

Nanofinishing of freeform/sculptured surfaces: state-of-the-art

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Abstract. Freeform surfaces are being used in a multiplicity of applications in different kinds of industries related to Bio-medical (Bio-implants), micro channels in micro fluidics, automotives, turbine blades, impellers of artificial heart pumps, automobiles etc. Different parts in these industries need nano-level surface finish as their functional inevitability. It is very difficult and challenging to achieve high level of surface finish, especially on the components having freeform (or sculptured) surfaces, complex shapes, and 3-D features. Surface finish is a significant factor, which affects life and functionality of a product. Many traditional and advanced finishing processes have been developed for finishing of freeform/sculptured surfaces but still it has not been possible to achieve uniform nano level surface finish specially in case of freeform surfaces. To overcome the limitations of the existing nanofinishing processes, researchers are developing new processes for uniform nanofinishing of freeform surfaces. In this article, an attempt has been made to review different nanofinishing processes employed for freeform surfaces useful in different types of applications. In addition, experimental work, theoretical analysis and existing challenges of the finishing processes have been identified to fill the research gap.

Keywords: nanofinishing / MR fluid / flexible tool / surface roughness / freeform surfaces

1 Introduction

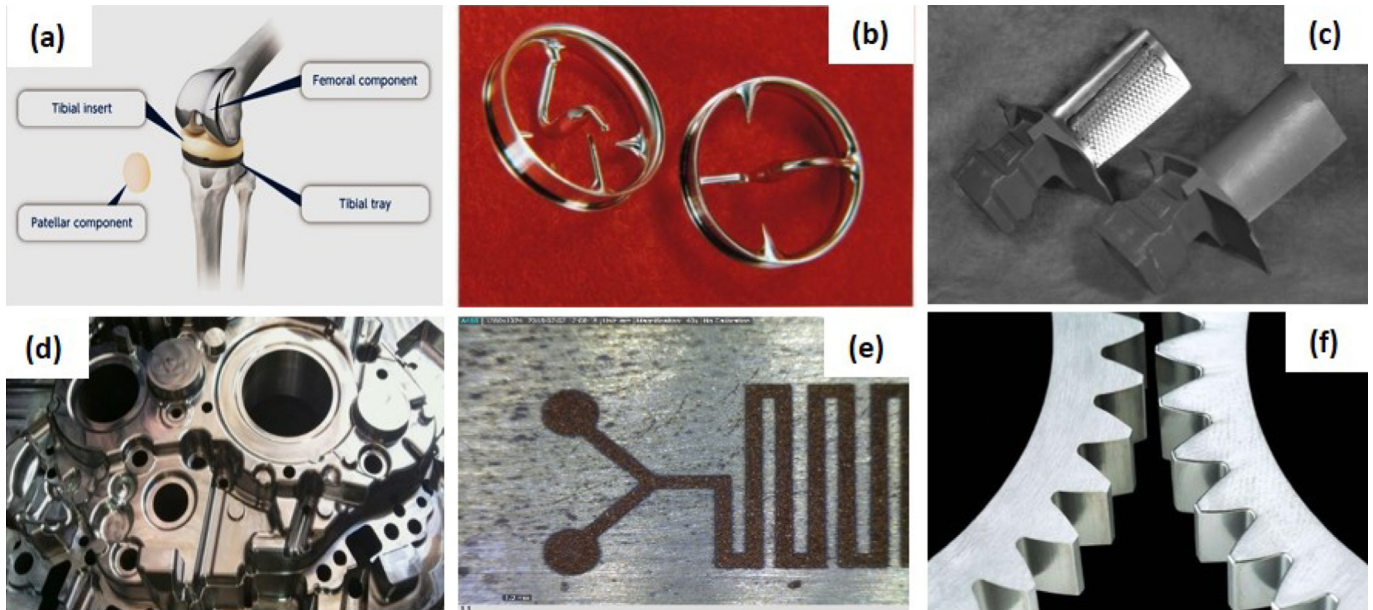
In manufacturing trades, the term nanofinishing relates to surface integrity which is one of the most vibrant and challenging task. Researchers are discovering innovative products and materials, and they need ultra-precision finish with appropriate functional requirements in different fields, for example, biomedical implants such as knee joint, hip joint, etc., these being considered as freeform surfaces. A surface which has no axis of rotation is called freeform/sculptured surface and cannot be expressed by a single mathematical equation [1,2]. These implants are the devices where nano level uniform surface finish in contact zone plays vital role in their functional performance. Nowadays, mould and die manufacturing industries are making complex and intricate surfaces, and final quality of their products depend upon surface quality. Hence, selection of appropriate manufacturing and finishing processes is important for any product.

To achieve nano level uniform surface finish on freeform surfaces is difficult due to non-rotational symmetry, and irregular and complex geometries. In addition, it also

depends on the selected finishing processes and workpiece material. Generation of tool path, tool orientation identification and tool geometry for freeform surface are equally important for achieving a nano level surface finish [3,4]. However, in case of freeform surfaces, it is not possible to achieve the desired level of uniform surface finish by the conventional finishing processes (Honing, grinding, and lapping) due to non-flexibility of the finishing tools to adapt to the continuously changing curvature of the workpiece surface. Various conventional and advanced finishing processes have been discussed in detail and recommended to achieve nano level surface finish on simple as well as freeform surfaces by Jain [5].

Nanofinishing is a process used to change the surface characteristics mainly undulations created by the preceding manufacturing process (e.g., machining, forming, casting, etc.). during creation of features or otherwise. Surface roughness is a kind of index used to express surface characteristics either in terms of CLA (Central line average) value (R_a), or root mean square (R_q) or peak to valley height (R_t), but all in one dimension (micrometer or nanometer). Area surface roughness considers area of the nanofinished surface rather than 1-D. Low surface roughness of a component is necessary to minimize friction forces, and to enhance wear resistance and mechanical

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Source: (a) Aesculap Implant Systems, LLC, www.soactivesofast.com); (b, c, f) Kennametal Extrude Hone, (www.extrudehone.com), (d) Google image, (e) Complex micro channel made by ECM.

Fig. 1. (a) Knee joint implant, (b) Heart valves, (c) Air foil, (d) Engine crank case die, (e) Complex microchannel, and (f) Automotive gear.

properties such as fatigue life and toughness. Optical properties and aesthetic appearance of a component improve by having nano-level surface finish. In case of a knee joint (bio-implant), wear by abrasion is one of the main causes for its failure due to continuous movement between the metal and plastic parts (Fig. 1a). This relative motion leads to the cracks and pits formation in polyethylene [6]. It may also cause microscopic particles to break off which in turn attack the body's immune system. Surface roughness of a knee joint implant has significant effect on the force acting at the interface, reaction of tissues in the joint area and behavior of germs in the bone tissue [7]. For better functioning and long service life of the bio-medical implant (e.g., knee joint) which belongs to the category of freeform surfaces requires less than 100 nm of surface roughness according to the ASTM requirement [8]. Surface conditions affect the fluid flow resistance, friction and optical losses, and fatigue strength of the component. Optics, micro-channels in micro fluidics, moving assembly such as piston-cylinder and bearing in automobile industries are some examples where surface finish plays a major role. Figure 1a–f show possible application areas of nanofinishing processes.

