WEDM respectively. The process parameters for both conventional and micro WEDM were optimized by preliminary experiments and analysis. The gears were investigated for the quality of surface finish and dimensional accuracy which were used as the criteria for the process evaluation. An average surface roughness (R_a) of 50 nm and dimensional accuracy of 0.1-1 μm were achieved in micro WEDM. Whenever applied conventional WEDM for meso/micro fabrication, a R_a surface roughness of 1.8 μm and dimensional accuracy of 2-3 μm were achieved. However, this level of surface roughness and dimensional accuracy are acceptable in many applications of micro engineering. A window of conventional WEDM consisting of low energy discharge parameters is identified for micromachining.

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1. Introduction

Micro fabrication using focused ion beam (FIB), LIGA (Lithography, Electroplating, and Molding), and other lithography based techniques were complex, expensive, and time consuming. As a result researchers throughout the world were investigating micro/meso mechanical manufacturing (M^4) such as electrical discharge machining (EDM), wire EDM (WEDM) and micro milling, etc. for fabricating micro parts with hard metals to be used as a master tool for replication in second stage.[1] Because of high cost and less availability of micro fabrication facilities, conventional EDM and WEDM were also used for micro machining where sub-millimeter sized holes, slits, etc. were successfully produced.[2,3] In WEDM, a thin wire was used as an electrode and the relative motion between the wire electrode and workpiece was maintained by a computer numerical control (CNC) program to cut the workpiece into desired shapes. This process was economical to cut complex products and difficult-to-machine materials.[4] As a result micro EDM and micro WEDM are found to be suitable for micro factory to produce small product economically.[5] The surface produced by WEDM consisted of many craters caused by electrical spark. The higher the discharge energy, the worse the surface finish was because of rippled surface, cracks, recast layer, etc..[6,7] The input parameters for micro/meso machining with WEDM were discharge current, gap voltage, pulse duration, pulse rate, polarity, etc..[8,9] Investigations have been carried out to improve the surface finish, material removal rate (MRR), when fabricating macro/meso/micro sized components using EDM and WEDM.[10-13] However, in relation to micro fabrication, the possible set of conventional WEDM parameters was to be identified for micro machining to achieve high surface finish and accuracy. The surface finish played an important role in micro fabrication as the tools were usually used as a master to replicate micro structures from different materials.[14,15] On the other hand, micro WEDM is a dedicated machine for micro fabrication with nanometric surface finish and sub-micro meter accuracy.

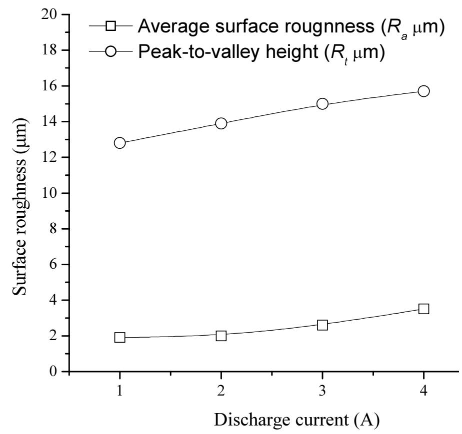
Micro gear was one of the key elements in micro drive systems for operating micro motors for controlling MEMS. It can be fabricated directly or by replication using polymer, metals, ceramics, etc..[16] Robotics, optical adjustment, drug delivery, surgical instrument, control of micro fludic nozzles, etc. are the few of many applications of micro gear systems.[17] Moreover, micro gear was a representative sample for micro machining as it involved linear, curvature and involute profile. This paper discusses the micro machining of spur gear using conventional and micro WEDM. These two processes were compared based on product's surface finish, dimensional accuracy as well as process capabilities and simplicities.

