On Abrasive Flow Finishing of Straight Bevel Gear

Anand Petare, Neelesh Kumar Jain, and I. A. Palani

Abstract Abrasive flow finishing (AFF) is a non-traditional nano-finishing process for radiusing, polishing, surface stress reliving, geometry optimization and deburring. This paper reports on finishing of straight bevel gear by using AFF. Experimental setup of AFF and a special fixture for holding workpiece straight bevel gear were developed. Finishing result produced by AFF is significantly influenced by two process parameters, namely finishing duration and extrusion pressure. Eleven experiments for AFF of straight bevel gear were conducted in two phases by varying extrusion pressure and finishing time using one factor at a time approach. The outcome showed high improvement in maximum surface roughness and average surface roughness of gear which will further improve their service life and operating performance. Surface morphology study of AFF finished straight bevel gears revealed that their flank surfaces are free from cutter marks, burrs, nicks, micro-cracks, micro-chips, and micro-pits. Result produced establishes the feasibility AFF for precision finishing of straight bevel gear.

Keywords Abrasive flow finishing · Gear finishing · Surface roughness · Straight bevel gear

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1 Introduction

Abrasive flow finishing (AFF) is one of advanced non-traditional finishing process developed in 1960s by Extrude Hone Corporation (USA) for radiusing, polishing, deburring, surface stress relieving and geometry optimization of complicated shapes and inaccessible areas. It uses abrasive laden viscoelastic medium called putty (i.e. mixture of abrasive particles, viscoelastic polymer, blending oil and other additives) which extruded across or through the workpiece at high pressure. The continuous back and forth movement of putty causes abrasion and imparts fine finishing to the workpiece. AFF frequently used for finishing components of aerospace, automotive, diesel, and turbine engines, pump industries, medical implant, mould and die, additively manufactured components, recast layer removal and to finish difficult machine materials and inaccessible areas [1]. The straight bevel gear is one of the essential components used in the automobiles, farm and agriculture machinery, railways, and cement mill, material handling equipment, rolling mills, machine tools, wind turbines, marine applications, and various industrial machines for transmitting motion and/or power between two perpendicular shafts with constant velocity ratio. It frequently used in many machines due to high power and torque transmitting capability compared to another type of gears therefore demand for this type of gear is very high. Continuous demand for small cars, wind turbine power station, and ships increases production of gears to several billion [2]. Gears are expected to transmit high power with good motion transmission characteristics, light in weight and smaller size, less maintenance, high load carrying capacity with minimum noise and vibration, better surface quality and high wear resistance. These expectations achieved by gear finishing using appropriate finishing process. Grinding and lapping are traditional finishing processes which are used frequently for finishing bevel gears. Gear grinding is very old and established process for all type of case hard or hardened gears having Rockwell hardness at C scale below 92. (i) generates grinding burns causes thermal damage to the ground gears; (ii) transverse grind lines on the ground gear flank surface causes noise and vibrations; (iii) requires frequent supply of coolant and redressing of grinding wheels; and (iv) costly and requires skilled operators [3]. Gear lapping can correct minute errors in profile, lead, pitch, runout and minute distortion caused by heat treatment in the gears made of hard or hardened materials but (i) longer lapping cycles affects the form accuracy of the lapped gears adversely; and (ii) only mating gears are lapped in a pair and they cannot be interchanged [4]. To overcome limitation of traditional gear finishing process, there is need to explore and develop highly productive, easy operative, economic and sustainable hybrid or advanced gear finishing process. Recently, some researcher has explored AFF for finishing different type of gears. AFF were used by Xu et al. [5] to finish helical gear, and they revelled reduction of average surface roughness (R_a) from 1.42; 1.10; and 2.73 μm to 0.22; 0.21; and 1.75 μm at left flank, right flank, and addendum with improved fatigue strength and contact stiffness in a very less time. Venkatesh et al. [6] explored US-AFF to finish straight bevel gears (SBG) made of EN 8 steel and reported 73% reduction in average surface roughness with glazed surface texture.

