Surface Morphology Investigation of Miniature Gears Manufactured by Abrasive Water Jet Machining

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Abstract

In this paper, surface morphology investigation of miniature spur gears manufactured by abrasive water jet machining is discussed. Water jet pressure, abrasive flow rate and stand-off-distance are the varying input parameters to study the surface morphology (surface roughness and topography) of the machined gears. From the investigation, the water jet pressure has highly influenced (with 47% contribution) the surface quality and found as a predominant process parameter. SEM micrograph study found that wear scars and clinging effects are the major surface defects found over the machined surfaces of the gear teeth. Maximum and minimum peaks of the wear tracks are observed with white light spectroscope. The best surface morphology with average surface roughness value 1.08 µm was achieved at 350MPa water jet pressure, 225 g/min abrasive mass flow rate, and 1mm stand-off distance. The present work identifies the potential of AWJM process for manufacturing of high quality miniature gears.

Keywords: abrasive, gear, machining, surface, wear

Biography:

Dr. Kapil Gupta is working as Associate Professor in the Dept. of Mechanical and Industrial Engineering Technology at the University of Johannesburg. He holds a Ph.D. in Advanced Manufacturing. Advanced machining processes, sustainable manufacturing, green machining, precision engineering and gear technology are the areas of his interest. He has authored several International Journal and Conference articles. He has also authored and edited fifteen international books on hybrid machining, advanced gear manufacturing, micro and precision manufacturing, high speed machining and sustainable manufacturing. He is in editorial and review boards of journals, and member of the advisor/technical committees of international conferences. He has delivered keynote and distinguished speeches in international conferences and symposiums, and seminar talks at international universities. He possesses good experience in postgraduate supervision.

Dr. Adam Khan holds a Ph.D. in Mechanical Engineering and currently working as Postdoctoral Research Fellow at University of Johannesburg. He is specialized in advanced materials processing and manufacturing. He possesses a vast experience in the field and has played a major role in various international projects on development, processing, machining, and surface engineering of a wide range of engineering materials and products. He has authored over forty research articles in the international journals of repute.

Dr. Sunil Pathak is currently working as a senior lecturer in the Faculty of Manufacturing and Mechatronics Engineering Technology at Universiti Malaysia Pahang. He obtained PhD in Advanced Manufacturing from the Indian Institute of Technology Indore, India in 2016. His areas of specialized and interest are gear engineering, and advanced and hybrid manufacturing processes. He possesses over seven years of research and academic experience and has successfully completed research projects on gear machining, finishing, and metrology. He has authored many international journal and conference articles, and books.

Introduction

During last two decades there has been an accelerated demand of miniature products in precision, scientific, biomedical, and various industrial applications. Miniature gear is one of the important mechanical parts used in many devices and machines for motion and torque transmission (Gupta et al., 2017; Chaubey and Jain, 2019). The operating conditions for these gears may vary in wide range with type of systems where they are used. The surface morphology that includes surface roughness and topography play major role to determine the functional performance of miniature gears (Davis 2005, Townsend 2011). Machining gears by manufacturing processes at appropriate set of process parameters is majorly responsible to obtain the desired surface quality. Traditional manufacturing processes are not capable enough to obtain good surface quality (Townsend, 2011). Moreover, the process chain of gear manufacture by conventional way is extremely long.

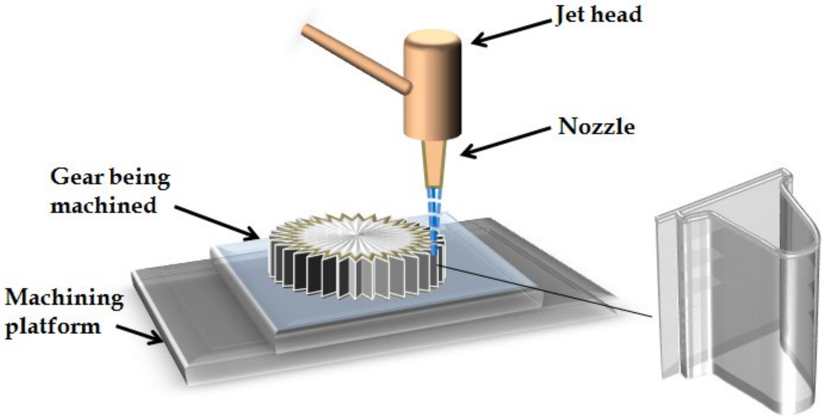
To overcome the limitations of conventional manufacturing of miniature gears, advanced manufacturing processes have been explored in the recent past to machine quality miniature gears of various materials (Chaubey and Jain, 2019; Popa et al., 2018). A recent investigation on wire spark erosion machining of miniature gears conducted by Chaubey and Jain (2019) reveals the suitability of wire-EDM for high quality miniature gear manufacturing. The miniature bevel and helical gears manufactured were made of stainless steel. The average roughness value R_a- 1.1 µm obtained. The gears manufactured at optimum parameters were found much better in quality than same type of gears manufactured by conventional milling and hobbing. Popa et al. (2018) machined meso size gears of stainless steel using laser beam cutting. They obtained excellent surface quality characteristics with average roughness R_a- 1.04 µm and mean roughness depth R_z- 5.79 µm at a laser power of 2400 W, 0.75 m/min cutting speed, -1.5 mm focal position, and 15 bar gas pressure. Abrasive water jet machining (AWJM) is one of the most important and extensively used advanced type machining process. AWJM possesses many significant benefits such as process sustainability, low work piece damage, high production rate and surface quality etc. (Balachandar et al., 2018, Jagadish et al., 2015, Yuvaraj and Pradeep Kumar, 2018). In AWJM, the water at high jet pressure is made to pass through an orifice to increase the intensity of the fluid. High velocity abrasive particles mixed in water increase the cutting efficiency while striking to the work surface, and thus cut hard materials and machine complex shapes (Yuvaraj and Pradeep Kumar, 2018; Kartal, 2017). Abrasive water jet machining was attempted to explore as an alternate method of gear manufacturing a long back (Liu et al., 2011; Liu and Schubert, 2012). An assembly of planetary gear set consists of seven precision gears has been successfully machined to be used in a micro-motor (Liu et al., 2011). 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. No further details on surface quality characteristics of gears are found in their work.