2. Machining of Meso/Micro Gear

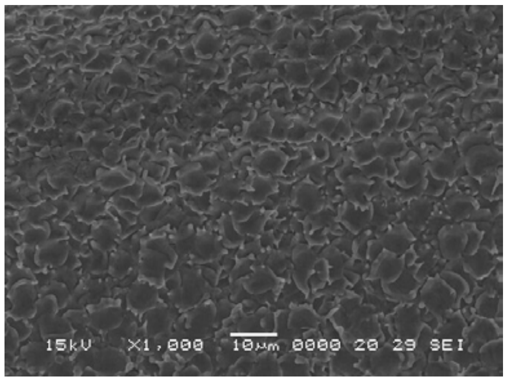
This section discusses the micro fabrication of micro gears using conventional and micro WEDM. At first, experiments were performed on beryllium copper substrate to identify the influence of discharge current of conventional WEDM on surface finish. Thin plates of 8 mm x 10 mm cross-sectional area were cut using the parameters as listed in Table 1. These parameters were selected based on literature review and preliminary experiments.[18,19] A conventional CNC WEDM (FX10K, Mitsubishi, Japan) with direct current (D-C) electrical circuit was used for these experiments. De-ionized water was used as a dielectric fluid. The surface roughness of the machined thin plates was investigated using surface profiler (Surftest SV-500, Mitutoyo, Japan) and scanning electron microscope (SEM) (JSM-5600, JEOL, Japan). The measured surface roughness values are plotted against the discharge current as shown in Figure 1(a). One of the SEM images of the surface texture is shown in Figure 1(b). The spur micro gear of 3.58 mm diameter and 17 teeth with fillet radius of 70 μm was first designed in CATIA as shown in Figure 2(a). Then, micro gear was fabricated on 6 mm thick beryllium copper blank by using the same WEDM machine. The optimum WEDM parameters for this micro fabrication, as determined by preliminary experiments, were 1 A discharge current, 5 V gap voltage, 6 μs pulse-on time, and 5 μs pulse-off time.[19] Other fixed parameters were remained the same as listed in Table 1. The average surface roughness (R_a), peak-to-valley height (R_t) and dimensional accuracy of the fabricated micro gears were measured. The SEM images of the micro gear are shown in Figure 2(b) and Figure 2(c). The measured surface roughness values were found to be 1.8 μm R_a and 7 μm R_t. The dimensional accuracy of the micro gears was found to be 2-3 μm.

Table 1 Selected conventional WEDM (FX10K, Mitsubishi, Japan) parameters for micro machining of a micro gear

Parameters	Values/description
Discharge current (A)	1, 2, 3, 4
Pulse-on time (μs)	6
Pulse-off time (μs)	5
Gap voltage (V)	5
Wire feed rate (μm.s^{-1})	20
Wire electrode diameter (μm)	100
Wire electrode speed (μm.s^{-1})	200
Workpiece polarity	+ve
Workpiece material	Be-Cu alloy
Dielectric fluid	De-ionized water
Wire electrode material	Brass
Results	
Micro gear diameter (mm)	3.58
Average surface finish (μm)	1.5
Dimensional accuracy (μm)	1.8
MRR (μg.min^{-1})	245
Machining time (min)	18
Average set up time (h)	2



(a)



(b)

Fig. 1 Analysis of surface roughness of conventional WEDM. (a) Plot of surface roughness with discharge current (6 μs pulse-on time, 5 μs pulse-off time, and 5 V gap voltage) and (b) SEM image of the machined surface texture (1 A current, 5 V gap voltage, 6 μs pulse-on time, and 5 μs pulse-off time)

In micro WEDM the key was to limit the discharge energy (i.e., the level of capacitance) to achieve higher surface finish and accuracy. Experiments were performed using a resistance capacitance (R-C) circuit micro WEDM (DT110, Mikrotools Inc., Singapore) to generate low energy discharge at high frequency. The experimental setup of micro WEDM is shown in Figure 3. An empirical relationship of surface roughness with capacitance is established for constant gap voltage and feed rate as shown in Figure 4(a). The texture of the machined surface as taken by SEM is shown in Figure 4(b). Then a micro gear of 1.2 mm diameter, 17 teeth, and 40 μm fillet radius was drafted using CATIA, as shown in

Figure 5(a), and then G code was generated. Then micro gear was cut from same material beryllium cooper blank. The process parameters for this micro gear are listed in Table 2. This micro gear has also been investigated in the similar way as described for conventional WEDM. The SEM images of this micro gear are shown in Figure 5(b) and Figure 5(c).

