

Abstract

The surface roughness of any component is a major concern in the medical, automotive, aerospace, military, and other industries. The performance and life of the components depend primarily on their surface quality. The components explored in the current study for finishing purposes are miniature gear and poppet valve. The poppet valve accurately regulates the perfect air/fuel mixture into the combustion chamber of a gas propulsion engine or internal combustion (IC) engine to reduce hydrocarbon emissions. Miniature gears are used in biomedical devices for pumping, cutting, and various other works, also in small servo motors, which are widely used in the UAVs, automotive, and aerospace industries. Previous finishing methods (mentioned in the literature) generate defects like burrs, pits, scratches, dents, etc. The uniform nano-scale finishing on such components is tough to achieve due to constraints related to the fixture design and fixture material. The surface roughness requirement of these complex components is at the nanometer level and should be uniform over the entire surface. The rotational magnetorheological fluid-based finishing (R-MRFF) process is proposed in the present study to counteract the problems faced during finishing miniature gear and poppet valve profiles while providing the required uniform surface finish and surface characteristics. A novel flow restrictor and workpiece fixture are designed and developed to uniformly nano-finish SS316L miniature gear teeth profiles. Also, a novel magnet fixture is designed and developed to nano-finish Nickel-Al-Bronze alloy (AB2 grade) based poppet valve ridge profiles uniformly. Magnetorheological (MR) polishing fluid is used in the R-MRFF process to finish both components.

For designing the proposed uniform flow restrictor, first of all, uniform magnetic flux density, normal and shear stress distributions are calculated along the gear teeth profiles. For this purpose, magnetostatic fluid-flow analysis is carried out using a finite element (FE) based Comsol[®] Multiphysics software package. Further, based on FE analysis results, the optimum uniform flow restrictor and workpiece fixture model is designed among different proposed geometries of uniform flow restrictors. Three types of MR polishing media with varying sizes of iron particles and different abrasives concentrations have been prepared. After finishing with the novel workpiece fixture and Type-III MRP media, the minimum surface roughness (R_a) of the gear-tooth involute profile was decreased to 34.3 nm and 24.5 nm (without and with using a uniform flow restrictor, respectively) from its initial value of 265 nm. No recast layer, pits, or dents were observed on the finished surface.

While finishing with the uniform flow restrictor, almost the same surface roughness values are achieved at each gear tooth profile. From the analysis of variance (ANOVA), each process parameter's influence on % ΔRa and MRR are analyzed, and significant process parameters are selected. The value of the optimized process parameters, i.e., a volumetric proportion of IPs/SiC abrasives, extrusion pressure, and rotational speed of magnets, are 1.5, 35 bar, and 109 rpm, respectively, obtaining 90.75% improvement in Ra and 0.00192 g/min MRR. After comparing the predicted and experimental (validation experiments) results of % ΔRa and MRR, the maximum error is found to be less than 10 %, which depicts the feasibility of the proposed model. Surface roughness simulation and material removal model are also performed using finishing force analysis and FEA findings. The maximum percentage error of 11.5% and 8.69% between experimental and simulated MRR and surface roughness, respectively, was observed for miniature gear teeth profiles using a flow restrictor, which is also within a feasible limit.

Magnetostatic simulation is conducted using FEA based Ansys[®] software package to optimize the size, location, and the number of permanent magnets for poppet valve profile polishing. Three MRP fluids are prepared in an acid-based medium having carbonyl iron particles (CIPs) and SiC abrasives. Type-3 MRP media generates more oxide layer on poppet valve profiles, which improves its chemical inertness and corrosion resistance capability. After finishing the poppet valve, the achieved final surface roughness value is 20.1 nm from its initial value of 320 nm. Also, an ANOVA study is carried out to develop the statistical model. The quadratic regression equation predicts 93.25% improvement in Ra, at optimum process parameter conditions of 900 rpm rotational speed, 0.01 mm/min feed rate of poppet, 35% CIPs concentration, and 7% abrasives concentration. The predicted results are validated with experiments. A magnetostatic fluid-solid-interaction simulation of the R-MRFF process is conducted to study normal and shear stress distribution on poppet valve profiles during finishing. Surface roughness simulation and material removal modeling are also performed using finishing force analysis and FEA findings. The maximum percentage error of 12.87% and 11.5% between experimental and simulated MRR and surface roughness, respectively, was observed within a feasible limit for poppet valve profiles. The R-MRFF process will enhance the sealing effectiveness between super-finished poppet valve and its seat to reduce hydrocarbon emissions at elevated pressures and temperatures during its use.