Nanofinishing of tiny gear using magnetorheological abrasive flow finishing process

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Abstract

Precise finishing of small gear increases its life and performance. To impart nanofinishing on small gears, it is necessary to remove defects on gear's working surfaces due to manufacturing. The defects include scratch marks, burrs and pits. Very few finishing processes are applied to small gears due to the narrow spacing between the gear teeth. Magnetorheological abrasive flow finishing process is a magnetorheological polishing fluid based finishing process which delivers nanometer level finishing. In the present study, this process is employed to nanofinish steel gear. This problem is addressed by developing gear workpiece fixture and synthesize optimum polishing fluid in the finishing process. Wire electro discharge machining is used to manufacture the steel gear. After finishing the steel gear, minimum surface roughness of 47 nm is achieved. Maximum percentage improvement of surface roughness obtained as 79.91%. Also, all manufacturing defects are removed after the finishing process. After analyzing the finished surface, it is concluded that recast layer on the initial surface is completely removed after the finishing process.

Keywords: Nanofinishing, magnetorheological abrasive flow finishing process, magnetorheological polishing fluid, tiny steel gear

1. Introduction

Tiny gears are an essential component in the transfer of power and other resources in the small devices used in the aircraft, automobile, and commercial sectors. A nanoscale surface finish on a gear's tooth surface can help to ensure seamless power delivery, noiseless movement, and a prolonged serviceability. The gear tooth surface suffers considerable amount of damage due to manufacturing defects and repetitive operations. Burrs, scratches, cuts, pits, and other manufacturing flaws may be found in small gears. Burrs degrade the performance of the gear [1]. The pits are defined as the composition of dents and plastic deformation of the surface [2]. For a tiny gear, finishing of the tooth surface is much more complicated than a conventional macro gear. Different types of methods such as hobbing, grinding, honing are available for deburring macro gears but not for tiny gears due to its complex geometry. Tiny gear is difficult to polish in conventional process [3], [4]. According to literature survey, no methods are reported to remove burrs and pits from tiny gears till 2010 [2]. A new method is proposed by researchers to remove pits and burrs from tiny gear tooth edges using a tool shaped as a gear which is composed of glass-fiber-reinforced-plastic (GFRP) [2], [3]. This process is able to dislodge the microscopic burrs and pits from the surface of tiny gears. Almost all the techniques utilized for the finishing of gears, deal with conventional macro sized gears which are used for automotive and other purposes. To solve the drawbacks of known processing techniques, an ultra-precision polishing technology i.e. magnetorheological abrasive flow finishing (MRAFF) process is employed in the present study to finish tiny gears. In this study, MRAFF process is used for removing manufacturing defects from the teeth profiles of the gear and to achieve nanofinishing on gear working surfaces. Das et al. [5,6] utilized MRAFF technique to polish complex metallic components at the nanometer level. MRAFF utilizes magnetorheological polishing fluid (MRPF) [7] which has the capability to increase the viscosity considerably in the existence of magnetic field. MRPF is a mixture of iron powder and abrasive grains in a base media [8–10]. MRPF comprising 26.6 Vol. % iron and 13.4 Vol. % SiC abrasive particles is utilized for polishing stainless-steel workpiece and the optimum surface roughness (R_a) achieved was 16 nm [5].

In the present experimental investigation, tiny gear is made from SS316L alloy. Wire electro-discharge machining (WEDM) is used to build and produce the steel gear component. The gear is then finished by MRAF finishing process. The process variables are first calibrated using preliminary experimental study. Further, the optimum experimental conditions are used to nanofinish the workpiece. The finished workpiece surface is analyzed and characterized with the help of optical profilometer (make: Taylor Hobson, with monochromatic green light source) and digital microscope (make: Tool makers).

2. Experimental setup and procedure

In MRAFF experimental set up, the desired workpiece is finished by flowing thickened MR polishing fluid over the surface in the polishing region under the presence of external magnetic field. Two symmetric hydraulic cylinders are fixed on the top and the bottom of the experimental set up which are filled with oil and provides a vertical to and fro motion on the existing MR polishing fluid. Due to this to and fro motion, the MR medium is forced through the workpiece fixture from top to bottom polishing cylinder and bottom to top polishing cylinder [5]. The MRAFF process experimental setup is demonstrated in Fig. 1. A tiny gear fixture (Fig. 1) is planned and developed to finish small gear in MRAFF process. The workpiece fixture holds the small gear workpiece during finishing. The workpiece fixture is surrounded by a magnet fixture as shown in Fig. 1. The workpiece fixture is designed in such a manner which is capable to adjust, hold and disassemble easily.