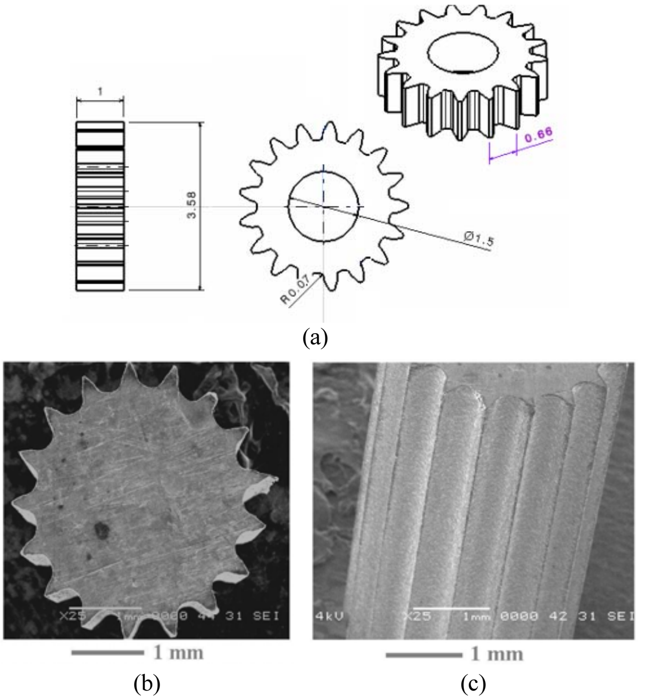


Fig. 2 Micro sized spur gear machined by conventional WEDM. (a) CAD model and SEM image of (b) top, (c) isometric view of machined micro gear. (Gear specification: Diameter 3.58 mm, pitch 0.66 mm, height 6 mm, and number teeth 17. Process parameters: 1 A discharge current, 5 V gap voltage, 6 µs pulse-on time, and 5 µs pulse-off time)

Table 2 Selected micro WEDM (DT110, Mikrotools Inc., Singapore) parameters for micro machining of a micro gear

Parameters	Values/description
Capacitance (nF)	0.1
Gap voltage (V)	90
Wire feed rate (µm.s^{-1})	3.8
Wire electrode diameter (µm)	70
Wire electrode speed (µm.s^{-1})	200
Workpiece polarity	+ve
Workpiece material	Be-Cu alloy
Dielectric fluid	EDM-3 synthetic oil
Wire electrode material	Zinc coated copper
Results	
Micro gear diameter (mm)	1.2
Average surface finish (µm)	0.050
Dimensional accuracy (µm)	0.25
MRR (µg.min^{-1})	90
Machining time (min)	60
Average set up time (h)	0.5

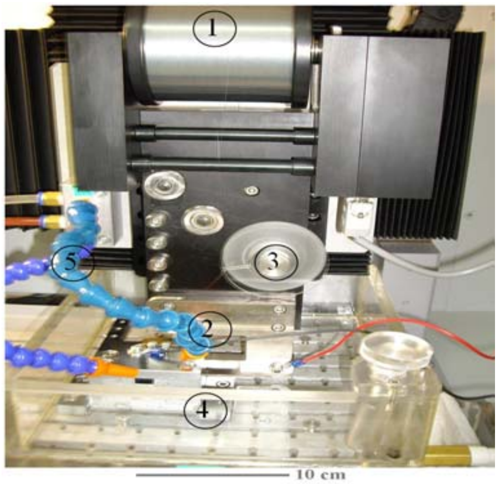


Fig. 3 Experimental setup of micro WEDM (DT110, Mikrotools Inc., Singapore). (Legend: 1. wire electrode supply spool, 2. workpiece and clamping device, 3. used wire collector spool, 4.dielectric tank, and 5. dielectric supply nozzle)

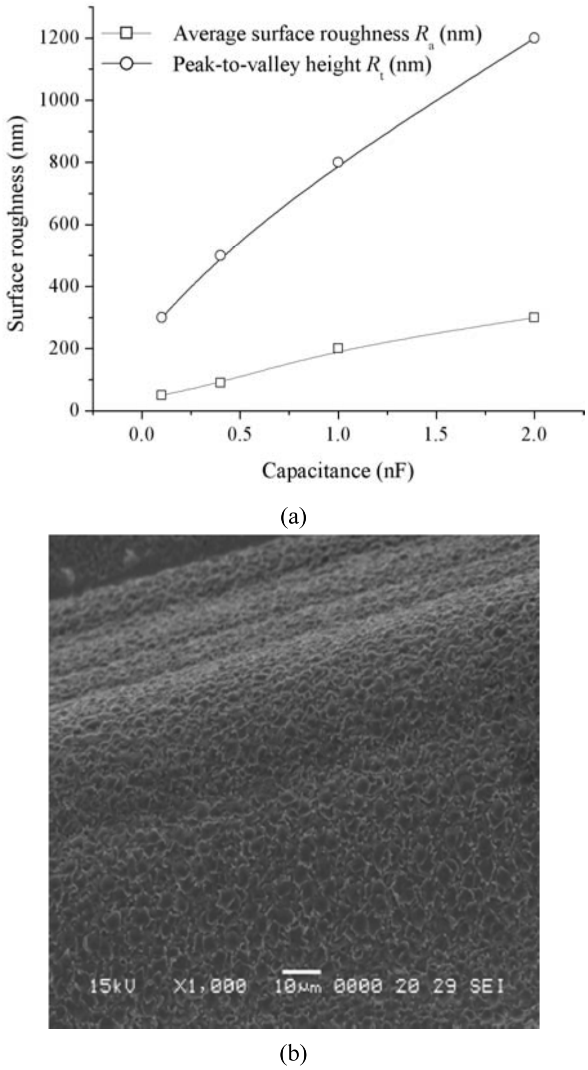


Fig. 4 Analysis of surface roughness of micro WEDM. (a) Plot of surface roughness with capacitance (3.8 µm.s-1 feed rate and 90 V gap voltage) and (b) SEM image of the machined surface texture (0.1 nF capacitance, 90 V gap voltage, and 3.8 µm.s-1 feed rate)

