On Abrasive Water Jet Machining of Miniature Brass Gears

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Abstract: Miniature gears are the key components of various miniaturized devices. Manufacturing quality, surface finish, and surface integrity of miniature gears are of prime importance to determine their functional performance and service life. This article presents the results of some experimental investigations conducted to machine precision miniature brass gears by abrasive water jet machining process. The fabricated gears are external spur type and have 8.4 mm pitch diameter, 12 teeth, and 5 mm thickness. It reports important results i.e. micro-geometry and surface roughness of miniature gears machined by abrasive water jet process. The manufacturing quality DIN 8 and surface finish 1.03 μm have been obtained in the present research. It also discusses important aspects of various stages of this research along with the discussion on the effects of machining parameters on surface quality of gears, and a detailed surface integrity analysis. The present research identifies AWJM as a sustainable alternate to the conventional processes of miniature gear manufacturing that needs further exploration with other gear types and materials.

Keywords: Abrasive water jet machining; Miniature gear; Precision; Profile; Surface integrity

1. INTRODUCTION

Miniaturization is a growing field that keeps manufacturing sector involved in continuous research and development for micro-manufacturing of miniature products. Miniature pumps and motors, medical devices, MEMS, scientific instruments and appliances are some important miniature products. The functional performance of these products is majorly dependent on the quality of their parts. Miniature gear is such an important part whose geometric accuracy and surface finish determine quality of the aforementioned products [1, 2]. Amount of errors in micro-geometry of gear determine its geometric accuracy. These are profile error and pitch error. The profile error is the amount of deviation of the actual involute curve from the theoretical involute and is measured in axial and radial directions on gear teeth. Errors in profile are mainly responsible for noise generation in gears [3, 4]. Based on the amount of profile errors, a quality number can be assigned to gears. Two major quality standards followed globally are Deutsches Institut für Normung (DIN) and American Gear Manufacturer Association (AGMA) [5, 6]. Surface finish of gear affects its service life, wear characteristics, and tribology behavior [2, 3]. Average and maximum roughness, mean roughness depth, skewness, and kurtosis are important roughness parameters.

It is well known that the conventional manufacturing processes such as gear hobbing, forming, and casting etc. are expensive and environmentally-unfriendly [1-4]. It compels to explore and establish some sustainable alternate processes.

There are some investigations conducted where advanced machining processes have been researched to manufacture gears [1-4]. Some recent results identify the potential of advanced processes and encourage further investigation on manufacturing of miniature gears by these processes.

Abrasive water jet machining (AWJM) where a high velocity stream of water laden with abrasives is used to remove material is an important advanced machining process introduced in 1970 [7, 8]. In AWJM, the kinetic energy of high-speed waterjet is transferred to the abrasive particles and the mixture impinges on to the workpiece to remove the required amount of material or to form a particular shape/geometry based on the principle of mechanical erosion. The working principle of AWJM is illustrated in Fig 1. Aluminum oxide (Al_2O_3), silicon carbide (SiC), and Garnet etc. are majorly used abrasive types in AWJM. Water jet pressure, abrasive mass flow rate, traverse rate, nozzle distance, and types of abrasive particles etc. are some of the important parameters of AWJM process. Water jet pressure is the pressure of the abrasive mixed water jet comes out from the nozzle, and it is required to accelerate the abrasive particles for machining. Abrasive mass flow rate is responsible for the cutting ability of the jet and is defined as the rate at which the flow of abrasive particle is involved in mixing and machining process. The distance between nozzle and work surface is known as stand-off distance. It helps to maintain the flow of abrasive particles for efficient machining. Precision machining is possible by AWJM provided the jet-lag (which is the deviation of abrasive water jet from its theoretical value) should be at its minimum value [8]. Based on its previous track record to precisely machine the engineering components with sustainability, AWJM has been selected to attempt manufacturing of miniature gears in the present research.

Liu and Schubert [9] and Liu et al. [10] have reported to machine precision micro-gears using AWJM. But, no complete details are given on how surface quality is obtained. A detailed review of the available literature doesn't reveal the availability of any article systematically describing the mechanism of gear manufacturing by AWJM, effects of its parameters on surface quality of gears, and process optimization to secure high quality with productivity and sustainability. The present investigation fulfills this gap.