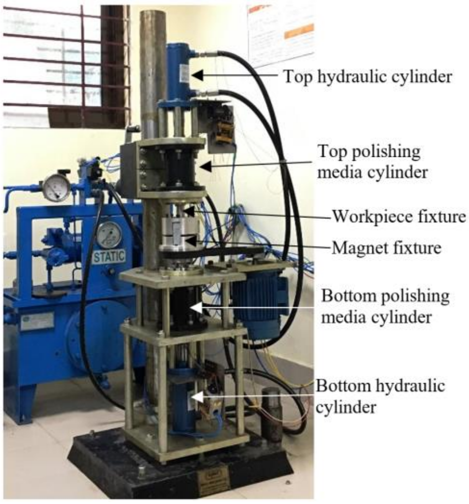


Fig. 1. MRAFF process experimental set up

The hydraulic cylinder exerts the pressure on MR polishing fluid. This extrusion pressure helps MRP media to flow across gear surfaces in upward and downward direction for precise finishing. The workpiece fixture is fixed in between two polishing media cylinders along with the magnet fixture. Eight holes on the outer side of both the flanges were made for allowing the MR polishing fluid to flow across the workpiece. The retention of more MR polishing fluid helps in better finishing of workpiece. Sufficient area is left in the workpiece fixture to retain enough MR polishing fluid inside the workpiece fixture for finishing gear workpiece. The material used to manufacture the gear workpiece is SS316L. The radius of the small gear is 7.5 mm. In the present study, steel gear workpieces are manufactured using wire EDM process. The schematic diagram of flow of MR polishing media inside the workpiece fixture during the MRAFF processing is demonstrated in Fig. 2. Key process parameters in case of MRAFF process are hydraulic pressure, number of finishing cycle, MR polishing fluid composition and concentration and magnet fixture rpm [11]. Hydraulic pressure and MR polishing fluid concentration are reserved constant during the whole polishing period and their value is given in Tables 1 and Table 2, respectively. MRPF composition and number of finishing cycles is varied to obtain the necessary process parameter values to finish small gear workpiece effectively.

The volume concentration of each constituent of MRPF to polish steel gear component in MRAFF method is listed in Table 1. The base media vol. % is increased to enable the MR polishing fluid to move more freely within the gear fixture. According to preliminary studies and literature reviewed, an abrasive particle size of 800 mesh is adequate to obtain nano-scale surface finish on the steel gear component. 800 mesh sizes are taken into account for iron particles. A initial experimental work is conducted to assess the optimal iron particle mesh size. The experimental condition as given in Table 2 for each preliminary experiment is kept same. Also, vibrating sample magnetometer (VSM) is utilized to find out the magnetic property of the MR polishing fluid with different iron particle mesh size as given in Table 3.

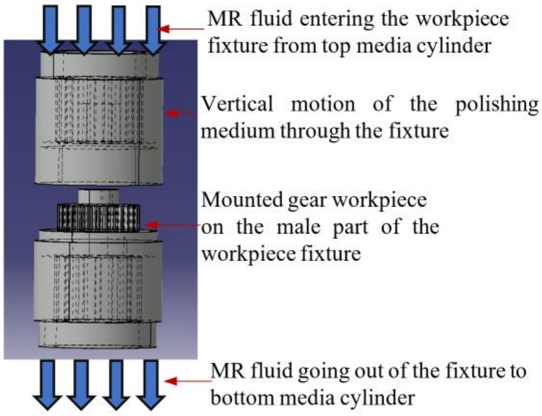


Fig. 2. Side view of the flow of MRPF during the polishing procedure

Table 1. Volume concentration of MRPF constituents

Constituents	Volume concentration (Vol.%)
Iron particle	22
Abrasive particle	8
Grease	10
Paraffin oil	60

Table 2. Experimental condition during preliminary experiment

Experimental conditions	Value
No. of finishing cycle	800
Pressure	30 bar

Table 3. Magnetic properties of iron particles of different mesh sizes

Magnetic properties	Unit	Mesh size	
		800	400
Coercivity	G	69.474	69.519
Magnetization	emu/g	138.02	147.46
Retentivity	emu/g	2.0549	2.3046

The aforementioned values indicate that the chain structures formed by the iron particles of 400 mesh size iron particles are stronger than iron particles of 800 mesh size. As the magnetization force for 400 mesh sized iron particles is found comparatively higher than the 800 mesh sized iron particles, the formed chain structure is also a bit stronger. If the formed chain structure is stronger, the abrasive particles get trapped in between the chain structure more firmly. As a result, the chains formed while finishing process do not get broken easily and contributes to the finishing process longer than that of the weak chain structures. As the finishing force on the surface of the specimen was more, the material removal rate during finishing is higher.