The objective of the present work is to review different branches of nano-finishing processes applicable for freeform/sculptured surfaces. In addition, the existing challenges and their possible solutions have been

identified to bridge the research gap in the field of nanofinishing.

2 Classification of finishing processes for freeform surfaces

As shown in Figure 2, finishing processes for freeform surfaces can be divided mainly into two classes based on the time of evolution of the processes: Traditional finishing processes (TFPs) and Advanced finishing processes (AFPs). These processes have been further divided in different sub-classes as discussed in the following sections.

2.1 Traditional finishing processes (TFPs) for freeform surfaces

Traditional finishing processes are also known as conventional finishing processes. In these finishing processes, pre-defined single point cutting tool or multi points cutting tools come in direct contact with the workpiece surface (grinding, honing, lapping etc.). Traditional finishing processes are further classified into three sub-sections – (i) Rigid tool based finishing, (ii) Robot based finishing, (iii) Computer numerical control (CNC) based finishing. All these sub-categories have been discussed in brief, in the following sub-sections.

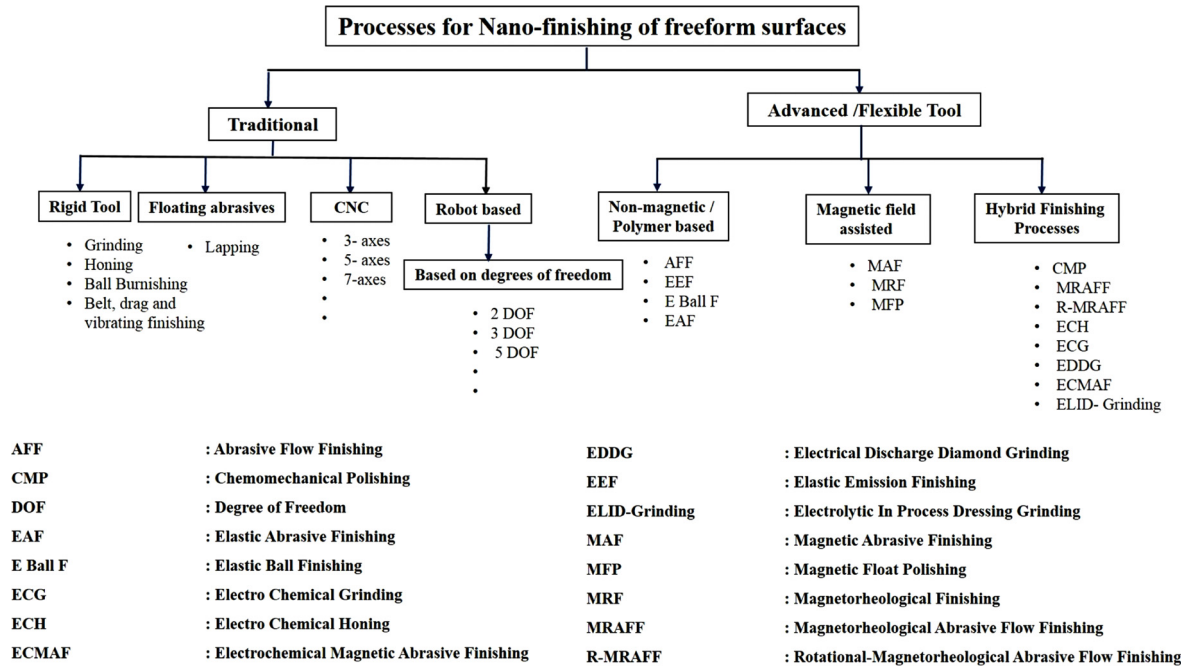


Fig. 2. Classification of finishing process for freeform surfaces.

2.1.1 Rigid tool based finishing processes

2.1.1.1 Grinding and turning

Grinding is a well-known and widely used conventional finishing process. Zhong and Nakagawa [9] discussed new methods of grinding toroid mirrors, elliptic and circular cylinders with a large curvature. Mirror surfaces with low roughness values can be obtained by means of direct grinding operations. Aspheric mirrors have been ground by using a micro displacement table with piezoelectric actuators. Zhao et al. [10] developed a new method of automatic finishing of curved aluminum alloy surfaces of the moulds. It is difficult to grind and polish the curvilinear surfaces of aluminum alloy. In this research work, polishing of curved aluminum alloy surface at constant pressure has been examined. A parameter *S* (comprehensive polishing parameter) is defined which expresses the factors (peripheral velocity of wheel, polishing time, feed rate, average constant pressure, etc.) influencing the automatic polishing and also give a relationship between factors affecting polishing quality. The wheel cannot work continuously due to blockage by the adhesion and attraction of molecules on the contact surface between the wheel and workpiece. Different preventive measures are taken such as using a wheel of low bond strength, using fluids which have good flow ability, decreasing the peripheral velocity of the wheel, or a combination of these measures. A limitation of this process is that uniform surface finish is not achieved because of variable pressure.

The Ultra precision diamond grinding (UPDG) of hard and brittle materials such as glass involves two important characteristics: very high value of effective negative rake angle and a high ratio of radial to tangential components of mean force [11]. UPDG is employed to hard and brittle materials and single point diamond turning is used for soft

and ductile materials. Here, the resultant chip is in the form of continuous ribbon with serrations on one side and a relatively smooth, highly deformed ribbon on the tool face side. In these processes, there is an exponential increase in specific energy with decrease in un-deformed chip thickness. The main limitation of this process is the appearance of subsurface defects usually in the form of micro cracks.

The hybrid system of FTS (Fast tool servo) and STS (Slow-tool servo) is used to maximize the tool path accuracy and precision during the machining of freeform surfaces in diamond turning as reported by Balasubramaniam et al. [12]. In this hybrid DTM system, STS is used to position the cutting tool at “macro” level and FTS is used to give motion to the cutting tool at “micro” level. Still there is need of development of complex programming so that this hybrid system can be used for more complex and 3D shaped components. After machining, feed marks on the machined surface can be seen to be a limitation of the process. These processes are highly expensive and time consuming, and hence, it led to the development of advanced finishing processes which can finish any kind of complex shaped components as well as 3D shaped components up to nano-level surface finish. The detailed state-of-the-art of material microstructures that affect the surface integrity after machining has been reviewed by Pan et al. [13].

