On Productivity of Abrasive Water Jet Machining for Miniature Gear Manufacturing

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Abstract. Quality, productivity, and sustainability are three major indicators to evaluate the performance of any manufacturing process. Abrasive water jet machining (AWJM), which is an advanced or nonconventional machining process possess numerous benefits over conventional and other advanced processes for manufacturing of precision engineering components. Material removal rate directly indicates about the process productivity, and often finds contradictory to quality and sustainability. This paper reports the productivity of AWJM process while manufacturing miniature gears of brass. It is a part of experimental investigation conducted to manufacture high quality miniature brass gears using AWJM process. Taguchi L9 orthogonal array based experimental study where a total of nine experiments with two replicates each was conducted to evaluate the effect of AWJM parameters on miniature gear quality, process productivity and sustainability. AWJM parameters were optimized to enhance material removal rate and an optimum value of 18.80 mm³/min was obtained. Furthermore, AWJM was identified as a superior to conventional machining processes for manufacturing of miniature gears.

1. Introduction
There is a recent increase on the emphasis of miniaturization of assorted products used in various industries including science, industry and scientific applications. There is also a continuously growing demand for manufacturing high quality fine pitched miniature gears that are one of the key components/parts of the assorted products. Miniature gears are gears that have their outside diameter below 10 mm and further termed differently according to the size of the outside diameter. Miniature gears that have their outside diameter below 1 mm are called micro-gears while miniature gears with outside diameter ranging between 1 and 10 mm are referred to as meso-gears [1]. The gears are also classified further according to their motion carrying capacity and power transmission capability. The key components of most miniaturized devices specifically in measuring instruments, micro electromechanical systems (MEMS), timer mechanisms, electronics, nano electromechanical systems (NEMS), home appliances, business machines, automotive parts, miniature motors and pumps are mainly miniature gears [2].

The functional performance characteristics of the aforementioned devices are greatly relying upon the quality of the miniature gears utilized. Consequently, manufacturing processes of high accuracy and precision are necessitated for the manufacture of such gears.

Fine-pitched miniature brass gears operate at great speeds as high as 50 000 rpm and are chiefly applied in motion transmission. Therefore, the desired characteristics for these miniature brass gears...
include minimum running noise, longer service life and accurate motion transfer. The traditional or conventional processes of manufacturing miniature gears made from metals are widely grouped into three categories i.e. forming- stamping and extrusion, additive- casting, and material removal-hobbing. All these conventional processes suffer from certain inherent limitations and, in common, all are not capable to manufacture good quality gears [3]. Furthermore, all seek the assistance of post finishing operations for producing high quality miniature gears. This causes long process chain of gear manufacture, and consequently results in escalated manufacturing cost and high environmental footprint.

It is therefore necessary to develop and explore a sustainable alternative to these techniques to manufacture quality gears that are both cost effective and environmentally friendly.

On such process with the potential is abrasive water jet machining (AWJM), as it has a history of being the preferred choice for the production of miniaturized parts, because of its capabilities including free of burrs, corrosion resistant, ability to cut conductive and nonconductive materials regardless of their toughness or hardness, wear resistant surface and high quality surface finish without any post finishing operation [4-7].

Abrasive water jet machining is an extended version of water jet machining where abrasive particles such as aluminium oxide, silicon carbide, or garnet etc. are contained within the water jet with the purpose of raising the rate of material removal beyond that of a water jet machine [8, 9]. First AWJM commercial system came into the market place during the late 1980’s as a prime improvement within the field of non-conventional processing technologies. A typical abrasive water jet system consists of a pump system of high pressure, a catcher unit, abrasive feed system, a position control system, an abrasive water jet cutting head and a water supply system. This manufacturing technique operates on the mechanical erosion principle in which acceleration of abrasive slurry through a high-pressure fine jet is used to cut the material of interest. Abrasive type, size, and mass flow rate; water jet pressure; stand-off distance; and traverse speed are the important parameters of AWJM process.

There has been a previous track record of this process to machine precision engineering parts, to cut difficult-to-machine materials, and making complex shapes and features. Some of the important past work as regards to that is discussed here as under.