Sustainability, productivity and surface quality are three major factors to evaluate the performance of any manufacturing process. Stringent environmental regulations have prompted gear manufacturing sector also to develop the sustainable innovative techniques [11]. Due to the long process chains of gear manufacturing by conventional processes i.e. gears made by conventional processes require subsequent finishing to improving quality; it is difficult to achieve the overall sustainability. However, sustainability interventions are being provisioned there as well. The alternate way is to make gears by advanced processes and achieve the desired quality at machining stage itself with no further requirement of finishing. For this it is necessary to understand the mechanism and appropriate settings of optimum machining parameters.

Considering that the present work on abrasive water jet machining of miniature gears has been conducted in three stages. First, some preliminary experiments have been conducted to bracket the range of AWJM parameters feasible to machine miniature gears of brass. In second stage, main experiments have been done based on the Taguchi's robust design of experiment technique. In third stage, the main experiments were followed by confirmation experiments where optimum settings of machining parameters have been obtained using statistical and evolutionary optimization techniques to produce miniature gears equipped with good surface quality and integrity. A detailed surface integrity and tribology analysis of the miniature gears machined at optimum parameters have done. At the end, the work is complemented by a sustainability assessment of AWJM for gear manufacturing.

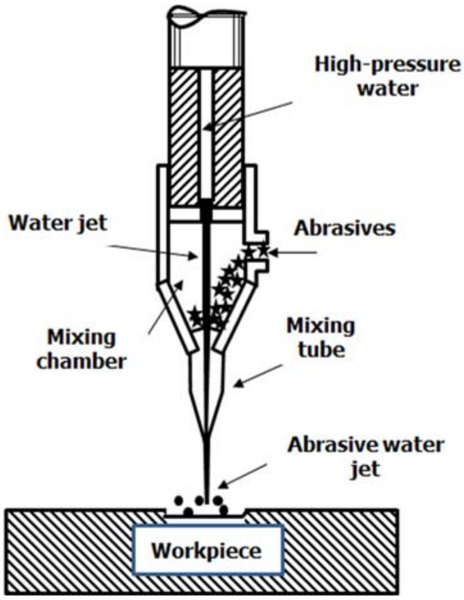


Figure 1. Working principle of abrasive water jet machining process

2. EXPERIMENTAL PROCEDURE

As mentioned, in the first stage around thirty preliminary experiments have been conducted where the effect of AWJM parameters mainly water jet pressure, abrasive mass flow rate, traverse speed, and stand-off distance have analyzed on surface roughness and material removal rate for machining rectangular pieces of brass. Based upon the results of preliminary experiments, the ranges and values of the aforementioned AWJM have been fixed to further machine miniature spur gears. In second stage, nine main experiments have been conducted to study the effects of water jet pressure, abrasive mass flow rate, and stand-off distance on material removal rate, and surface quality of miniature gears to understand the process mechanism. After a detailed analysis of the effects of AWJM parameters, it was found that the trend of variation of surface quality parameters and material removal rate with all AWJM parameters are different and a trade-off exist which needs optimization to secure the one set of machining parameters for the best values of all surface quality parameters and material removal rate. Moreover, in order to improve the surface quality parameters individually, optimization was required to be done. Statistical, evolutionary, and hybrid optimization techniques have been used for single and multi-objective optimization. In third stage, some confirmation experiments have been done to verify the predictions of the implemented optimization techniques. Thereafter, a detailed surface integrity analysis of miniature gears was done to check their wear behavior, tribology fitness, and functional performance during intended service life. Subsequently, based on the results obtained, a sustainability assessment has been done which identifies AWJM as a sustainable substitute of conventional gear manufacturing processes. Figure 2 presents the various stages of investigation.

Miniature brass gears were machined on 5 axis Omex water jet machine. Table 1 presents the details of miniature gear specification and composition of gear material brass [ATM B36 C26800]. Surface quality was investigated in terms of roughness, micro-geometry, and integrity. The surface roughness parameters investigated are average roughness, maximum roughness, and mean roughness depth. Micro-geometry parameters investigated are profile error and pitch error. Micro-hardness, bearing area, skewness, kurtosis, friction coefficient, and residual stresses were measured to evaluate the surface integrity of miniature gears.