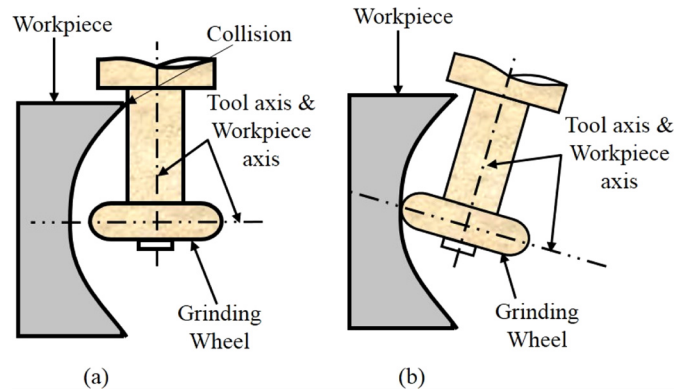
Hilerio et al. [14] reported manufacturing and finishing of a series of the femoral components. They made knee joints by investment casting and finished by different abrasive bands. During the last stage, tribo-finishing was performed and compared the results obtained with hand polishing of the knee joints. There was substantial difference between the surface roughness obtained by these processes. The process could be improved by a better control of input parameters. Different abrasive belts were used which affected the topography of the joint and hence

the final surface finish obtained was not uniform. Tam et al. [15] reported the work related to finishing of aspheric surfaces using fixed abrasive tool. This method is capable of computing the profile after each tool path, and it optimizes feed rate for different tool paths. Lazoglu et al. [16] developed a novel optimized process for tool path generation which finally reduces cutting force acting on the workpiece. Simulated results are verified by conducting experiments. Plichta and Baran [17] designed and fabricated multi tool polishing head with independent pneumatic drive system for effective machining of freeform surfaces. The multi tools grinding and polishing head is comprised of 6 tools group, in which abrasive discs designed for grinding and polishing are embedded. This multi tools polishing head can be effectively mounted on machining centers.

The conventional grinding process is capable to give precise surface finish but up to certain level. Requirement of high level (nano-level) of surface finish is still an issue, and challenge especially in case of freeform surfaces. Because the abrasive particles are fixed and rigid on the grinding wheel or belt (abrasive belt), and their interaction with the workpiece is very rigorous and unpredictable. As a result, at the finishing zone, high temperature and high pressure are generated which are prone to produce defects in the workpiece such as micro cracks, deep indentation, heat affected zone and residual stresses.

To overcome the weaknesses of a grinding process in general and non-flexibility in particular, researchers proposed different versions of grinding process by hybridizing it with other processes. Two of them are discussed here. Umehara and Komanduri [18] studied magnetic fluid grinding of hot iron pressed (HIP) silicon nitride rollers. The final surface roughness of nearly 5 nm was achieved. Different kinds and different sizes of abrasive particles were used as variable parameters to study their effects on the final outcome or responses. High material removal rate and high surface finish were achieved with B_4C and Cr_2O_3 abrasive particles, respectively. The benefit of this process is that both front and side faces achieve rounded edges. Volumetric material removal rate (MRR) increases almost linearly with polishing time up to 60 min. Surface roughness value decreases gradually with time till critical surface roughness value is achieved beyond which it starts increasing. MRR increases with the increase in hardness of the abrasive particles used ($Cr_2O_3 < SiC < B_4C$). With an increase in abrasive particle size, MRR increases but surface roughness deteriorates. Kuriyagawa et al. [19] developed a new system and named it as Arc envelope grinding method (AEGM). It is a new approach towards positioning and maneuverability of the earlier diamond based system. The AEGM based system (Fig. 3b) gave high performance even in case of aspheric ceramic mirrors including large aspheric objects. This system is applicable for manufacturing both large-scale optics for outer-space applications, as well as micro-size optics for micro devices. On-machine form-measuring instrument (resolution <10 nm) is helpful in achieving better form accuracy.

Brinksmeier et al. [20] have used a form grinding process where the shape of the grinding wheel is an inverse replica of the workpiece to be finished. In this process, pin



Source: Kuriyagawa et al. (1996)

Fig. 3. (a) Conventional grinding method, and (b) Arc Envelope Grinding method based system.

type and wheel type polishing tools were made of polyamide to improve surface finish of the structured molds. Abrasive polishing of V-grooves requires specially shaped polishing tools which do not get flexibility in terms of the shape of the component. In this process, a separate tooling is required for each workpiece.

2.1.1.2 Honing and ball burnishing

Nowicki et al. [21] reported non-traditional honing as a finishing process where profiling and finishing are done on the same machine tool. In this method, abrasive tool is plastically pressed against the workpiece surface which has 4 degrees of freedom (DOF). Many sculptured surfaces such as press forming dies, propellers, and screw propellers can be finished by this process. Large freeform surfaces of size greater than 1 square meter can also be finished by this method. Dynarowski and Nowicki [22] conducted experiments on concave and convex freeform surfaces. It was found that the finishing time reduced. In this process, the abrasive tool was elastically pressed against the surface. Robot with more degrees of freedom can be used as an aid for covering a larger area which will reduce the finishing time. Shiou et al. [23,24] developed a ball-burnishing surface finishing process on a machining center for freeform surfaces, say, plastic injection mold. The newly designed ball-burnishing tool can be used for both plane surface ball burnishing and freeform surface ball burnishing. By applying the optimal burnishing parameters, the surface roughness improvement of the injection mould part of plane surface was about 62.9% and that on freeform surface was about 77.8%. However, it may be difficult to make the tools necessary to work on certain other geometries. To improve these, a hybrid process combining multitasking and artificial intelligence can be developed so as to increase efficiency of the final operation even in case of complex geometries.

2.1.1.3 Belt finishing, drag finishing and vibratory finishing

Dedicated machines have been developed such as drag finishing, vibratory finishing, and belt finishing (OTEC and ROSLER) [25,26]. Drag finishing is specially used for

complex surfaces and it is a popular alternative for finishing of high value added delicate components that do not have scratches or blemishes on them. In drag finishing system, the parts are mounted on a carousel which in turn is equipped with multiple workstations. It may have 4–12 workstations “dragged” through a circular work bowl filled with grinding or polishing medium. In vibratory finishing, work bowl is filled with a mix of grinding or polishing medium and the parts that need to be finished. By way of vibration and/or centrifugal force, parts and the medium are kept in motion. The constant “rubbing” of the medium on the parts over a certain period of time (from a few minutes to several hours), produces the desired surface finish. This process is time consuming and unpredictable process. Many operations like burr removal, radiusing of sharp edges, degreasing and de-rusting/de-scaling of metal parts with high-gloss polishing of metal components can be done. But, uniform surface finish cannot be achieved because of the process limitations.

Song et al. [27] discussed mirror finishing of Co–Cr–Mo alloy using elliptical vibration cutting. The elliptical vibrations cutting claims to give superior performance. These alloys are used for artificial joint due to their excellent compatibility and fatigue strength. The head must be mirror finished so as to reduce abrasive resistance. Diamond cutting is not preferred as it is constrained by micro chipping of cutting tool. The tool edge is vibrated elliptically in a plane which is determined by the nominal cutting direction and the chip flow direction. Micro chipping, tool wear and chip flow are significantly reduced by this process. Jafer et al. [28] discussed the finishing of micro channels using low kinetic energy abrasives. The roughness of micro channels machined by AJM is generally greater than other methods; it is suggested to post blast the surface with abrasive particles possessing low kinetic energy. The effect of particle size, shape, velocity, dose, and angle of attack on the reduction of surface roughness of borosilicate glass was examined. It was found that roughness decreased up to 70% after post blasting. Hence, finishing with small particles until reaching the steady-state is not practical when a shallow channel is desirable.