In context of gear finishing, AFF find more suitable because of use of flexible finishing medium which can go easily inside the intricated root flank surfaces of bevel gear and form a complementary shape of tooth gap. The complementary shape of finishing medium acts as flexible grinding stone and a continuous movement of it causes abrasion and impart finishing to it. Referring to previous research work, it found that a very limited work performed on finishing of gear by AFF, and it mainly emphasized on reduction of average surface roughness. No work reported on reduction of maximum surface roughness and on improvement of surface morphology of straight bevel gear using AFF. Therefore, this work aim to improve maximum and average surface roughness of straight bevel gear using AFF and to study their surface morphology and bearing area of straight bevel gear which shows higher reductions in surface roughness.

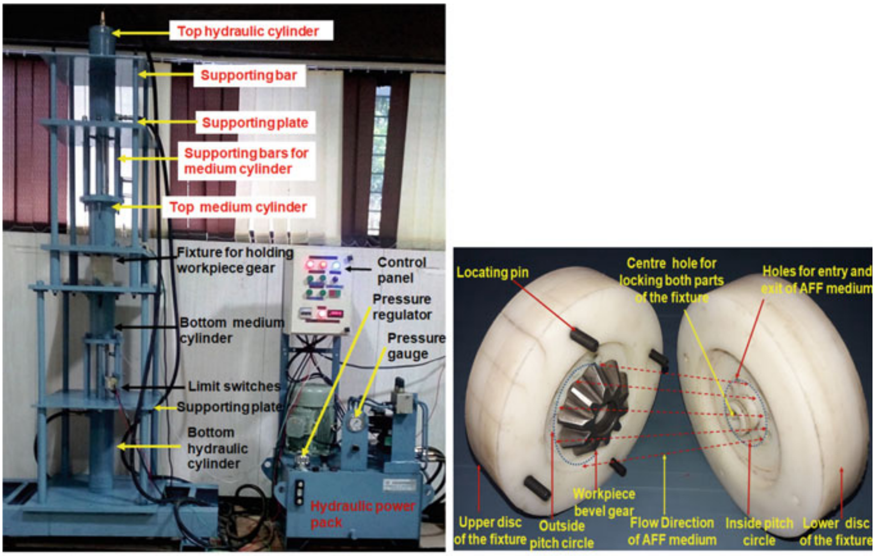
2 Materials and Methods

2.1 Gear Material and Specifications

Alloy steel 20MnCr5 which is widely used for commercial applications of straight bevel gears was selected having 91.3 Rockwell hardness at B scale (HRB). The chemical composition of gear material is 1.10% Cr; 1.19% Mn; 0.18% C; 0.019% P; and 0.017% S; and balance Fe (by wt%). The specifications of gear are involute gear teeth having 4.8 mm module, 10 number of teeth, 32° pitch cone angle, 20° pressure angle, 15 mm face width, 48.9 mm pitch circle diameter, 59 mm outside diameter and 20 mm bore diameter.

2.2 Experimental Setup and Fixture for AFF of the Gears

A two-way vertically configured experimental setup of AFF was developed a photograph of same is shown in Fig. 1a. It contains two hydraulic cylinders placed vertically opposite to each other and two medium containing cylinders. A hydraulic power unit is connected to hydraulic cylinders to reciprocate their piston and further to the piston of medium containing cylinders. A special fixture was developed for holding, and supporting work gear as shown in Fig. 1b and to enable their finishing by AFF process. It has two cylindrical discs made of Metalon having an axial cylindrical boss to hold and support the work gear. It has 10 circumferential holes of 8 mm diameter in upper disc and 5 mm diameter holes in bottom disc according to pitch circle diameters of the work gear. A central hole in both part of fixture provided along with four locating pins at upper part of disc corresponding to drilled holes in lower part of disc to avoid any dislocation of both part of fixture while extruding finishing medium. The work gear was placed on boss in its fixture such a way that drilled holes located



(a) (b)

Fig. 1 **a** AFF experimental setup; and **b** fixture for finishing straight bevel gear

in tooth gaps of both part of disc. After placing gear in upper disc, their locating pins matched with lower disc, and they were bolted together through a central hole to avoid shifting while extruding finishing medium at high pressure. Initially, AFF medium were filled in bottom medium cylinder, and it extruded towards top medium cylinder through workpiece containing fixture. The circumferential holes in lower disc allow entry of the AFF medium on the flank surfaces in tooth gap of a work gear along the face width during upward stroke. Thereafter medium exit from upper disc, and it collected in top medium cylinder. During downward stroke same sequence is repeated. This continuous back and forth movement of finishing medium over flank surface causes abrasion which shear off roughness peaks and improves their surface finish.