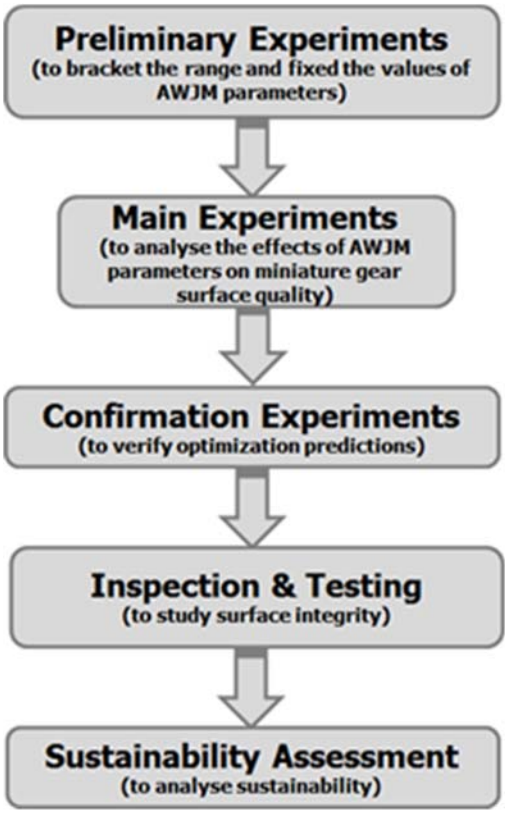


Figure 2. Stages of experimental investigation on AWJM of miniature gears

Table 1. Composition of miniature gear and its specification

Material composition	
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%	
Miniature gear specifications	
Type: external spur	Number of teeth: 12
Outside diameter: 9.8 mm	Thickness: 5 mm

The bracketed ranges of AWJM parameters after preliminary experiments are shown in Table 2 where they are placed at three levels all for further i.e. main experiments. The traverse speed is kept fixed at 66mm/min. Water jet pressure, abrasive mass flow rate, and stand-off distance all three factors are planned to vary at three levels. Therefore, Taguchi robust design of experiment technique has been chosen to plan the main experiments for three factors at three levels. The main aim behind choosing this technique is to minimize the number of experiments in order to save time and cost. A total of nine main experiments have been conducted and values of profile error, pitch error, average roughness, maximum roughness, mean roughness depth, and material removal rate have been measured/obtained corresponding to each experiment. Figure 3 shows the experimental setup used in the present work.

Table 2 Details of fixed and variable parameters of AWJM used in main experimentation

Variable parameters	Unit	Level			Fixed parameters
		L_1	L_2	L_3	Abrasive type and mesh size- Garnet (80); Nozzle diameter- 0.75 mm; Traverse speed- 66 mm/min
Water jet pressure 'A'	MPa	150	250	350	
Abrasive mass flow rate 'B'	g/min	150	225	300	
Stand-off distance 'C'	mm	1	1.5	2	