Critical review of the past work on manufacturing of miniature gears by advanced processes reveals that there has been a very limited research work conducted and reported on AWJM of miniature gears. Few available articles provide a superficial understanding, which necessitates a systematic study on mechanism of gear manufacturing and their surface morphology when machined by AWJM.

The outcomes of the work reported in this paper fulfil the research gaps. This paper reports the investigation on the effect of AWJM parameters on surface morphology of miniature gears where variation of surface roughness, topography generation, profile evaluation, and wear characteristics are mainly studied to find the potential of AWJM process for manufacturing of precision miniature gears. These aspects make this study innovative and it is believed that the results will facilitate gear manufacturing industries for mass production of quality miniature gears for applications in timer mechanisms, miniature motors and pumps, micro-harmonic devices, and other scientific and industrial products.

Materials and Methods

In this research, miniature gears of brass material have been machined by AWJM process. The composition of the commercially available brass material [ASTM B36 C26800] is as; 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%. The basic design specifications for the projected gear are: type- external spur gear; module of gear- 0.7 mm; pitch circle diameter- 8.4 mm; outside diameter- 9.8 mm; number of teeth- 12; thickness- 5 mm. Experiments are performed on Omax five axis abrasive water jet cutting machine. Figure 1 presents the schematic representation and actual picture of AWJM set-up for gear manufacturing.



(a)

(b)

Figure 1: Miniature gear manufacturing by abrasive AWJM (a) Schematic diagram, (b) actual picture

Three most important process parameters of AWJM namely water jet pressure (150, 250 and 350MPa), abrasive flow rate (150, 225 and 300g/min) and stand-off distance 'SoD' (1, 1.5

and 2mm) have been varied. The garnet is the commonly used hard abrasive to a particle size of 80 mesh machined with a processed clean and pure water to avoid surface reactions. The diameter of the nozzle is 0.75 mm and the traverse speed is 66 mm/min are kept constant throughout the experimentations. Experiments are design and performed based on Taguchi robust design of experiment technique with L_9 orthogonal array. Minimum of two set of gears are manufactured for replication of results to minimize experimental error.

The surface roughness of the gear has been measured using stylus profilometer projecting from the direction of cutting zone to dross regime. Two measurements are made from each experiment and their average value is considered for evaluation. Electron microscope is use to study the surface topography and morphology. The variation in cutting profile are identified and the wear mechanism are observed through SEM micrograph for better interpretations. Further the samples are observed with white light spectroscope for three-dimensional profile analysis. The output of the white light spectroscope is used to prove and justify the wear mechanism discussed through SEM analysis.

Results and Discussion

Table 1 presents the nine experimental combinations and corresponding values of average surface roughness. Table 2 shows the results of analysis of variance (ANOVA) for statistical fitness of the measured data. From the ANOVA, the influence of jet pressure has been found dominating the surface quality of the machined gears with 47.01% of contribution followed by the mass flow rate of abrasive particles with a contribution of 16.33% and SoD with 24.63% of contribution. It has been verified and justified with the surface topography analysis.

Table 1: AWJM process parameter combinations and average surface roughness values

Exp No.	*Jet pressure (MPa)*	*Abrasive flow rate (g/min)*	*Stand-off distance (mm)*	*Average Surface Roughness (Ra)*		
				Replication 1	Replication 2	Average value
1	150	150	1	2.05	1.83	1.94
2	150	225	1.5	2.1	2.1	2.10
3	150	300	2	1.9	1.68	1.79
4	250	150	1.5	1.62	1.78	1.70
5	250	225	2	1.75	1.83	1.79
6	250	300	1	1.29	1.45	1.37
7	350	150	2	1.92	1.72	1.83

8	350	225	1	1.08	1.18	1.13
9	350	300	1.5	1.46	1.46	1.46

Table 2: ANOVA results

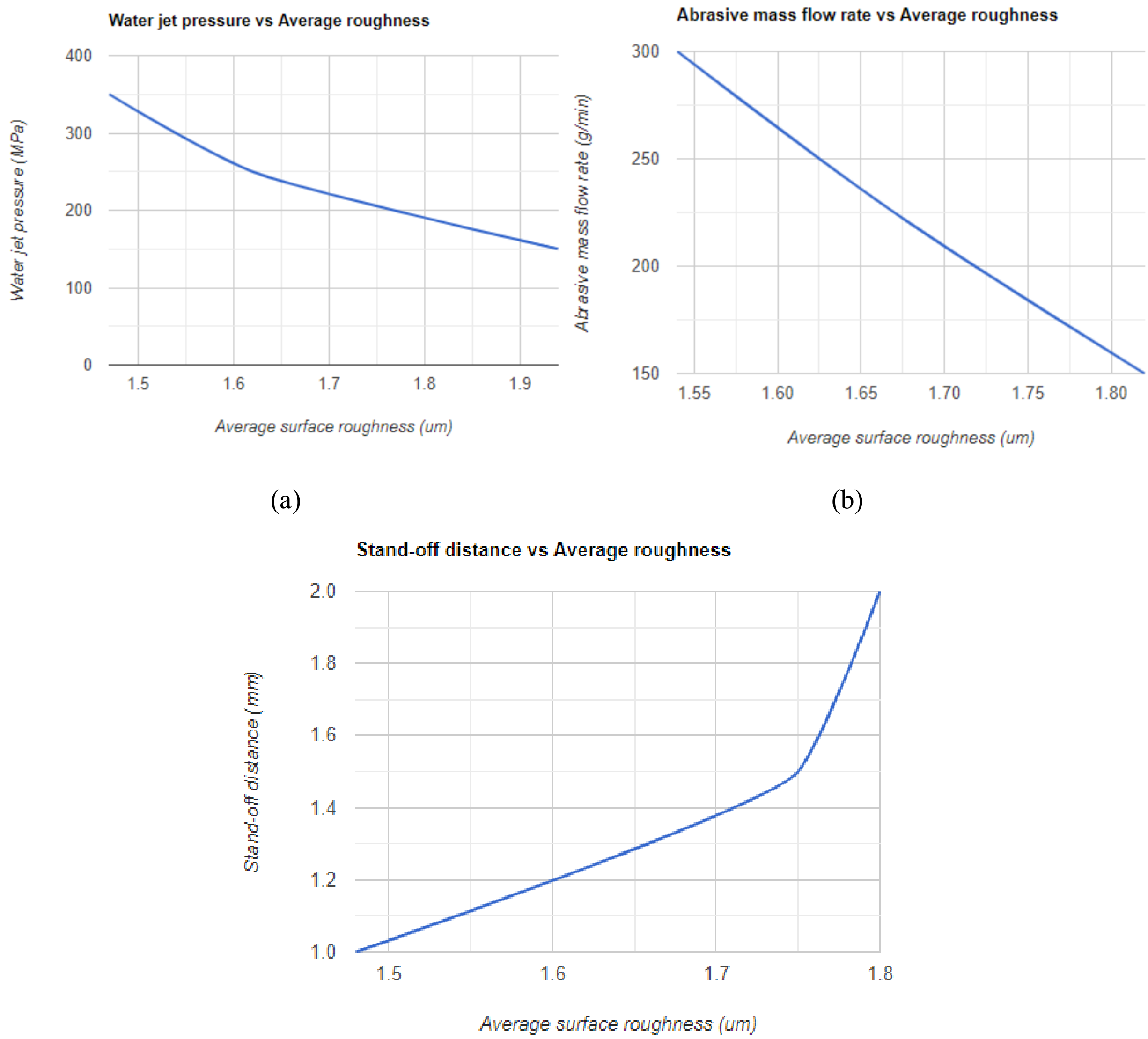
Source	Degrees of freedom	Sum of square	Mean square	F ratio	P value	% contribution
Water jet pressure	2	0.34696	0.17348	3.91	0.204	47.01
Abrasive mass flow rate	2	0.12056	0.06028	1.36	0.424	16.33
Stand-off distance	2	0.18176	0.0908	2.05	0.328	24.63
Error	2	0.08882	0.04441			12.03
Total	8	0.73809				
Model summary statistics-		R-sq: 87.97%, R-sq (adj): 51.86%				