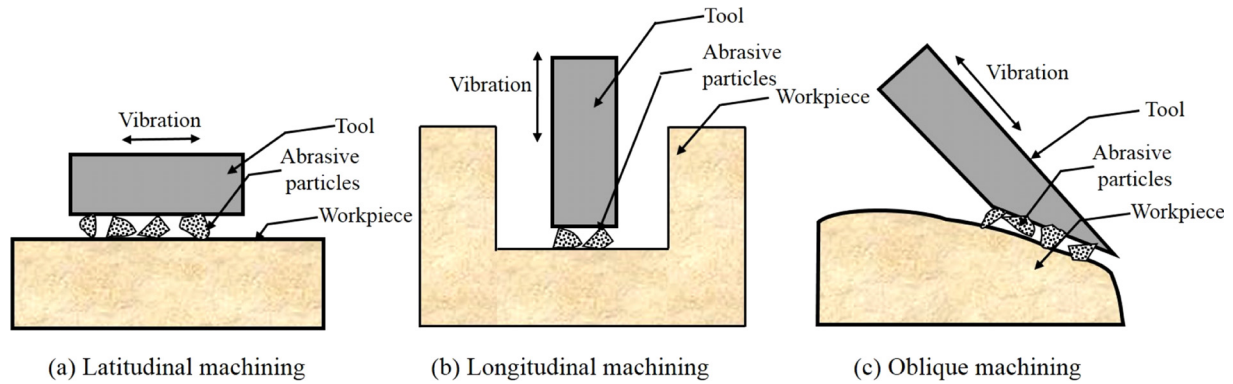
2.1.2 Robot based finishing of freeform surfaces

From the above discussion it is concluded that the manual grinding is inflexible, unclean, time consuming, un-healthy and noisy process. Hence, researchers coupled grinding with robotic arms to make it to follow the desired path. Based on the DOF of the robot, finishing area and finishing time are controlled. Hence, a robotic grinding system as compared to the normal grinding system is more efficient, no hazardous work environment and gives better finished surface quality. Also, it enhances productivity, reduces cost and improves the integrity of the finished surface. Huang et al. [29] used a robotic grinding and polishing system to automate the manual operation of turbine-vane overhaul. The robotic grinding and polishing system has enabled the overhauled vanes to meet stringent quality requirements such as profile smoothness, surface roughness and minimum wall thickness. The system hasn't yet been employed to obtain polishing of other engine components, such as

impeller blades. The extension of its applications is a notable area for future research work. Researchers [30,31] fixed a grinding wheel to a robotic arm with two DOF which resulted in a small contact area. Hence, this system could not cover the whole finishing area of the workspace and resulted in a more time consuming system.

Mizugaki et al. [32] concluded that the best performance by any robotic system is delivered when it is synchronized with a CAD/CAM system. A robot system with 6 DOF for polishing a metal mold was developed as a subsystem of a CAD/CAM system. An automated robot system was developed for performing finishing operations during manufacturing of various dies and molds [33]. A number of robotic systems are available for manufacturing of dies and molds, but such systems cannot perform a finishing operation, which is usually carried out manually, consuming 30–40% of the total manufacturing time. The main drawback of a finishing process is that irregular objects require highly precise inspection and finishing, and to go for an automated process for the same is difficult. The finishing of a freeform surface is always subjective, because surface roughness of a workpiece may differ from point to point. Hence, a highly advanced inspection system (consisting of limited artificial intelligence in order to modify the process during the midst of it) has to be developed. Consideration for the parameters such as robot performance, cutting performance, material hardness etc. can't be neglected. Most of these problems are overcome to a great extent in the proposed design of a robotic system containing 6 DOF for precise intermediate inspection and appropriate finishing. Optical inspection using laser scanners fitted strategically to the system is performed and the resultant surface profile is plotted. This way, the relevant elements from the uncertain or subjective elements are separated.

Richard et al. [34] reported the development of a novel industrial process, embodied in a new robotic polishing machine, for automatic grinding and polishing aspheric optics. The machine is targeted at meeting the growing demand of finishing inexpensive axially symmetric spherical lenses, mirrors, non-axisymmetric and conformal optics of many kinds, planarization of silicon wafers and associated devices, and controlling form and surface texture in other artifacts including prosthetic joints. Zhao et al. [35] developed a new precision ultrasonic polishing method for finishing of freeform surfaces at an oblique angle. In this process, computer assists to control the motion of the robot system which is made up of several joints. Based on the equations of the surface, a soft elastic polishing tool moved along the workpiece surface. Material is removed from the workpiece surface by mechanical action of the abrasive particles. Machining and shot blasting both take place simultaneously. During the finishing process large abrasive particles rotate or slide on the workpiece surface and crush the upper layer of the surface known as superficial layer of the surface by shear deformation. In the shot blasting process, very small abrasive particles move at a very high speed on the surface and crash onto the workpiece surface resulting in a finished surface of the workpiece. When the machining angle is $(\theta =) 0^\circ$, then the machining process is known as latitudinal



Source: Zhao et al. (2000)

Fig. 4. Ultrasonic abrasive finish machining methods.

machining, and when it is 90° then it is known as longitudinal machining processes (Fig. 4a, b). Figure 4c shows the oblique machining process. The main limitation of this process is that the robot system should have minimum of three DOF and continuous ultrasonic elastic contact during the process.

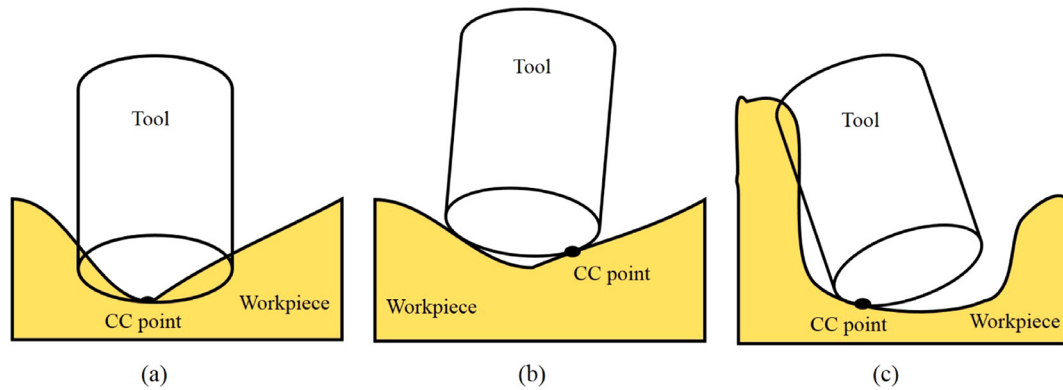
Brecher et al. [36] have developed a 6-axes DOF industrial robot with force controlled orbital head for finishing freeform surfaces where finishing is performed in different stages as follows: grinding, lapping with brass ring, polishing with a plastic ring, and at last polishing with felt pad. Parameters like multidirectional velocity profiles and consistent pressure conditions in the finishing spot are decisive for a reproducible polishing process. The complexity of the introduced polishing head points out that for a flexible and reliable surface finish a variety of kinematic DOF in a compact design envelope is necessary in order to fulfil all the process requirements. The preparation of different polishing tools in terms of dressing and shaping within the tool tray, automated cleaning between different process steps as well as automated referencing between mould and polishing head are the objectives of ongoing and future scientific work. The development of a force controlled orbital polishing head in combination with path planning strategies would enable a fully automated polishing system for mould and die making industries.