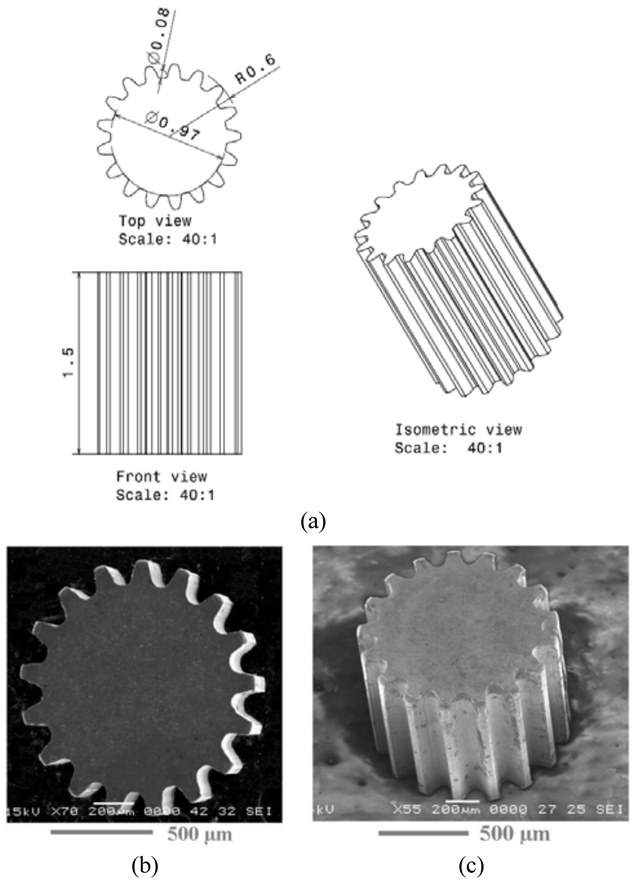


Fig. 5 Micro sized spur gear machined by micro WEDM. (a) CAD model and SEM image of (b) top, (c) isometric view of machined micro gear (Gear specification: Diameter 1.2 mm, pitch 200 μm, height 1.5 mm, and number teeth 17; Process parameters: 0.1 nF capacitance, 90 V gap voltage, and 3.8 $\mu m.s^{-1}$ feed rate)

3. Results and Discussions

Maximization of MRR was an important issue in fabricating macro-sized parts. However, in micro machining, the MRR was always very low and considered as one of the less significant responses. The main concern was the quality of the products which includes proper geometry, surface finish, process reliability, etc. The capability of the machine to produce miniaturized intricate geometry is also another critical issue. In this section, the discussion is based on the characteristics of several micro spur gears machined by conventional and micro WEDM.

(1) From the plot of discharge current and the measured surface roughness (Fig. 1(a)), it was found that the both average surface roughness (R_a) and peak-to-valley height (R_t) were greatly affected by discharge current. The surface roughness increased with the increase of discharge current. The minimum value of discharge current (1 A) provided the best surface finish of 1.5 μm R_a and 8 μm R_t.

(2) Lower discharge current (less than 1 A) would produce better surface finish but the machining time was very long with very low MRR. The longer pulse-on time did not change the energy level but prolonged the machining with more melting on the workpiece. As a result longer pulse-on time produced smoother surface as it widened the periodicity of the surface ripple. The pulse-off time was set to a constant value of 5 μs for all experiments. This time was to wash-away the debris and had no significant influence on surface finish. But if pulse-off time was set to a very low level, surface finish will be poorer because of short circuit with the wire electrode and debris that was not washed-out.

(3) The higher discharge current increased the spark size and created deeper crater on the surface of molten metal. At constant discharge current, if the pulse-on time decreased excessively, the EDM action struck deeper and worsened the surface finish. Higher gap voltage also increased the discharge energy and resulted higher material removal rate but generate poorer surface finish.

(4) In the R-C type micro WEDM, the processing parameters were different from the conventional WEDM with D-C power circuit. The main parameters of micro WEDM were capacitance and gap voltage. For the plot of capacitance and surface roughness (Fig. 4(a)), it can be seen that very high surface finish at nanometric level could be achieved compared to conventional WEDM (Fig. 1(a)). The surface roughness increases with the increase of capacitance which is the main factor for high energy discharge.