The mechanism behind the abrasive water jet cutting in machining bulk materials is repeatedly striking the bulk with hard-sharp cutting edge of abrasives (Kartal, 2017, Akkurt 2010). The striking velocity of the hard particles is determined by the water jet pressure. At maximum jet pressure, the cutting force exerted will be more compared to other cutting conditions. It is also clear to infer that the surface roughness value is 1.13 µm for 350MPa jet pressure. On the other hand, the striking force exerted at this condition will be maximum to slice the bulk metallic material. The amount of abrasives used 225g/min at the lowest SoD. As a summary, the experimental results have been fit within the linear scale to a maximum of 87.97% (R^2 value) and the error percentage is 12.03%. Further, the machined surface is individually analysed and investigated using scanning electron microscope and white light spectroscope.

Surface Roughness Analysis

Figure 2 shows the trends of variation of average surface roughness with AWJM parameters. It is observed that the average surface roughness of the machined gear decreases with increase in water jet pressure.

Similarly, for abrasive mass flow rate, the surface roughness is at the lowest with high flow rate and deterioration in surface quality is observed with minimum flow of abrasives. In contrast to the jet pressure and abrasive flow rate, effect of nozzle SoD encompasses. It says that, the amount of surface quality of the bulk material removal while machining will be better at maximum jet pressure and abrasives. It will produce lapping effect by the abrasives and the cutting force of individual abrasives will be maintained throughout the machining. When the pressure and abrasive flow are reduced, the cutting mechanism will be disturbed. The disturbance of jet pressure may also be due to the high SoD. When the jet nozzles are lifted more (longer SoD), the atmospheric pressure will deviate the cutting pressure and the distraction will be there in the jet (Abdelnasser et al., 2016).

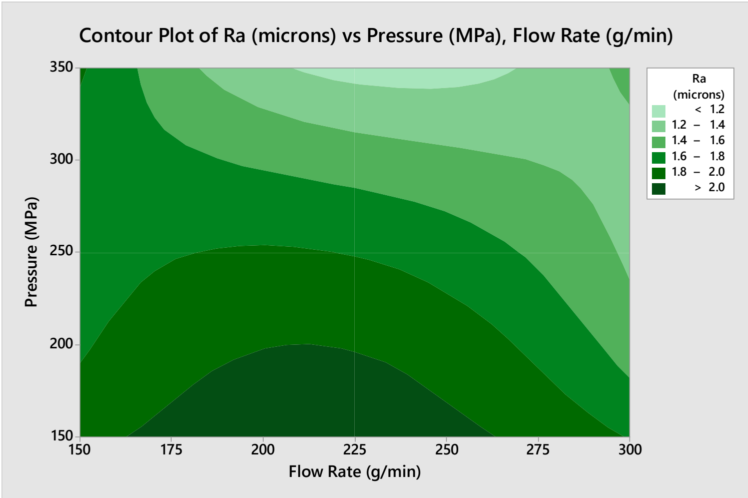


(a) (b)

(c)

Figure 2: Variation of average surface roughness with AWJM parameters (a) WP vs R_a, (b) AMFR vs R_a, (c) SoD vs R_a

Further, the interaction of process parameters is studied with the help of contour (vector) plots as shown in Figure 3. First contour is plotted between the water jet pressure and the abrasive flow rate. Variations in surface roughness with reference to these two parameters are given in scale aside the contour. The interpretation on this graph makes clear to understand that, the surface roughness of the gear will be same even there is no change in flow rate at low jet pressure. However, when the jet pressure increases, minimum surface finish of 1.2µm will be achieved under abrasive flow rate range 200 – 260g/min.