After the preliminary experiments, it has been discovered that finishing steel gear with iron particles (IPs) of 800 mesh size is very successful. A better surface finish (nanometric scale) is obtained after finishing with 800 mesh sizes. However, no difference in surface roughness is found in-between the gear teeth. Since 400 mesh size is weightier and bigger than 800 mesh size, MRPF sedimentation is detected. As a consequence, the IPs disperse from the base media, and the IPs have no impact on the intricate surfaces of the specimen, such as the surface in-between gear teeth. From preliminary experimental study, it is observed that after around 200 cycles the

IPs are getting detached from the base media and the liquid (paraffin oil) was leaking out of the media cylinder. To get rid of the sedimentation problem and in order to get finer finishing iron particles of 800 mesh size is selected. After finishing with 800 mesh size of IPs, nanometeric scale surface finish is accomplished all throughout the gear workpiece. After the preliminary finishing experiments using iron particles of 800 mesh size the sedimentation problem reduced and also the obtained surface finish is better.

Following the selection of the MRPF composition, the number of finishing cycles are varied to determine the optimal number of finishing cycles. Initially,with experiment for 200 cycles, no difference in surface roughness is detected. Further, for 400 finishing cycles, obtained surface finish was in nanometer level. After 800 finishing cycle, surface finish more improved. With further experimrntation, minimal surface finish improved, however, more pitting and deformation at gear teeth involute profile is detected. Thus, 800 finishing cycles are chosen for further experimentation. After selecting the optimum process parameter conditions, further experiments are carried out to characterize the finished surfaces of the steel gear component. Surface roughness and surface topography of the initial and final workpiece surface at different position are analyzed. Also, macrograph of workpiece before and after finishing are analyzed.

3. Result and Discussions

3.1 Surface topography and surface roughness analysis of steel gear

The characterization of the steel gear workpiece is carried out before and after the finishing experiments. Optical profilometer is utilized to study surface roughness and surface topography. Macrographs of the workpiece are observed using a digital microscope. Gear involute profile is characterized to analyze the MRAFF process capability to deliver nanometer level finished miniature gear with fine finish. Surface topography and surface roughness of gear teeth involute profile pre and post finishing process is demonstrated in Fig. 3. The involute profile before finishing is covered with pits, scratch marks and burrs as shown in Fig. 3(a). After finishing with MRAFF process, the burrs and pits are removed from the profile as demonstrated in Fig. 3(b). The final average surface roughness value (*Ra*) is achieved as 47 nm from the initial *Ra* of 234 nm as shown in Figs. 3(c) and (d). The percentage improvement in surface roughness in case of involute profile is 79.91%.

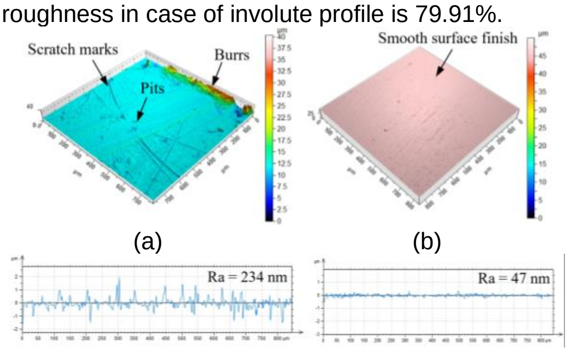
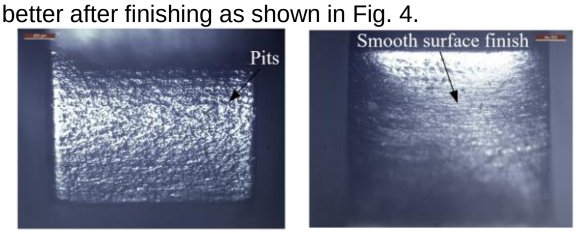


Fig. 3. 3D surface topography of gear tooth involute profile (a) before and (b) after finishing; surface roughness profile of gear tooth involute profile (c) before and (d) after finishing

According to the surface roughness study, the 79.91% enhancement in surface roughness is accomplished at involute surface of gear tooth. In MRAFF process, the involute surface of the gear workpiece is subjected to more shear force than tangential force due to MR polishing fluid reciprocating movements. Due to this difference in finishing forces material removal is higher in involute surface.