2.3 Details of Experimentation and the Considered Responses

AFF finishing medium comprises of abrasive particle selected based on the hardness, material properties, desired finishing, size and shape of workpiece, viscoelastic carriers, blending oil and other additives [1]. Silicon carbide selected as abrasive particles based on the hardness of gear materials. Moulding clay selected as a viscoelastic carrier to make putty due to its easy availability, the capability to hold abrasive particles together and low cost. Silicone oil used for blending and to change the viscosity of the finishing medium. In these experiments, silicon carbide with 100 mesh selected as abrasive particle according to the module of gear [7]. Moulding clay was used for putty because of low cast, easy availability and its capability to hold the abrasive particle against high extrusion pressure. AFF medium of selected abrasive particles, putty and blending oil (whose quantities are calculated according to required composition of the AFF medium) were prepared by thorough hand mixing followed by pressing in a deep drawing machine. Volumetric concentration of blending oil was increased correspondingly reducing volumetric percentage of the putty in the AFF medium to maintain of 1156 cm^3 volume (determined from the dimensions of the AFF medium containing cylinder). Extrusion pressure, finishing time, concentration, type, hardness and size of abrasive particles, medium viscosity, geometry and hardness of workpiece are significant AFF process parameters.

In Phase-1, four experiments were performed to identify optimum value of extrusion pressure by varying it at four levels (i.e. 2.5; 5; 7.5; and 10 MPa) and using constant values of finishing time 't' as 15 min, size of abrasive particles as 100 Mesh (with corresponding diameter 150 μm), volumetric concentration of abrasive particle as 30% and volumetric concentration of silicon oil as 10%. Seven experiments were conducted using one factor at a time approach in Phase-2, by varying finishing time 't' at seven levels (i.e. 10; 15; 20; 25; 30; 35; and 40 min) and using optimum value of extrusion pressure 'P' obtained in Phase-1 experiment, size of abrasive particles 'M_a' as 100 Mesh (with corresponding diameter 150 μm), volumetric concentration of abrasive particle 'C_{av}' as 30%, and volumetric concentration of silicon oil 'O_c' as 10%. Maximum surface roughness '$R_{\max}$' and average surface roughness 'R_a' were used as the responses in all these experiments. Additionally, surface roughness profiles and surface morphology were studied for those straight bevel gears which have shown maximum reduction in the considered parameters surface roughness. They have been referred to as the best-finished gears.

Gears are subjected to fluctuating stresses, and therefore, surface roughness is very important aspect because it affects their service life and operating performance. Higher surface roughness causes less available contact area with its meshing gear and frequent breakage of roughness peaks which result faster wear of flank surfaces of a gear by pitting, micro-pitting, scuffing, abrasive wear and adhesive wear.

2.4 Measurement of the Responses

2.4.1 Measurement of Surface Roughness

Maximum surface roughness '$R_{\max}$' and average surface roughness 'R_a' of straight bevel gears were measured before and after finishing by AFF using surface roughness tester (LD-130 MarSurf from *Mahr Metrology, Germany*) by probing in both left and right flank surfaces at two different location. An average of all assessed values of 'R_a' or '$R_{\max}$' were used to calculate the changes in maximum surface roughness '$\Delta R_{\max}$' and average surface roughness 'ΔR_a'. Following relation was used to calculate change in max. surface roughness 'ΔR_{max}':

$$\Delta R_{max} = \text{Avg. } R_{max} \text{ of a gear before AFF - Avg. } R_{max} \text{ of the same gear after AFF}(\mu\text{m}) \quad (1)$$

Also, change in average surface roughness 'ΔR_a' was calculated.

2.4.2 Surface Morphology Examination

Surface morphology of flank surface was examined for before finished and AFF fine finished straight bevel gears using optical microscope (Leica DM2500M from *Leica Microsystems, Germany*) to assess the finishing mechanism by AFF process.

3 Result and Analysis

Table 1 presents the results of the four experiments conducted in Phase-1 by varying extrusion pressure along with considered responses.