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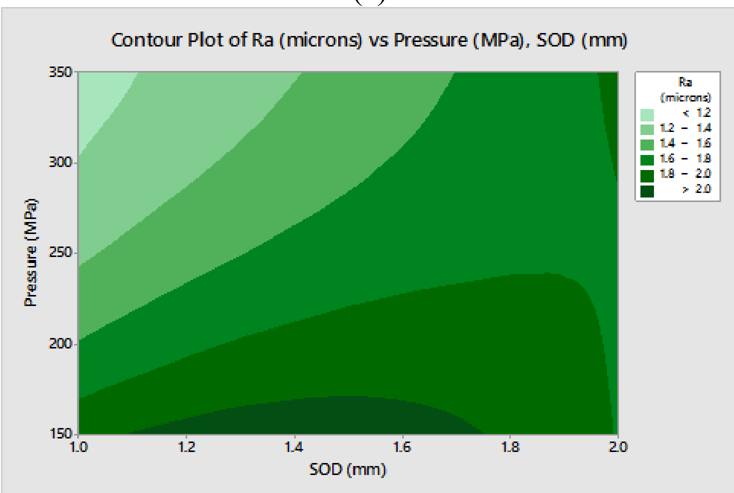

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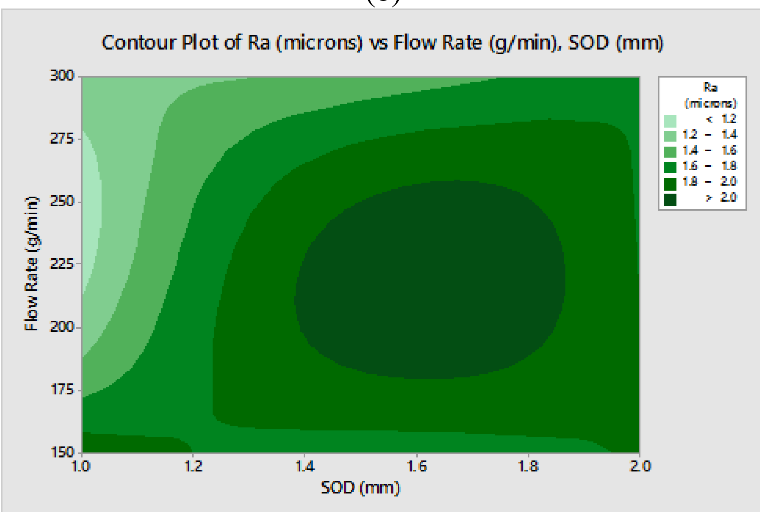

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Figure 3: Contour plots to study influence of interaction between (a) water jet pressure and

abrasive mass flow rate, (b) water jet pressure and SoD, (c) abrasive mass flow rate and SoD, on average surface roughness.

While comparing the jet pressure and SOD, effect of SOD on proposed machining conditions are negotiable. Same effect on surface with a minimum R_a of 1.2µm can be achieved at high jet pressure. This is not common in between the interactions of abrasive flow rate and SoD. Just like in the jet pressure-abrasive flow, minimum surface roughness (1.2µm) can be achieved at 200-275g/min. The recommended process conditions can be the jet pressure at 350MPa, abrasive flow rate at 200-275 g/min and minimum SoD (1mm).

Desirability analysis is one of the extensively used optimization techniques in research and industry (Montgomery, 2012). 'Smaller is better' type desirability function was used to optimize AWJM parameters to minimize surface roughness and obtain the least value of average surface roughness. Table 3 presents the desirability predictions based on the trends of variation of average roughness with parameters and their interactions. A set of two gears were manufactured during confirmation experiments at optimum AWJM parameters to validate the desirability predictions. The measured values of average surface roughness for the gears machined at optimum parameters are shown in Table 3. Confirmation experiment validates the results of desirability optimization where the least value of R_a – 1.08 µm (very close to the desirability predictions) obtained at 350 MPa water jet pressure, 225 g/min mass flow rate, and 1 mm stand-off distance.

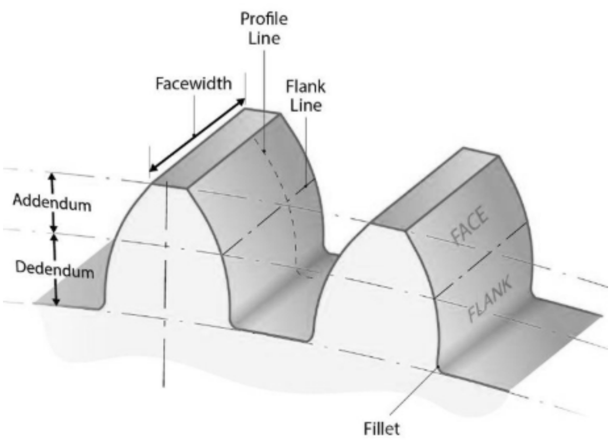
Table 3: Results of desirability optimization and confirmation experiment

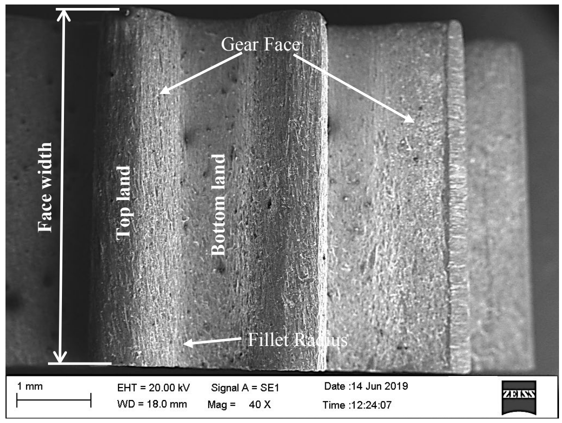
Optimum AWJM parameters	Average surface roughness R_a (µm)			
	Desirability result	Confirmation experiment result		
		Replication 1	Replication 2	Average value
Water jet pressure – 350 MPa Mass flow rate – 225 g/min Stand-off distance – 1 mm	1.03 µm	1.08	1.08	1.08

It is worth mentioning that the machining time for gear at optimum AWJM parameters is three minutes.

Surface Topography Analysis

Figure 4 presents the schematic diagram and actual picture of miniature gear to understand the important terminologies regarding surface topography of gear. Macro and micro-geometries (that constitute surface topography) of machined miniature gears varied with the AWJM process parameters. The important parameters which reflect the surface topography of gears i.e. top land, face width, profile (flank and face), bottom land, fillet radius, pitch and tooth thickness have been analysed at various locations.