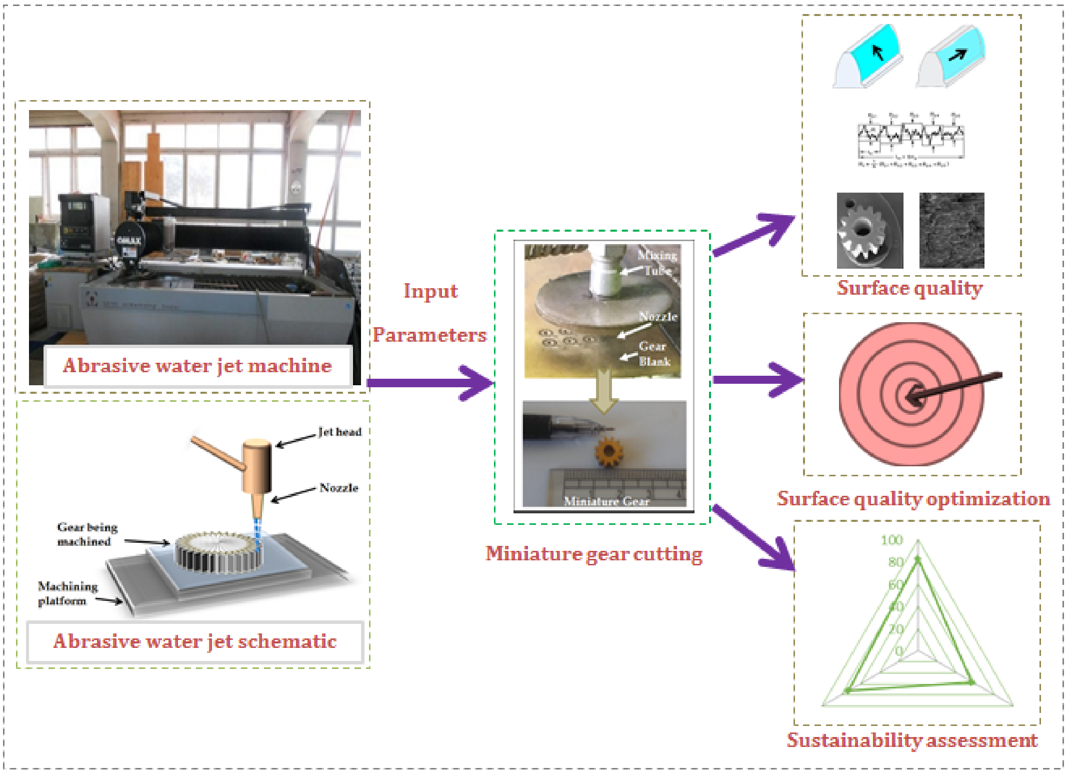


Figure 3 Experimental set-up of abrasive water jet machining of miniature gears

3. RESULTS AND DISCUSSION

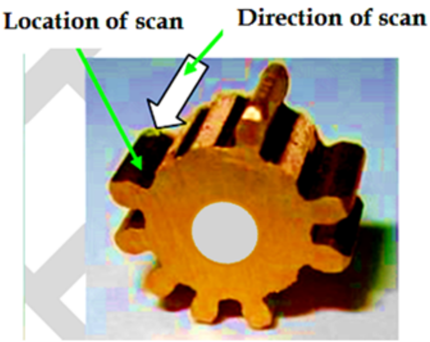
The values of mean roughness depth and profile error corresponding to each experimental run are given in Table 3. It is observed that the highest levels of water jet pressure and abrasive mass flow rate, and optimum value of stand-off distance have produced best surface quality of miniature gears. At aforementioned levels of the AWJM parameters, smoother cutting action have taken place due to low magnitude of jet-lag, and high penetration and cutting ability of the jet.

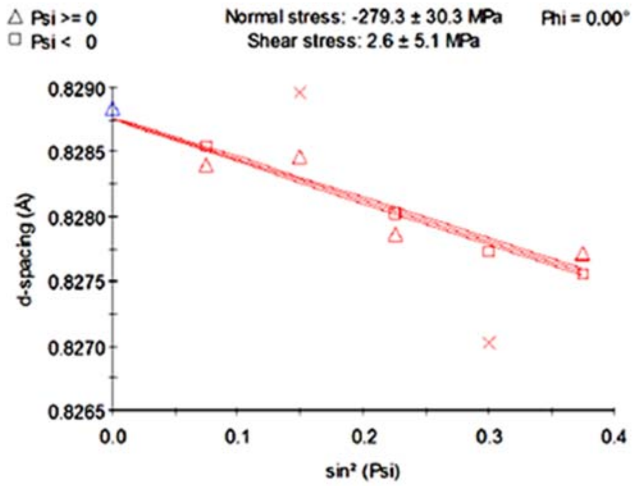
Table 3 Mean roughness depth and profile error of miniature gears machined by AWJM [1].

Exp. No.	Input parameters			Responses	
	Water jet pressure (MPa)	Abrasive mass flow rate (g/min)	Stand-off distance (mm)	Mean Roughness Depth	Profile error
1	150	150	1	6.15	18.2
2	150	225	1.5	6.40	17.4
3	150	300	2	5.80	17.0
4	250	150	1.5	5.22	15.6
5	250	225	2	5.63	16.1
6	250	300	1	4.70	14.8
7	350	150	2	5.85	15.6
8	350	225	1	4.34	14.8
9	350	300	1.5	4.9	14

The similar trends for profile error and mean roughness depth on AWJM parameters were observed except stand-off distance. Furthermore, to secure the best values of both profile error and mean roughness depth at a single setting of process parameters, multi-objective optimization has done using statistical technique desirability analysis. The optimum values of profile error- 14.15 μm and mean roughness depth- 4.6 μm were obtained at optimum AWJM parameters i.e. water jet pressure- 350 MPa, mass flow rate- 300 g/min, and stand-off distance- 1 mm. A detailed surface integrity analysis of this gear has been done and discussed here as under.