3.2 Macrograph analysis of steel gear

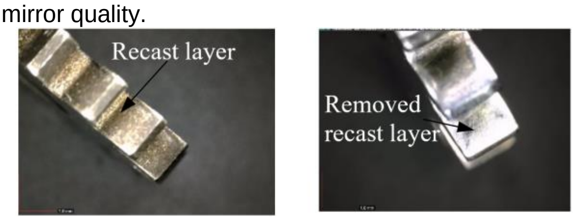
Digital microscope is used to carry out the macrograph analysis of the gear workpiece before and after finishing. Macrograph analysis helps to observe and analyze different kind of defects on working areas of gear workpiece. The surface finish on the involute surface of the gear tooth is observed and it is found that the surface finish on the involute tooth profile is better after finishing as shown in Fig. 4.



(a) (b)

Fig. 4. Microscopic image of gear involute profile (a) before and (b) after finishing

The presence of pits with a rough surface is observed at gear tooth involute profile. After the finishing process, fewer dent marks with smoother surface is observed. Surface texture of finished surface has less scratch marks, dents and pits than the initial surface as observed from the macrograph. The steel gear workpiece is manufactured using wire EDM process for which it is subjected to recast layers. The presence of recast layer is found by performing a macrograph and 3D surface topography analysis of the gear. The recast layer is present on gear involute surface before finishing is shown in Fig. 5(a). After finishing process, recast layer is completely removed from involute surface of gear (Fig. 5(b)). The loose materials, scratch marks and surface finish on different working surfaces are improved after the finishing. The steel gear before and after the finishing process is shown in Fig. 5. It is observed that the recast layer as shown in Fig. 5(a) is completely removed from the finished gear (Fig. 5(b)). The finished gear shows finer finishing with mirror quality.



(a) (b)

Fig. 5. Steel gear workpiece (a) before and (b) after finishing

3.3 Material removal rate (MRR) of steel gear

The material removal rate is the amount of material that is removed per minute. In the present case, the required time to complete the total finishing experiment and volume of the workpiece before and after finishing is measured to calculate the MRR. The MRR is calculated from the following relation (Eq. 1) and calculated MRR/min of steel gear workpiece is shown in Table 4.

$$\text{MRR}=\frac{\text{Initial volume-Final volume}}{\text{Finishing time}} \quad (1)$$

Table 4. MRR of steel gear workpiece

Total Finishing time (min)	Initial weight (gm)	Final weight (gm)	MRR(gm/min)
260 (800 cycles)	1.6783	1.5870	0.0003511
130 (400 cycles)	1.6785	1.6757	0.0000215
65 (200 cycles)	1.6821	1.6814	0.0000101

4. Conclusions

Small steel (SS316L) gear workpiece is finished using MRAFF process. The finished surface is analyzed to find out the finishing process capability to remove burrs, pits and recast layer from the working surface of gear workpiece. Preliminary experimental study is conducted on the steel gear workpiece to determine required process parameter conditions for finishing of gear workpiece. Initially, iron particle of 400 mesh size is used in the MR polishing fluid which turned out to be not effective for finishing steel gear workpiece. Due to its heaviness the MR polishing fluid faces sedimentation problem during finishing process which results in separation of iron particles from the base medium. Hence, these iron particles are not effective during finishing of the workpiece complex surfaces. Later, iron particles of 800 mesh size is used which is finer in size than 400 mesh size. Nanometer level surface finish on all the surfaces of the steel gear workpiece is achieved. In order to get finer finishing on all the surfaces, 800 mesh size iron particles are used which provided desired surface finish on all the surfaces. Number of finishing cycle is also optimized through preliminary experimental study and it is found that 800 number of finishing cycle provides the necessary surface roughness without deteriorating the gear workpieces form and already finished surface. The finished surfaces are compared with the initial surface with help of surface topography, surface roughness, micrographic image analysis. The minimum obtained surface roughness on the steel gear workpiece is 47 nm. Maximum percentage improvement of surface roughness obtained as 79.91%. After analyzing the surface topography and macrograph of initial and finished surface it is concluded that recast layer is completely removed from the finished steel gear workpiece. Also, the analysis shows that pits and burrs are removed from the finished steel gear.

Acknowledgements

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