2.1.3 CNC based finishing of freeform surfaces

This section deals with two aspects: first one deals with the application of CNC machines in making of freeform surfaces of different components using the capabilities of CNC machines of moving the tool and workpiece simultaneously with many degrees of freedom. Second part deals with the use of rigid finishing tools discussed in the preceding sections (say, Sect. 2.1.1.1) and the features of CNC machines of simultaneously moving tool and workpiece in different degrees of freedom. Hence, some overlap in the different sections is unavoidable. CNC machines are widely used in manufacturing industries to make different types of complex parts. CNC machines are adequate to cut material at very fine depth of cut but due to the tool tip geometry, the flat end mill is not suitable to

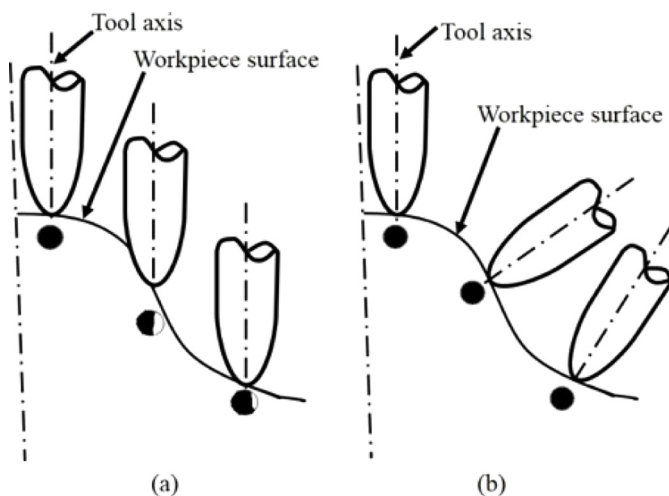
machine the sculptured and non-flat surfaces. Elber [37] developed an algorithm to machine a freeform surface using a combination of flat and ball end mill with very low scallop effect. For machining the non-flat and sculptured surfaces, Chen et al. [38] used a ball nose end mill with minimum acceptable roughness value. Lasemi et al. [3,4] discussed the state of the art on recent developments in CNC machining of freeform surfaces, including issues such as tool path generation, tool orientation identification, and tool geometry selection that affect the quality of freeform surface. Usually, 5 or 7 axes CNC milling machine is used to manufacture and create complex geometries from extremely wear resistant, corrosion resistant, bio compatible, hard alloys and ceramics. Surface finish of these components does not meet the required specifications related to a high surface finish because of gouging, Figure 5. Above stated problem can be solved by NURBS method. Brecher et al. [39] reported about the Non-uniform-rational-basis-spline (NURBS) method to finish freeform surfaces to the nano scale. NURBS is the realization of a closed data chain and an easy data exchange for finishing optical surfaces. Local tool path manipulations are allowed for the correction of local form deviations. Pre-processing time is reduced by trajectory calculation using online data processing. Estimation of the shape of the feature is done using optical methods which can be improved by using contact based shape estimation and then NURBS can be implemented.

Baptista and Simoes [40] observed that 5 or more axes machining operation gives better results because the tool is able to maintain a fixed angle between its axes and the work surface, leading to uniform surface finish (Fig. 6b) compared to the 3-axes CNC system (Fig. 6a). Ahn et al. [41,42] investigated an intelligent polishing system for the sculptured die surface using acoustic emission (AE) technique. For finishing sculptured die surface, 5 axes CNC polishing machine was employed having three rectilinear and two rotational motions. Walker et al. [43,44] used commercial product known as “Precessions” for fine finishing spherical and aspheric surfaces. In this technique, a semi – spherical tool with polishing slurry is used for finishing a workpiece. A semi spherical tool is coupled with 7-axes CNC polishing machine that has been custom designed. Blunt et al. [45] and Charlton and Blunt [46]



Source: Lasemi et al. (2012)

Fig. 5. Three types of gouging: (a) Local gouging, (b) Rear gouging, and (c) Global gouging.



Source: Baptista and Simoes (2000)

Fig. 6. (a) 3-Axes CNC milling, (b) 5-Axes CNC milling.

developed a new method to polish freeform surfaces of a knee joint using seven axes CNC Zeeko IPR 200 polishing machine to the required form and surface finish. The primary objective was to prolong the life of the replacement. The best surface finish of S_a (area roughness) = 28 nm was achieved on the knee surface. The main drawbacks of this technique are continuous monitoring and corrections required because of degradation of tool during finishing operation.

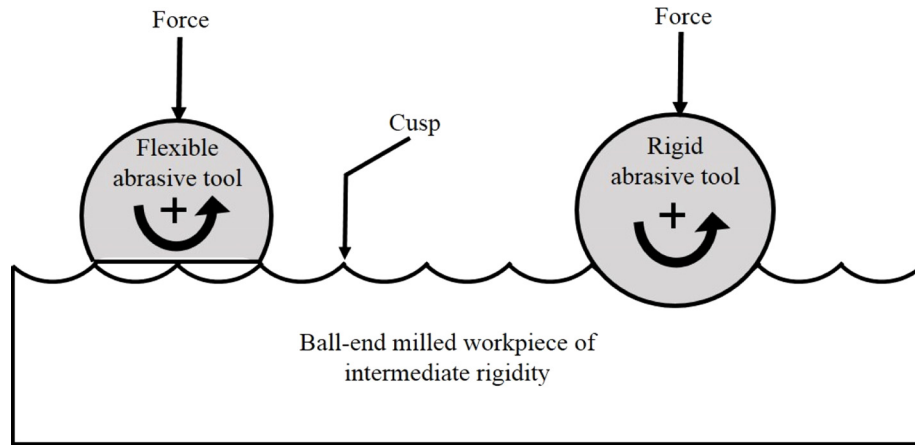
Cheung et al. [47] developed an ultra-precision freeform polishing technique and carried out finishing operation on the femoral component using 7-axes CNC system, providing different tool paths including raster, spiral and random. A flexible tool is developed consisting of membrane bonnet covering a polishing cloth. Using corrective polishing technique, surface roughness (R_a) varying from 145.5 nm to 9.5 nm was achieved. From the patient comfort and implant life point of view, surface roughness should be uniform throughout the femoral. Hence, modifications are needed in the existing process which should lead to the uniform surface on different faces of the implant.