Surface integrity parameters such as skewness, kurtosis, residual stresses, and micro-hardness etc. greatly affect the tribology behaviour and fatigue strength, and control wear and tear of gears [12-15]. Lack of systematic study conducted on abrasive water jet machining of gears necessitates exploring the aforementioned surface integrity aspects to evaluate the operating performance during the intended service life of gears. The average and maximum roughness parameter values for this gear are 1.03μm and 6.25 μm, respectively. Other important statistical parameters such as skewness and kurtosis are -0.242 and 2.99 respectively. The miniature gears with these parameters are acceptable for miniaturized applications, and imply long service life and good tribology characteristics of miniature gears. Therefore, proves the capability of AWJM to machine precision miniature gears of fine finish. No significant difference in the micro-hardness before and after machining of miniature gear was observed. The values of micro-hardness measured at some levels of indentation depth were around 130 VHN. It represents the quality machining of miniature gear by AWJM without any adverse machining effect. Residual stresses are the important indicators of fatigue life of mechanical components being engaged in sliding and rolling contact conditions [15]. Compressive nature of residual stress is beneficial and desirable for longer life of these components, because it tends to increase the fatigue strength and life, reduce the chances of crack propagation, and mitigates the aspects of environmentally-assisted cracking such as stress corrosion and hydrogen induced cracking etc. Residual stress for the miniature gear manufactured at optimal AWJM parameters was evaluated by X-ray diffraction (XRD) technique using $Sin^2\psi$ method. Compressive residual normal stress of magnitude 279 ± 30 MPa was measured on the tooth surface of miniature gear based on the direction and location of scan given in Fig. 4 (a) and (b). Compressive nature of the induced residual stress indicates no adverse effect of abrasive water jet machining on the gear, and ensures reasonably good strength against fatigue failure and therefore ensures long service life.





(a) **(b)**

Figure 4. Residual stress measurement for miniature gear machined at optimum AWJM parameters (a) Representation of direction and location of scan (b) $Sin^2\Psi$ V/s d-spacing plot.

Scanned electron microscopic images of the miniature gear machined by AWJM, are shown in Fig. 5. Miniature gear was found to be free from any thermal damage with defect- and crack-free tooth flank surfaces.

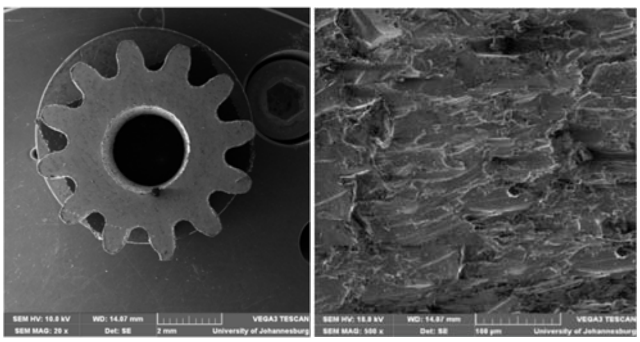


Figure 5. SEM Micrographs of abrasive water jet machined miniature gear [1]

4. CONCLUSIONS

The following conclusions can be drawn from the current investigation:

- The best value of profile error 14.15 μm obtained at optimum AWJM parameters make this gear to assign DIN quality number 8 which is much better than the quality obtained by conventional processes.
- The surface finish obtained is acceptable for miniature applications and at par with the gear finish obtained by other advanced processes as given in the literature.
- The surface integrity analysis shows that miniature gears machined by AWJM are tribologically fit, and possess high fatigue strength and long service life.
- The results of the current investigation indicate significant potential in abrasive water jet machining for manufacturing of quality gears.
- The findings of current investigation encourage future research in the area to establish the field further.

The following points highlight the scope of future research:

- Investigating abrasive water jet machining of worm, bevel, helical, and internal gears.
- Investigating abrasive water jet machining of gears of other materials such as aluminum, plastic, SS, and bronze etc.
- Roll testing, noise and vibration measurement and analysis of gears machined by AWJM.

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