It is clear from Table 1 that values of changes in max. and avg. surface roughness values increase with extrusion pressure up to 7.5 MPa and attain maximum values corresponding to experiment no.3; thereafter, it starts decreasing. It was also observed that increasing extrusion pressure from 5 to 7.5 MPa values of changes in max. and avg. surface roughness increases but the developed experimental setup become unstable due to the generation of excessive vibrations. Therefore, 5 MPa extrusion pressure considered optimum for Phase-2 experiments. Table 2 presents the results of the seven experiments conducted in Phase-2 by varying finishing time along with considered responses. Figure 2 depicts variation of considered responses (i.e. change in average and maximum surface roughness values of straight bevel gear) with finishing time by means of regression equations obtained using results mentioned in Table 1.

It was observed from Table 2 and Fig. 2 that changes in surface roughness values during finishing time of 10–15 min is less due to the presence of higher surface roughness peaks which abrasive particles of AFF medium try reduce and try to attain

Table 1 Result of Phase-1 experiment

Exp. No.	Extrusion pressure 'P' (MPa)	Responses	
		ΔR_a (μm)	ΔR_{max} (μm)
1	2.5	0.07	0.03
2	5	0.20	0.22
3	***7.5***	***0.54***	***5.34***
4	10	0.19	1.10

Table 2 Result of Phase-2 experiment

Exp. No.	Finishing time ‘*t*’ (minutes)	Responses	
		ΔR_a (μm)	$\Delta R_{\max}$ (μm)
1	10	0.02	0.04
2	15	0.06	0.11
3	20	0.08	0.17
4	25	0.11	0.23
5	***30***	***0.15***	***0.39***
6	35	0.14	0.37
7	40	0.09	0.26

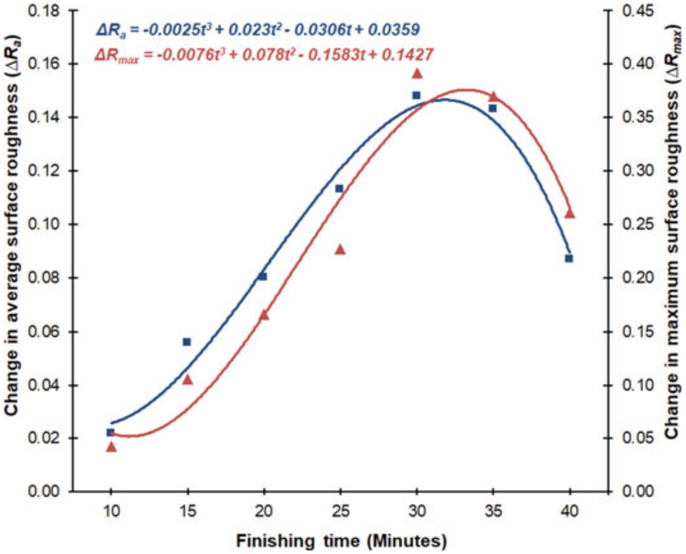


Fig. 2 Variation of change in maximum surface roughness and average surface roughness with finishing time

approximately equal heights after 15 min of finishing. During 20–30 min of finishing changes in surface roughness, values increase rapidly. They attain their maximum values at 30 min of finishing time corresponding to experiment no.5 (i.e. their max. and avg. surface roughness values after AFF attain their minimum values) due to the availability of surface roughness peaks of approximately equal heights. Changes in surface roughness values start decreasing for finishing time beyond 30 min because cutting edges of the abrasive particles get blunted.

Therefore, finishing time of 30 min and extrusion pressure of 5 MPa were identified as optimum parametric combination which yield higher reduction in max. and avg. surface roughness. The workpiece straight bevel gear finished at finishing time of 30 min and extrusion pressure of 5 MPa considered fine finished straight

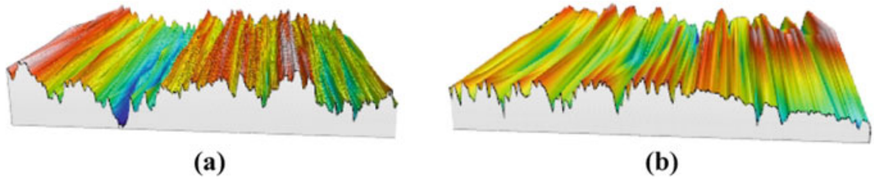


Fig. 3 Surface roughness profiles of the **a** before finished straight bevel gear; and **b** fine finished straight bevel gears

bevel gear for evolution of surface roughness, bearing area curve (BAC) and surface morphology. Figure 3 depicts 3D surface roughness profiles of the before finishing (Fig. 3a) and fine-finished straight bevel gear (Fig. 3b). It can be noticed from Fig. 3 that AFF decreased values of max. and avg. surface roughness values from 7.93 to 7.71 μm and from 0.82 to 0.68 μm for the fine finished straight bevel gear.