Researchers [48,49] discussed about the manufacturing conditions and their effects on wear of ceramic knee prosthesis. Geometrical accuracy and shape of the implant contact geometry have a major influence on the wear behavior of the prosthesis. The main aim of this work was to develop an automated process chain for manufacturing knee joint made of ceramic. The geometry is such that a high load could be transmitted over a large surface and it could eliminate the cause of fracture. When the load was applied with the same force of 700 N, it was found that the point load had more wear than line loadings. The main limitation of this process is that the initial roughness of the sample was not taken into account. They used ceramic implants due to their biocompatibility and wear resistance. In this work, 5-axes CNC machining system is used and finishing operation is performed on the ceramic implant. First, they did grinding and then polishing operation. Wear behaviour has been investigated by the influence surface conformity under the simplified knee joint motion. Curodeau et al. [50] discussed about the cast orthopedic implants with freeform surface textures from a 3-D printed ceramic shell. Here, the base object is made by 5-axes CNC milling machine, or by forging, or by casting. Then this object is modified by layer by layer deposition. By this method, print feature of size as small as 350 μm in length, 200 μm in width and 175 μm in depth can be obtained. Koumoulos et al. [51] discussed various 3D parts and freeform surfaces fabricated by additive manufacturing process but it was still not possible to achieve nano level surface finish for these products, because of the process limitations.

CNC based finishing processes are used for finishing of freeform surfaces but still we are not able to achieve the precision finishing because of the process limitations in this case. Researchers are looking alternative finishing processes to relax the above mentioned limitations.

2.2 Advanced finishing processes (AFPs) for freeform surfaces

In advanced finishing processes (AFPs), there is no direct contact between cutting tools and workpiece surface as in conventional finishing processes. During



Source: Cho et al. (2002)

Fig. 7. Schematic diagrams of flexible and rigid abrasive tools for finishing.

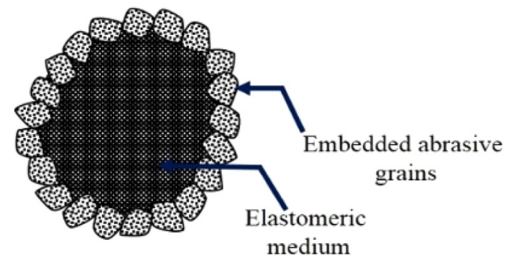
finishing operation, geometry of loose or bonded abrasive particles varies continuously in an unpredictable manner. AFPs are getting wide acceptance in different types of industries due to their inherent capabilities of flexibilities, self-deformability, control of the forces, and versatility. This section has been divided into three different groups depending on the nature of the processes; (i) Non-magnetic/Polymer based finishing processes, (ii) Magnetic field assisted finishing processes, (iii) Hybrid finishing processes. These processes are discussed under different headings as follows.

2.2.1 Non-magnetic/Polymer based finishing

First part of this sub-section deals with the elastic polymer based medium finishing processes while the second part deals with viscous fluid medium finishing processes as follows.

Nelson et al. [52] discussed about the non-axisymmetric stressed mirror polishing. Here, two times polishing is done. After the first polish, the sphere is null tested with forces applied and off-axis parabolic with no forces acting. The application of forces and couples on the edge of mirrors can produce a very wide class of non-axisymmetric mirrors. The main limitation of this process is that this process can be applied only to circular plates of constant thickness. Cho et al. [53] used a flexible abrasive tool (Fig. 7) that was made of thermosetting polyurethane elastomer with a coating of aluminum oxide abrasives for automatic finishing of curved surfaces on a CNC machine. The ball end type flexible abrasive tool has the ability of performing finishing operation and deforming itself according to the shape of the surface to be finished.

Huissoon et al. [54] developed a flexible abrasive disk type tool attached to a CNC machining centre. Effects of controllable parameters on the final finished surface have been studied. It has been seen that the tool has significant changes in abrasive sharpness after every 11 passes each of 200 mm length. The final surface finish of $3.05 \mu\text{m}$ was achieved, which shows that the existing process cannot be considered as a fine finishing process. Choi et al. [55]



Source: Sooraj and Radhakrishanan (2014)

Fig. 8. Schematic of elastic abrasive.

described the development of a hydrophilic fixed abrasive pad (FAP) and self-conditioning mechanism by water swelling of the polymer, and employed it for polishing die steel using 5-axes CNC machine. Wu et al. [56] developed a grinding center (GC) tool with an elastic ball type wheel. In this process, only cusp height produced during cutting process is removed. Therefore, it was possible to conduct polishing without changing form accuracy generated in the preceding operation. This polishing technique is helpful in polishing of freeform surface, say in a die and mold. Kar et al. [57] developed Butyl based rubber medium for nanofinishing purposes which was characterized using rheological properties and it was used for abrasive flow finishing (AFF) processes. It has been found that rheological properties depend on the temperature, shear rate, creeping time, and frequency which play major role in finishing operations. Sooraj and Radhakrishanan [58] developed elastic abrasive (Fig. 8) tool and used for nano finishing of hard workpieces. Using the elastic abrasives, impact erosion was minimized and flow of the fluid was also reduced. Final surface roughness achieved was 26.7 nm from an initial surface roughness value of 182 nm .

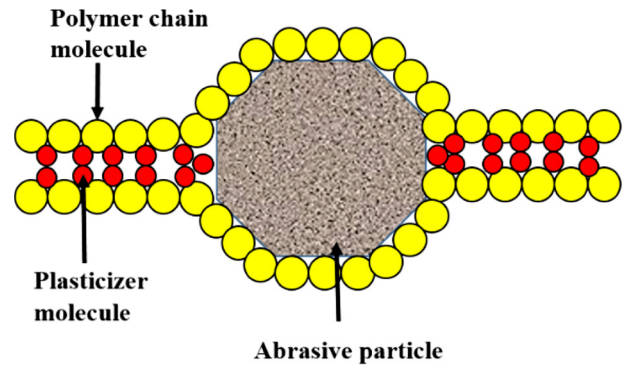
In the field of defense, aerospace, automobile, mold and die making, medical and other related industries, abrasive flow finishing is becoming a better option for finishing of simple and complex geometries [59–62]. AFF process uses viscous fluid medium for nano-finishing purposes. This

process also has been used for deburring, sharp edge rounding, removing recast layer and creating compressive residual stresses [63]. Tzeng et al. [64] discussed self-modulating abrasive medium and its applications in abrasive flow machining (AFM) process. Medium with coarse abrasive particles and higher abrasive concentration yields higher viscosity and improves surface finish. As finishing period increases, viscosity of the medium changes. It also revealed that the fluidity and stickiness nature of the self-modulating abrasive medium could be automatically adjusted, and used to finish tiny micro channels. Wang et al. [65] carried out experiments and removed recast layer of a complex hole by AFM process. Jain et al. [66] applied Finite Element Method (FEM) to study AFF of complex geometry. Theoretical models were developed for material removal and surface finish, and the theoretical results were compared with the experimental results. It was concluded that material removal is significantly affected by the extrusion pressure. It was also concluded that change in Ra value of conical surface was less as compared to a cylindrical surface while keeping the same extrusion pressure and no. of finishing cycles. Shankar et al. [67] developed different types of medium by homogeneously mixing soft styrene butadiene based polymer, plasticizer and abrasive particles for finishing complex shaped components (Fig. 9). The developed medium had the ability of better flow ability, self-deformability, and abrading ability. Rheological properties of the AFF medium are studied for evaluating finishing forces in this research work [68,69]. Theoretical model was developed whose results were in good agreement with the experimental results. Cheema et al. [70] presented the state of the art of the experimental investigations on simple and complicated geometries using AFF process. It has been concluded that the process is capable to produce nanometer level surface finish on intricate profiles including both internal and external surfaces. It has also been reported that the development of an appropriate medium for the given application is the key parameter in the success of the AFF process. Sarkar and Jain [71] developed a flexible tool which was analogous to the ball end mill by curing polydimethylsiloxane (PDMS). Flexible tool follows the path on the curved surface. A bowl shaped copper workpiece was finished. Final surface finish obtained was 53 nm from the initial roughness of 241 nm. Different sizes of abrasive particles were used to improve surface roughness value of the workpiece. Sarkar and Jain [72] also applied AFF process for finishing of femoral component which had complex geometry using AFF set up. Surface roughness achieved varied from 42.9 nm to 62.5 nm in various areas on the surface of the femoral component. Medium properties change with time during finishing process which is the main limitation of the process.