Abrasive water jet machining was attempted to explore as an alternate method of gear manufacturing a long back [10]. Thereafter, few attempts were made for cutting gears by this process. Planetary gears of good quality were machined by AWJM for possible application in micro-motor [7]. Liu and Schubert (2012) produced both meso and macro gears of stainless steel with outside diameters of 3.55 mm, 9.68 mm and 19.05 mm respectively by AWJM process using a 254 micro meter diameter nozzle [11]. Not only micro-gears, AWJM has also been successfully utilized to machine microelectronic components as well [5]. AWJM has also been used successfully for micro-pillar fabrication [6]. Furthermore, abrasive water jet machining has also been used for polishing (of hard brittle materials) and cleaning applications [12]. Downsizing of AWJM’s nozzle and orifice system efficiently helped for micromachining of precision thin structures and manufacture of micro heat sinks [13]. The thickness of heat sinks or fins manufactured by AWJM varied from 150 to 700 µm. In an important recent attempt, micro-holes and micro-channels have successfully been fabricated in amorphous glass by AWJM machining technology [14].

Many statistical and soft computing techniques have been used to optimize AWJM parameters for part quality and process productivity. In a recent work, Bhowmik et al. (2019) performed TOPSIS based optimization of AWJM parameters for optimum machining of sundi wood dust reinforced polymer matrix composites [15]. MRR, surface roughness, and geometric accuracy were significantly improved. Taguchi integrated RSM technique was used for surface finish optimization of Kelvar composites cutting by AWJM [16]. Another important study makes use of Jaya algorithm for single and multi-response optimization of AWJM process [17]. The best value of MRR obtained is 6769.7 µm³/µs, whereas average roughness is 2.7002 µm.

Literature review reveals the capability of AWJM for precision machining and cutting. However, there are very few articles available on systematic description of miniature gear manufacturing by
Moreover, on productivity of AWJM for miniature gear manufacturing, still some imp aspects are required to be reported.

Along with surface quality of the machined parts, material removal rate (MRR) is also an important machinability indicator. This paper fulfills the gap and reports on material removal rate of abrasive water jet machining process for manufacturing of miniature gears of brass. It further presents optimization of the process parameters for the enhanced MRR of AWJM.

2. Experimental details

In this research, a brass plate of rectangular shape has been used as a raw material, in which miniature external spur gears have been cut by AWJM. A total of nine experiments have been conducted with two replicates each based on the Taguchi robust design of experiment technique (L9 orthogonal array). Table 1 present the values and levels of AWJM parameters for gear machining. Figure 1 presents the experimental setup used to machine miniature gears by AWJM in this research work. Three important AWJM parameters such as water jet pressure (WP), abrasive mass flow rate (AMFR), and stand-off distance (SoD) have been varied at three levels each to analyze the effect on gear surface quality and process productivity. The values of fixed, and range and levels of variable parameters have been selected based on machine constraints, literature review, and some trial experiments. Garnet abrasives with 80 mesh size have been used for cutting/machining of miniature brass gears. Material removal rate has been evaluated using the formula given in Equation 1 below. A precision weighing balance with least count of .01 mg has been used for weight measurements and stop watch has been used for recording machining time. Analysis of variance study has also been done to find the significance of AWJM parameters.

Table 1. Process parameters of AWJM for miniature gear manufacturing

| Variable parameters       | Unit | Level | Fixed parameters                              |
|---------------------------|------|-------|-----------------------------------------------|
| Water jet pressure ‘A’    | MPa  | 150   | 250 | 350 Abrasive type and mesh size- Garnet (80); |
| Abrasive mass flow rate ‘B’| g/min| 150   | 225 | 300 Nozzle diameter- 0.75 mm;           |
| Stand-off distance ‘C’    | mm   | 1     | 1.5 | 2 Traverse speed- 66 mm/min;          |

Specifications of miniature gear: Type: external spur gear; Module: 0.7 mm; Pitch circle diameter: 8.4 mm; Outer diameter: 9.8 mm; Number of teeth: 12; Thickness: 5 mm.

Composition of gear material Brass [ASTM B36 C26800]
Cu: 64-66%; Sn: 0-0.10%; Pb: 0-0.05%; Fe: 0-0.05%; Al: 0-0.02%; Ni: 0-0.2%; Zn: 35%
3. Results and discussion

Table 2 presents the nine experimental combinations of AWJM parameters and corresponding values of material removal rate. Water jet pressure has been identified as the most significant parameter affecting material removal rate of AWJM while manufacturing miniature gears. The effects of AWJM parameter on material removal rate is described as below.