Figure 4 depicts bearing area of the before finished and AFF finished straight bevel gear at 30 min of finishing time. Improvement in surface finish makes bearing area of fine finished straight bevel gear (Fig. 4a) more uniform as compared to their before finishing state (Fig. 4b). These reductions in surface roughness and consequent improvement in bearing area of straight bevel gears will improve their wear characteristics which will result in their better tribological performance during their service life.

Figure 5 presents optical micrograph depicting surface morphology of the flank surface of the before finished and fine finished straight bevel gear. Roughness peaks, cutter marks caused by gear manufacturing process, pits and burrs were present on flank surface of before finished straight bevel gear (Fig. 5a) which were completely removed after their finishing by AFF as shown in Fig. 5b. The presence of micro-chips and abrasive flow marks indicate micro-cutting and ploughing mode material removal.

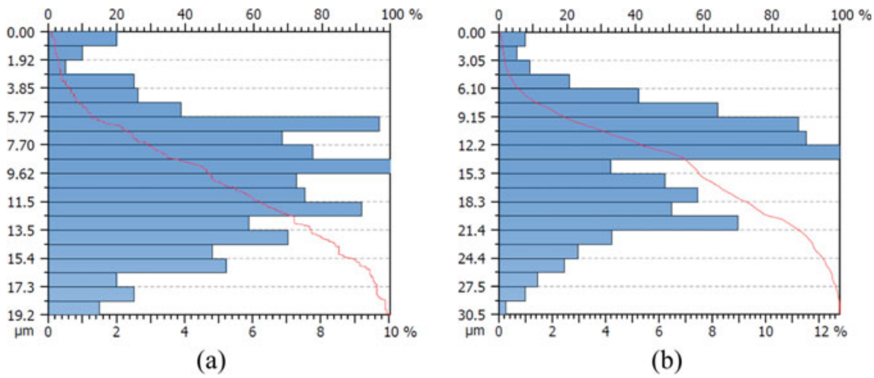


Fig. 4 Bearing area curve for **a** before finished straight bevel gear; and **b** fine finished straight bevel gear

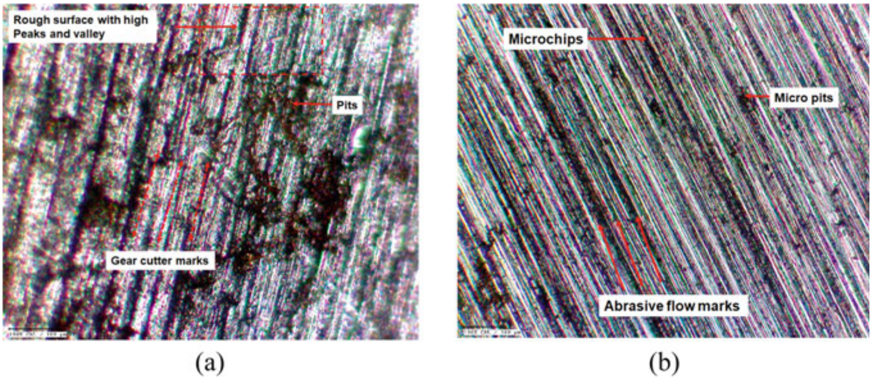


Fig. 5 Optical micrograph showing surface morphology of the flank surface of the **a** before finished straight bevel gear; and **b** fine finished straight bevel gear

4 Conclusions

The conclusions from this work can be summarized as follows:

- Reduction of surface roughness of gear flank surface improved bearing area which enhances wear characteristics and service life of AFF finished straight bevel gears.
- Surface morphology study of AFF finished straight bevel gears revealed that their flank surfaces are free from cutter marks, burrs, and nicks due to controlled and focussed abrasion caused by abrasive particle of the desired finishing area without any undesirable effect.
- Above work demonstrate capabilities of AFF to become cost-effective, productive and flexible gear finishing solution.

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