2.2.2 Magnetic field assisted finishing

2.2.2.1 Magnetorheological finishing (MRF)

In these finishing processes, magnetic field is used to externally control the forces acting on the workpiece through the abrasive particles. Magnetic field assisted finishing processes have been established for a wide variety

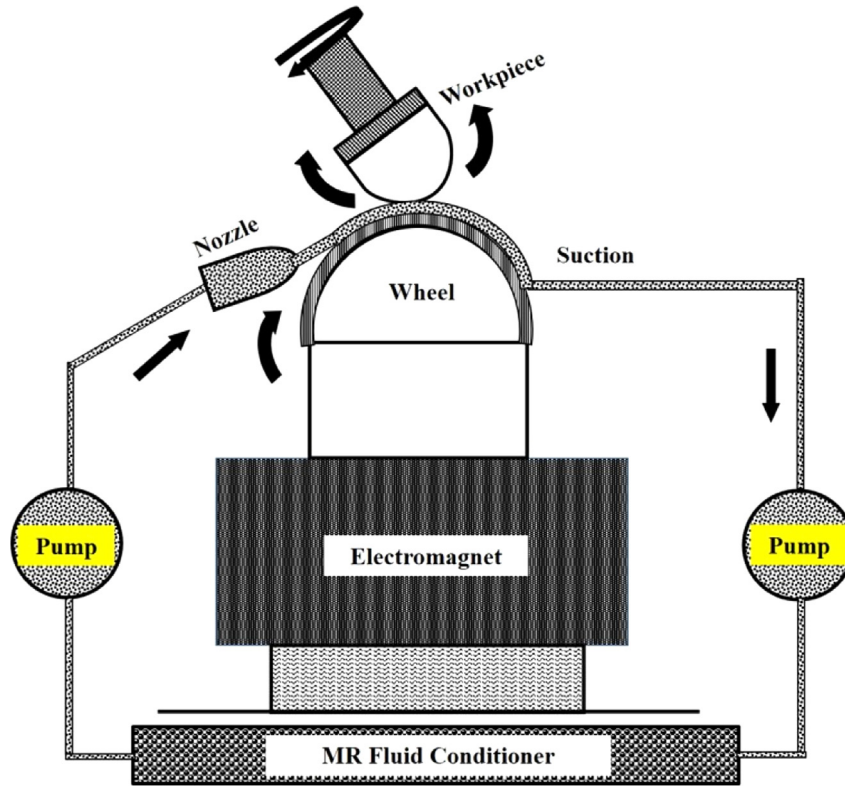


Source: Shankar et al. (2011)

Fig. 9. Schematic of abrasive particle held by polymer chains and plasticizer.

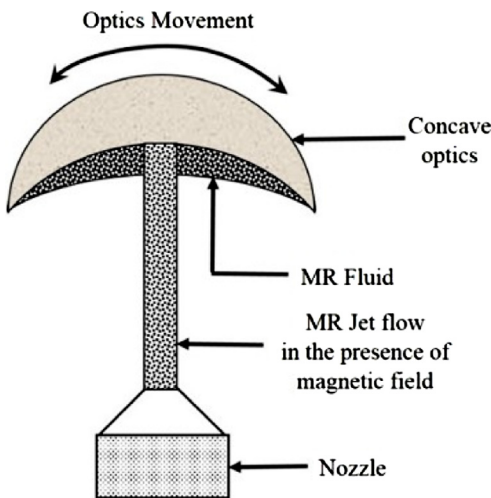
of applications including dies and molds, medical components, fluid systems, optics, electronic components, micro electromechanical systems (MEMS), etc. In these finishing processes, magnetorheological (MR) polishing fluid is used which changes its properties under the influence of magnetic field. The MR polishing fluid consists of ferromagnetic particles, non-magnetic abrasive particles, carrier medium, and some additives. When this fluid comes in the magnetic field zone, multiple flexible brushes (self adaptable/deforming brushes) are formed. These brushes are used for finishing freeform surfaces. Jacobs et al. [73,74] developed a magnetic field assisted method for producing complex optics with figure accuracy less than 50 nm and surface roughness less than 1 nm. On the setup designed and fabricated (Fig. 10), the experiments were conducted using different MR fluids and different materials. Kordon-ski et al. [75] developed the first versatile vertical wheel MRF prototype machine. They were successful in conducting the experiments on flat, concave and convex parts up to 100 mm in diameter.

Cheng et al. [76] conducted experiments on reaction bonded silicon carbide (RB-SiC) using MRF, and good surface finish and figure accuracy were obtained. Two different non-magnetic abrasive particles used were Al_2O_3 and diamond with MR fluid. Diamond powder gave better results but it was more expensive. Cheng et al. [77] proposed MR fluid based finishing process using 2-axis wheel shaped polishing tool for aspheric parts. Two ring magnets of high strength are kept on both side ends of wheel tool and another two rectangular bar magnets are located near to the tool cover. Localized magnetic field of high intensity is generated by this arrangement. It has been found that surface roughness of 1.2 nm is obtained from the initial surface roughness of 3.8 nm, after 10 min. But, this process is more time consuming for complex surfaces because of only two axes rotation of tool. Seok et al. [78] used MRF process for generating curved surface on silicon based microstructure. The profile of the finished surface is simulated by the FEM where the profile is generated by using a concave tool holder in which MR fluid makes multiple flexible brushes. Here, “edge effect” is obtained because of very high magnetic field intensity at the edges. The results could have been better if non-magnetic



Source: Kordonski et al. (1996)

Fig. 10. Schematic diagram of MRF Process.