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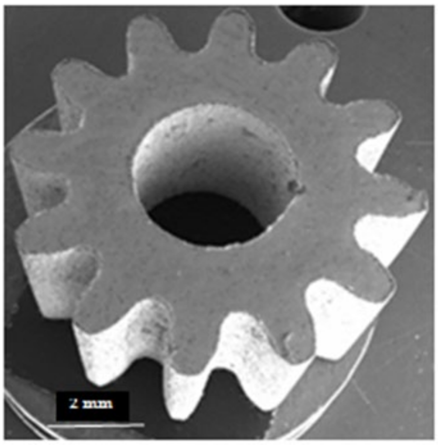


(c)

Figure 4: (a) Schematic of gear terminology, (b) and (c) SEM micrographs of the actual gear machined at 350MPa jet pressure with abrasive flow rate of 225g/min and 1mm stand-off distance

To study the influence of AWJM process on surface topography of miniature gears, a set of teeth in a gear has been randomly selected to observe under electron microscope. Variation in top land and bottom land with flank/face of the gear teeth is shown in Figure 5. The thickness of the top land is wide at cutting zone and getting narrow towards the dross section. Geometrically, the dimension of the top land and bottom land of the gear profile are not same. The dimensional variation is due to the timing of nozzle movement (Jani et al 2016, Chithirai et al 2012). To make it clear, Figure 6 infers the material removal mechanism involved during the variation in nozzle movement. The top land and bottom land of the gear has contour profile and require enough time to form completely. Movement of the nozzle is slow at contours and material removal will be maximum. When the nozzle moves slow, dimensional variation occurs due to maximum dross region that remains wide.

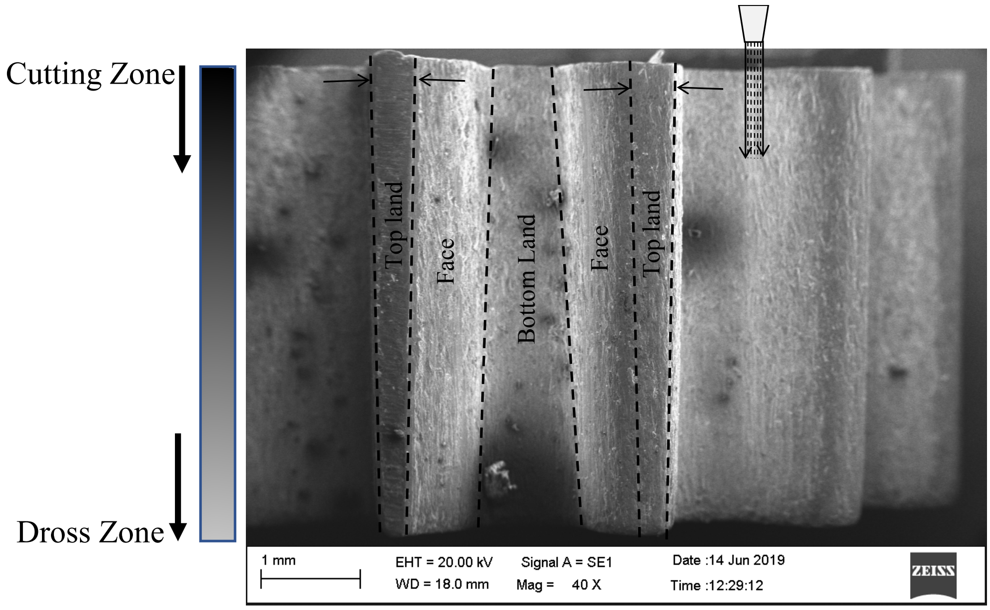


Figure 5: Dimensional variation in gear surface topography

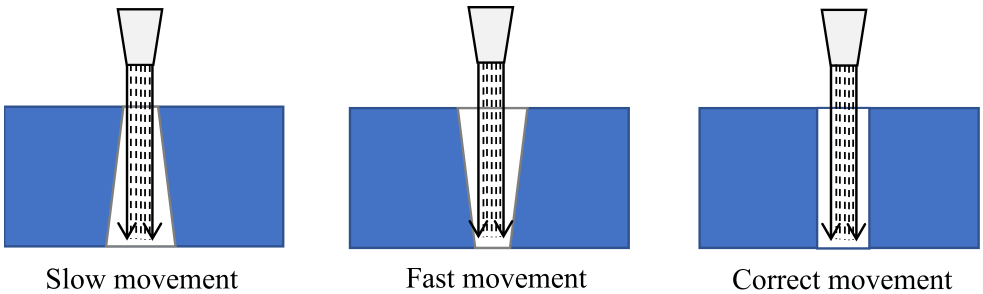


Figure 6: AWJM mechanism on material removal with reference to nozzle movement

Figure 7 shows the scan electron micrograph (SEM) of the gear top land. Surface reveals with a wear scars of the gear tooth top land, machined at 350MPa jet pressure with abrasive flow rate of 225g/min and 1mm stand-off distance. Image represents the traverse direction of the water jet nozzle and surface scars. The hard-abrasive particles used to cut the material are found clinged over the machined surface. It is due to the nature of gear material (ductile metal) and the hard particles stroked at a jet pressure of 350MPa and induced severe plastic deformation of the bulk material. Under higher magnification, the machined surface revealed with wear scars parallel to the direction of abrasive – jet flow along with craters on shear zone. Farayibi et al (2014) reported that these lateral wear scars and cracks are formed due to continuous strike of hard abrasive particles. At the end of gear top land, the intensity of the jet pressure has been reduced. On other hand, the cluster of hard abrasives got agglomerated at the end dross and led to maximum rough regime.

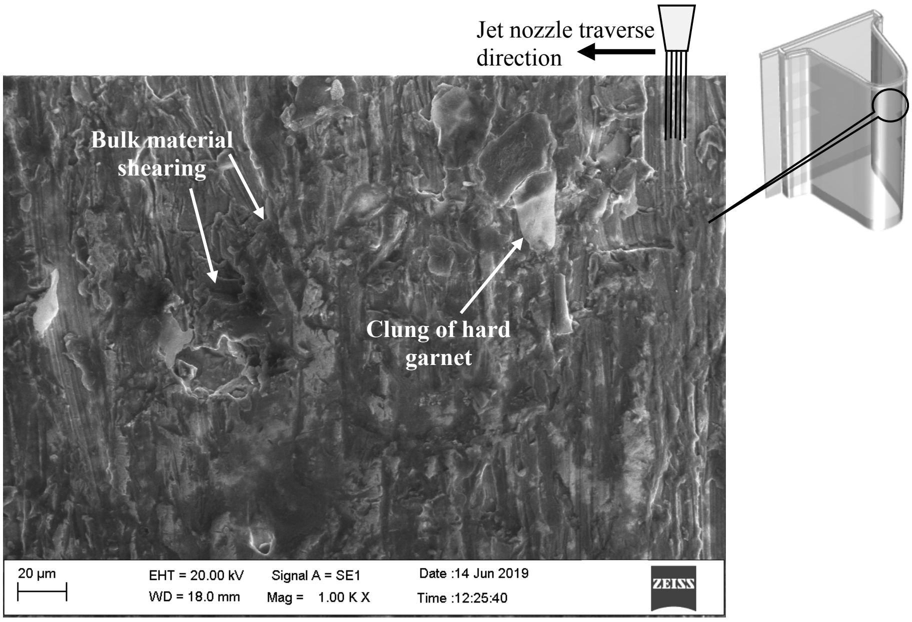


Figure 7: SEM micrograph of the cutting zone of the top land of optimum gear tooth