(5) From the fabrication of micro gears, it can be seen that the conventional WEDM can also be used for micro fabrication with some limitations on surface finish, accuracy, and overall dimensions. Initial studies are to be performed to identify the feasible window of conventional WEDM that can be used for micro fabrication. However, micro WEDM is straightforward for micro fabrication and it is dedicated for sub-millimeter sized components. General guidelines of the product specifications are listed in Table 3 for selecting conventional or micro WEDM for micro machining.

Table 3 Guidelines for selecting conventional WEDM or micro WEDM based on product specification and process capabilities

Specification	Conventional WEDM	Micro WEDM
Overall product dimension (mm)	2-5	0.1-3
Critical dimension (μm)	50	25
Dimensional accuracy (μm)	2-3	0.2-2
Average surface roughness R_a (μm)	1-3	0.01-0.05
MRR ($\mu g.min^{-1}$)	200-300	20-100
Processing time	low	high
Setup time	high	low

4. Conclusions

In this research, conventional WEDM and micro WEDM were used for machining meso/micro sized components. These processes were also compared. Using the conventional WEDM, miniaturized spur gears of 3.5 mm diameter were fabricated with 2-3 μm dimensional accuracy and about 1.8 µm R_a surface finish. Whereas, using the micro WEDM, miniaturized spur gears of 1.2 mm diameter were fabricated with 0.1-1µm dimensional accuracy and about 50 nm R_a surface finish. The following conclusions can be made from this research.

(1) Conventional WEDM can be used to machine miniaturized components with least cost compared to micro WEDM which required high capital investment and operational cost. The minimum sizes of the components depend on diameter of the electrode wire and the machine drive systems. It is recommended to use wire electrode of smallest diameter and low energy discharge machining parameters to achieve high geometrical integrity and surface finish. Although the micromachining process with conventional WEDM was slower than the conventional application of WEDM, it was faster than micro WEDM. The setup time of conventional WEDM for micro cutting was longer as the machine default setup is not for micro cutting. However, the setup time can be reduced if the conventional WEDM machine is repeatedly used for micromachining.

(2) The WEDM machine (DT110) used for machining of micro gear only has the G01 code of linear interpolation. However, G02 or G03 code of circular interpolation should be used to produce involute profile. As a result, the G01 code with very small distances is used to form the involute profile. Thus, the gear teeth profile was found to be not so perfectly invlouted. This is a specific problem with this machine and other machines with circular interpolation will not have this problem.

(3) The smallest diameter of wire electrode used for conventional WEDM was 100 µm. As a result, a fillet radius of 70 µm (larger than the wire electrode radius of 50 µm) was selected to allow the easy movement of the wire electrode at the filleted corner. So, considering a fillet radius of 70 µm, the possible smallest 17 toothed micro spur gear of 3.58 mm diameter was machined. The surface roughness of 1.8 µm R_a and 7 µm R_t were achieved which are acceptable for various applications in micro engineering. However, it is possible to produce smaller sized gear by using smaller wire diameter such as 70 µm as used for micro WEDM. Wire with the diameter of 100 µm was selected based on the availability during the experiment with conventional WEDM.

(4) When fabricating micro gears using micro WEDM, the fillet radius and wire electrode diameter were 40 µm and 70 µm respectively. Although it was very small, there was a clearance between wire and filleted corner to allow smooth movement of the wire to form the involute tooth profile. An average R_a surface roughness of 50 nm and dimensional accuracy of 0.1-1.0 µm were achieved. These levels of surface finish and dimensional accuracy were not possible to be achieved by conventional WEDM.

(5) To estimate the dimensional accuracy several micro gears were produced in confirmation experiments. The average dimensional variations were found to be 2-3 µm and 0.1-1 µm for conventional and micro WEDM respectively. The sub-micro meter resolution of micro WEDM axes ensured high level of dimensional accuracy. For the conventional WEDM the resolution was poor (25 µm). The other factors related to dimensional accuracies were measurement error, wire electrode vibration, etc.

(6) Micro gears produced by conventional and micro WEDM were inspected by SEM where no cracks were observed. A more powerful method such as x-ray radiography could be used for the identification of any micro cracks on or beneath the top surface.

(7) Finally it can be concluded that conventional WEDM can be considered as a “poor-man micro WEDM” for fabrication of 2-3 mm sized products with some limitations on surface finish and accuracy. The fabricated micro gear can be used as a hot embossing master for replicating internal micro gear from plastics.

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