Table 2. Experimental combinations and MRR results

| Exp. No. | Input parameters | MRR (mm³/min) |
|----------|------------------|---------------|
|          | Water jet pressure (MPa) | Abrasive mass flow rate (g/min) | Stand-off distance (mm) | |
| 1        | 150              | 150           | 1            | 15.84   |
| 2        | 150              | 150           | 1.5          | 14.95   |
| 3        | 150              | 300           | 2            | 15.35   |
| 4        | 250              | 150           | 1.5          | 16.49   |
| 5        | 250              | 225           | 2            | 15.94   |
| 6        | 250              | 300           | 1            | 18.00   |
| 7        | 350              | 150           | 2            | 16.40   |
| 8        | 350              | 225           | 1            | 18.72   |
| 9        | 350              | 300           | 1.5          | 17.81   |

Figure 2 illustrates the effect of AWJM parameters on MRR. It is seen that increase in water jet pressure substantially increased MRR (Fig. 2a). It is probably due to the increased kinetic energy of the abrasive particles, which led them to remove more material at a faster rate when water jet pressure is high [8]. As shown in Fig. 2b, abrasive mass flow rate (AMFR) increased MRR. It is due to the fact that increase in AMFR increased the number of abrasive particles performing cutting. This increased number of abrasive particles consequently removed more material, and hence MRR increased. Stand-off distance (SoD) significantly affects the divergence tendency of the abrasive laden water jet head. Generally, at low SoD values, the jet head is less divergent and directly forces the abrasive particles to the target surface where machining or cutting is required to be done. But, as the SoD increases abrasive particles strike with a lag and get distributed here and there. Same happened in the present case where increase in SoD resulted in inefficient cutting of the target surface and hence MRR decreased (Fig. 2c). Similarly, the effects of AWJM parameters on surface roughness and micro-geometry of miniature gears have been analyzed [1, 2].
Figure 2. Effects of AWJM parameters on material removal rate (a) WP vs MRR, (b) AMFR vs MRR, and (c) SoD vs MRR

To minimize the surface roughness and microgeometry error, and to maximize the MRR, optimization was done. In this paper, single response optimization (i.e. for MRR) of AWJM parameters is reported. Statistical technique desirability analysis has been used to optimize MRR. In Desirability analysis, any single response $Y_i$ is converted into desirability function $d_i$ whose value can range from 0 to 1 [18]. The desirability function for a response to maximize is given in the Eq 2 below, where $T$ is the target value, $L$ is the acceptable lower limit, and $Y_i$ is the value of the response for the $i^{th}$ data set. Eq 2 in the present case i.e. for maximization of MRR can be presented as given in Eq 3.

$$d_i = \begin{cases} 0 & Y_{ij} < L \\ \frac{Y_i - L}{T - L} & L \leq Y_i \leq T \\ \frac{1}{Y_i} & Y_i > T \end{cases}$$ …… (2)

$$(d_{MRR})_i = \left( \frac{MRR_i - MRR_{min}}{MRR_{max} - MRR_{min}} \right)$$ …… (3)
Where MRR$_{\text{min}}$ and MRR$_{\text{max}}$ are the minimum and maximum values of MRR respectively (selected from Table 2). Using Eq. 3, optimum values of AWJM parameters (WP- 350 MPa, AMFR-300 g/min, SoD- 1mm) and corresponding predicted value of MRR (18.99 mm$^3$/min) for the maximum Desirability value of 1.0 have been obtained. Confirmation experiment has been conducted on the predicted optimum AWJM parameters to verify the desirability predictions. Confirmation experiment resulted in the optimum value of MRR 18.80 mm$^3$/min.

Furthermore, microscopic study was conducted for this miniature gear machined at optimum AWJM parameters. Figure 3 presents the SEM micrographs where it is observed that the flank surfaces of this miniature gears possess uniform wear tracks and profile, and smooth surface with minimum burrs and defects. Also, the surface quality i.e. microgeometry (Profile error 14.15 µm which corresponds to German standard DIN 8) of this gear is found better than the gears manufactured by conventional processes and therefore AWJM can be identified as a superior alternate to them.

![Figure 3. SEM images of the brass miniature gear fabricated by AWJM](image-url)

4. Conclusion
This paper reports on productivity of AWJM process while manufacturing miniature gears of brass. The following points of conclusion and future research can be drawn-

- All process parameters of AWJM significantly affect the material removal rate.
- It is found that increase in water jet pressure and abrasive mass flow rate increases the material removal rate. Whereas low stand-off distance produces high material removal rate.
- Optimization resulted in the enhanced material removal rate of value 18.80 mm$^3$/min.
- Microscopic study revealed smooth gear flank surface and uniform profile with low burrs and defects.
- Future research avenues include life cycle analysis of AWJM for gear manufacturing; multi-performance optimization to secure best values of quality, productivity, and sustainability of AWJM gear manufacturing; and a detailed surface morphology investigation.
- Manufacturing of other gears shape and materials by AWJM process can also be explored in future research.

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