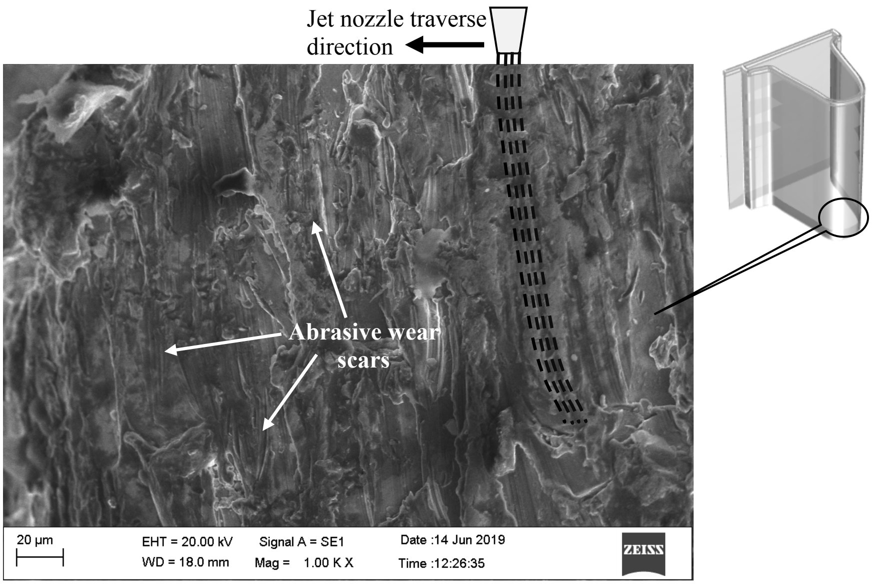


Figure 8: SEM micrograph of the dross region of the top land of optimum gear tooth

Figure 8 shows the SEM micrograph of the gear tooth at dross region of top land. At this region, the intensity of the jet pressure is deviated and the wear scars are in parabolic path. With reference to the traverse direction of jet nozzle, a small angle of deviation was noticed over the machined surface. Additionally, the surface has been induced to severity in cutting force and plastic deformation occurred. Wear scars thus produced are in random and not parallel to the water jet cutting direction. Rate of damage in cutting zone is severe than dross zone.

Similarly, electron microscopic analysis has been done at the root radius of the gear profile (Fig. 9). In gear manufacturing, the surface profile at the intersection of flank face and root radius is very complex. The wear tracks are in combination of craters, ploughing, chipping and plastic deformation. Linear wear scars revealed at the surface of the root land (Fig. 9). With reference to the root radius, the movement of jet nozzle was distracted and the exerted cutting force / pressure caused severe damage as same as in the gear top land. Hard abrasive was found on the machined surface with clinging effect. Wear tracks are rough and deep due to high jet pressure at the cutting zone of the gear.

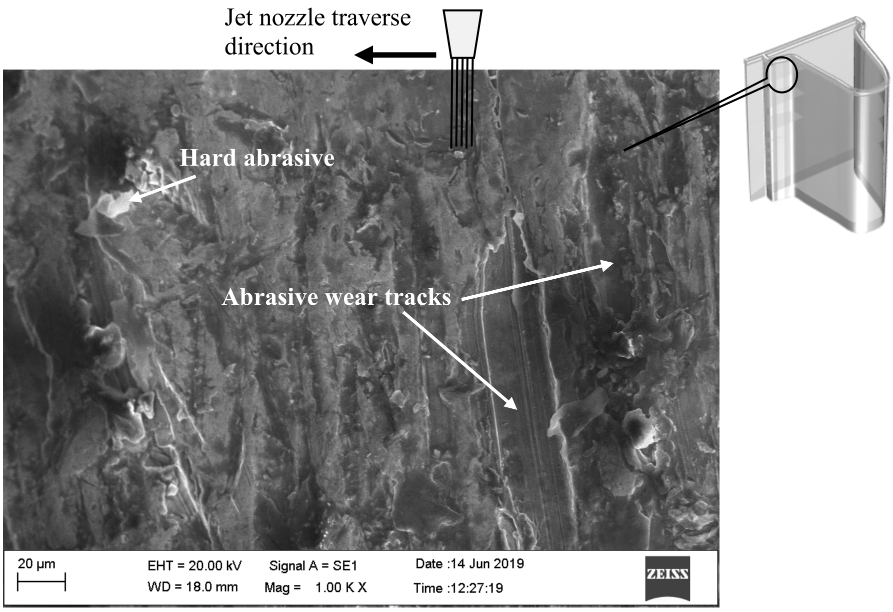


Figure 9: SEM micrograph of the optimum gear tooth observed at root radius

When the amount of abrasive flow has been increased, the rate of erosion became high. Figure 10 shows the surface topography of the gear machined at the maximum flow rate of abrasives (300 g/min). It is known that the cutting efficiency of the hard abrasive particles increases with high jet pressure as well as the increasing mass flow rate to remove the bulk material (Kantha 2006). Thus, at a maximum flow rate of 300g/min the removal of bulk material with severe wear scars are revealed. On continuous strike of hard abrasive particle, the rebound of metal deformed is observed as an elongated flake (lip formation). This is called as abrasive wear mechanism that involved due to mechanical cum hydro solid particle erosion (Ali et al 2010). The force exerted due to hydro-mechanical energy will lead to a long wear scar. To compare this wear mechanism, gear machined with 150MPa of jet pressure with same abrasive flow rate (300g/min) has been studied. It resulted in surface topography with a short wear scar (Fig. 11). The average surface roughness measured for 150MPa – 300g/min is 1.79µm and 350MPa – 300g/min is 1.46µm. The difference in surface roughness is due to the inefficient hard abrasive particles; at a combination of mass flow rate 300 g/min and low water jet pressure 150 MPa, which caused mechanical wear in the form of ridges and grooves (Hlavacova et al. 2016). Moreover, removal of material is also not complete for low jet pressure.

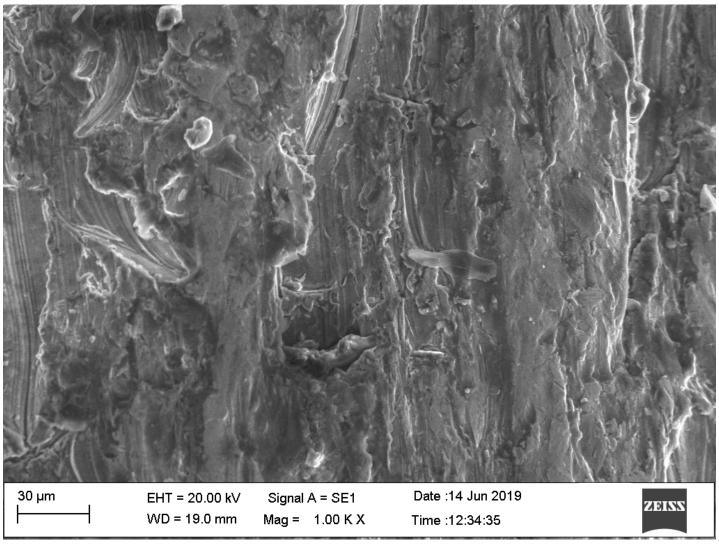


Figure 10: Surface topography of the gear machined at 350MPa – 300g/min – 1.5mm.

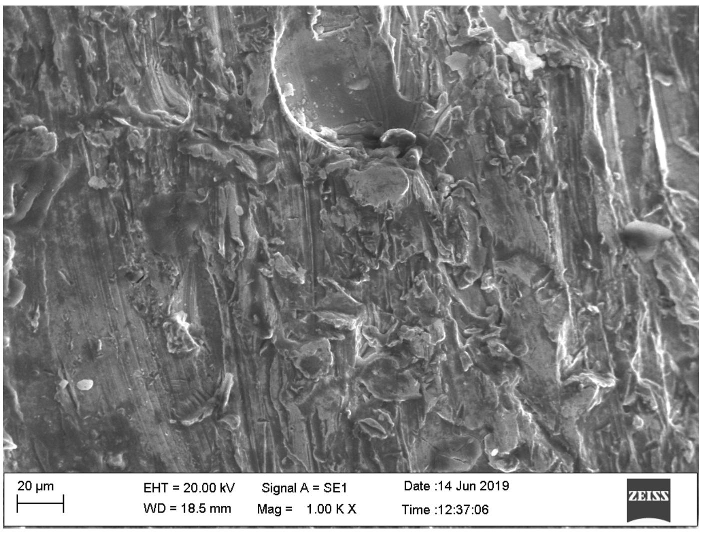
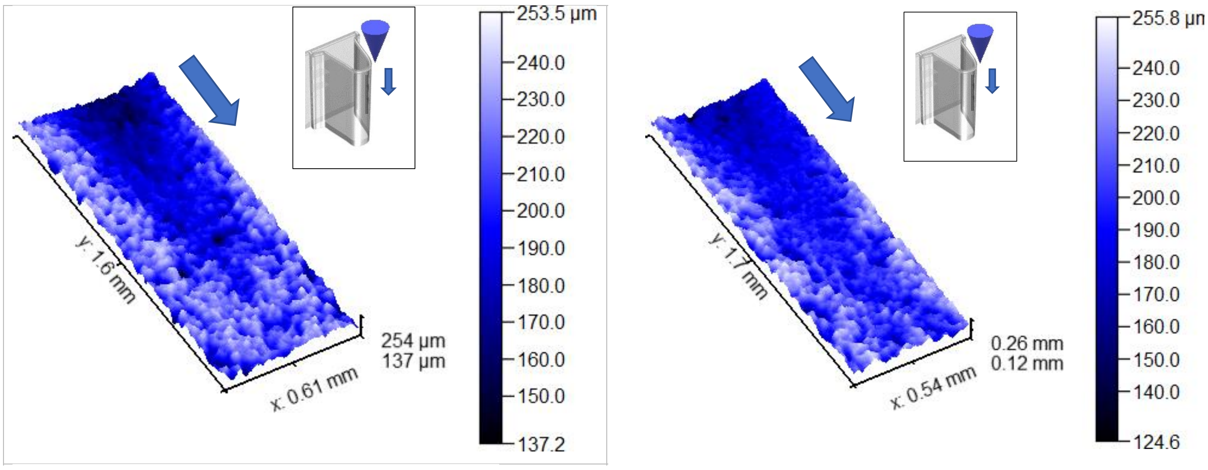


Figure 11: Surface topography of the gear machined at 150MPa – 300g/min – 2mm.

To know the depth of wear scars, the gear land has been investigated using the white light spectroscope. The three dimensional surface profile of the gear top land is measured and represented in Figure 12. In general, surface profile observed from the white light spectroscope reveals with the maximum peak and valleys over the projected machined surface area. The intensity of water jet pressure (machined at a process condition of 350MPa – 225g/min – 1mm) at the cutting zone has produced minimum ridges than the dross zone. The hedges i.e. the wear tracks in wave form in dross section are due to weak jet pressure, and resistance of metal to get deformed (Puneet 2015). In Fig 12, the profiles with dark shades represent maximum depth of wear and leading to a peak with light shades. Rate of metal cutting will be varying based on the amount of abrasive flow and jet pressure. Likely, the 3D surface profile of the gear machined with 300g/min has produced maximum crater and the range of peaks and valley in the surface profile is in wide (120 – 260 µm) compared to a flow rate of 225g/min (137 – 254 µm).



(a) 350MPa – 225g/min – 1mm (b) 350MPa – 300g/min – 1.5mm

Figure 12: 3D surface profile of the gear top land machined at two different cutting parameters

To discuss in detail, the surface of the gear top land observed at different spots are shown in Figure 13. The depth of crater is identified with reference to the colour shade. At cutting zone, the depth of crater revealed with dark shade with a wide variation in peaks and valleys. This can be confirmed with the 3D profile of gear top land (Figure 12) and SEM morphology as shown in Figures 7 and 8. The wear craters and the scars (in Fig 7) texture is reflecting on 3D profile (Fig 13 a & b). It is resulted due to the effect of abrasive flow rate. At average flow rate of 225g/min (Fig 13a), the peaks / craters are found uniformly distributed. For a maximum flow of 300g/min, the peaks / craters are maximum and uneven. Since, the effect of metal cutting in abrasive water jet machining is highly influenced with abrasive flow rate. The sharp peak infers the lip formation due to chipping of hard particles of bulk material machining. Subsequently, the jet pressure will activate the efficiency of particle behaviour and to shear the materials. Fig 13c represents the surface texture of the gear in dross zone. The profiles depict the continuous dimple textures formed at a regular track. It is due to the waves developed in the jet pressure at the dross zone. The cutting zone has a concave profile and dross zone has a continuous wave profile. Therefore the cutting zone has maximum deformation than in dross.

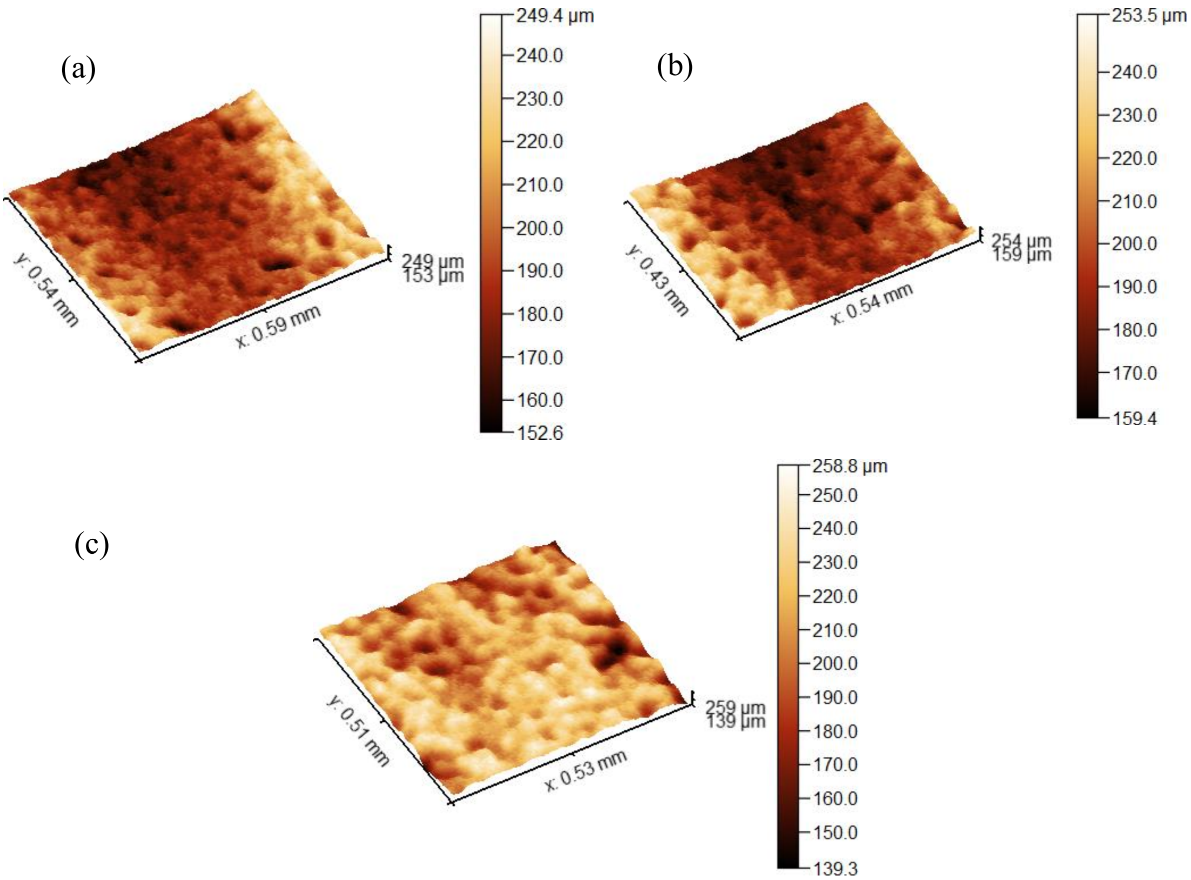


Figure 13: 3D surface profile observed at (a & b) cutting zone; and (c) dross zone, of the gear top land machined at 350MPa – 225g/min – 1mm.

Our overall results are in match with Trek et al (2018) and (Puneet 2015) who reported the same that the increase in jet pressure leads to the improvement in surface finish and the influence of SoD on surface quality is the least significant.

Conclusions

Surface morphology study of miniature gears of brass manufactured by abrasive water jet machining is reported in this paper. The following conclusions can be drawn from this work:

1. The minimum surface roughness of 1.08 μm was achieved at optimum condition of 350MPa water jet pressure, 225 g/min abrasive mass flow rate, and 1 mm stand-off distance.
2. The water jet pressure was found the most significant parameter affecting surface roughness with 47% of contribution for surface quality enhancement. The water jet pressure also increased cutting efficiency and hence the process productivity.
3. SEM investigation found that the amount of bulk material removal was maximum at the cutting zone of gear lands.
4. The deformation of the gear material is highly influenced by combination of abrasive flow rate and jet pressure. At a combination of 350 MPa jet pressure and 300 g/min mass flow rate, due to high cutting efficiency, material removal and wear were found maximum.
5. Impact of SoD found minimum and it is suggested not to increase the SoD above 1 mm as the jet pressure gets distracted and leads to surface deterioration.

In essence, abrasive water jet machining has the potential to manufacture good surface quality miniature gears of brass at high jet pressure with moderate mass flow rate and at low stand-off-distance. The miniature gear machined at optimum AWJM parameters possesses precise finish and good morphological characteristics. Due to low production cost and time for gear manufacturing, AWJM is identified as a viable alternate to the conventional processes for mass production of gears to be used in scientific, industrial, and aerospace applications. Future work can be done on abrasive water jet machining of other gear shapes, profiles, and materials.

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