Source: Tricard et al. (2003)

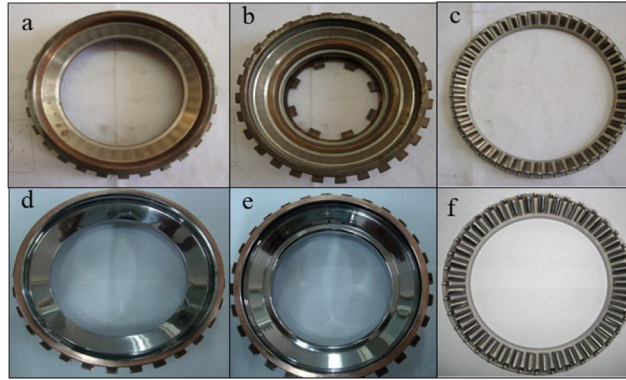
Fig. 11. Schematic diagram of the MR jet finishing process.

abrasive particles had been used in the MR fluid. Tricard et al. [79,80] developed a new technique for finishing concave and freeform surfaces using a round MR fluid jet. MR fluid jet becomes highly collimated, coherent and long stable in the presence of magnetic field (Fig. 11). This type of arrangement is required for steep concave workpiece. The workpiece is kept at the top of the jet and it is

continuously rotated. This technique can be used to finish concave surface of glass, single crystal silicon wafer and other complicated profiles, including the inaccessible areas. But, the main drawback of this technique is that the initial surface roughness should be 300 nm or more and the workpiece should be hard.

MRF was developed and commercialized by QED center for optics manufacturing in Rochester, USA [81]. MRF process uses magneto rheological fluid as a polishing tool to perform polishing operation with sub-nanometer surface roughness value. MRP fluid forms a flexible polishing tool which can polish different kinds of shapes with an appropriate combination of MRP fluid and finishing parameters. It is a deterministic process that has the ability to finish spherical and plane surface with an optimum value of accuracy of 30 nm peak to valley and surface roughness of less than 1 nm for optical glasses, single crystals and glass ceramic.

Sidpara and Jain [82] developed a magneto-rheological fluid based nano finishing tool for femoral (Knee joints), which has a complex profile. Permanent magnet of high strength was used to produce strong magnetic field in the finishing zone. The finishing tool was held in the tool head of 3-axes CNC milling machine. In the presence of magnetic field, MR fluid gets stiffened and forms a hemispherical shaped flexible brush. Different types of MR fluids (i.e. oil, water or chemical based) were prepared as a medium to finish Titanium alloy knee joint implant. It was concluded that water based MR fluid is more effective for finishing



Source: Pawan Kumar Basera, M.Tech. thesis, IIT Kanpur (2012)

Fig. 12. (a) Schematic diagram of MRF set-up for teeth finishing, (b) Photographic view of MRF set-up and (c) Photograph of partially finished tooth.

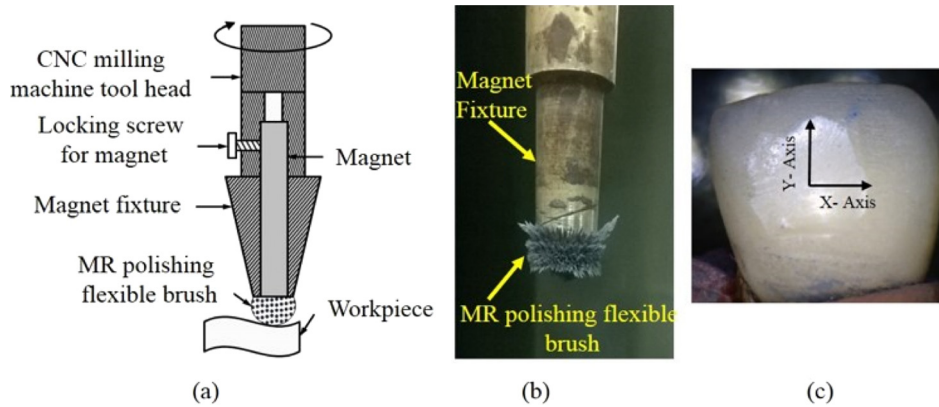
hard materials. Final Ra value of 28 nm was achieved from the initial Ra value of 268 nm in 16.4 h of finishing of one face of the knee implant. But, this process is more time consuming and produces non-uniform surface finish on four different faces of the femoral. In the same way, Baghel et al. [83] polished the artificial crown for a tooth, which is one of the examples of freeform surfaces using magnetorheological fluid based finishing process. They used 3-axes CNC milling machine for this purpose. Final surface roughness Ra value achieved was 30 nm and 57 nm from the initial surface roughness 2790 nm in X direction and 3180 nm in the Y direction, respectively (Fig. 12). It was found that area roughness value was $1.43 \mu\text{m}$ which got reduced to final surface roughness value of approximately $0.008 \mu\text{m}$. The profile of the crown was convex and the brush was not able to reach uniformly on the whole surface of the crown. Further, the distance between the brush and upper surface of the crown was not constant (that is machining gap) and hence, the surface was not uniformly finished. In Figure 12c, the polished area can be clearly seen.

Jang et al. [84] developed a new kind of deburring process using MR fluid. They deburred the micro molds and other micro features of complex shape of micro parts. The process was able to remove burrs having height of $200 \mu\text{m}$ and thickness of $1 \mu\text{m}$. Singh et al. [85,86] developed a setup for nanofinishing of 3-D surface using the ball end MR finishing tool. A ball end shape of MR polishing fluid was produced at the top surface of the rotating tool. In this setup, magnetic field is created by electromagnets and MR fluid is supplied through the central rotating core. It is observed that in case of non-magnetic materials, the magnetic lines of force do not pass through the workpiece and majority of the magnetic lines of force are diverted from inner core to outer core at the tip of the tool, and MR fluid becomes stiffened along these magnetic lines of force. It is concluded that the present process is more suitable to finish non-magnetic materials. Ball end magnetorheological finishing (BEMRF) tool has been also developed to finish mild steel work-piece surface by using both synthesized and unbounded magnetic abrasive based polishing MR fluid [87]. The percentage

change in surface roughness ($\% \Delta \text{Ra}$) was calculated in both the cases. It was found that $\% \Delta \text{Ra}$ with bonded magnetic abrasive particles was higher than unbounded magnetic abrasive based MR fluid. The performance of the ball end MR finishing process was satisfactorily demonstrated on the typical 3D ferromagnetic milled workpiece [88]. The surface roughness produced was as low as 16.6 nm, 30.4 nm, 71 nm and 123.7 nm on flat, 30° , 45° and curved surfaces of the 3-D workpiece, respectively. The variation in the magnetic normal force can be minimized by providing a tilting motion to the MR finishing tool so that a normal to the tool tip surface can always be made perpendicular to the 3-D workpiece surface being finished during finishing operation. This will produce uniform magnetic normal force and flux density zone irrespective of 3-D workpiece surface. This would lead to a better surface finish even in case of curved surfaces. Suzuki et al. [89] developed a method for curved shape workpiece (single-crystal LiNbL3) using magnetic field assisted finishing method. It is reported that when colloidal silica is used as non-magnetic abrasive particles, surface roughness of less than $10 \text{ nm } R_{\text{max}}$ can be achieved.

Bedi and Singh [90] reported the state-of-the-art on magnetorheological methods for nanofinishing. In this articles various MR fluid based finishing processes have been reported which full fill the demand of ultrafine surfaces. It has also been suggested that use of computer controlled nanofinishing method could be a better option for controlled magnetic field finishing for new engineering materials including different sizes and shapes. Selection of different abrasive particles, particles sizes and particles shapes can be more notable research area which would influence the finishing of new engineering materials.

Kim et al. [91,92] developed a new kind of deburring process using MR fluid for micro features of complex shape of micro parts in general and for micro moulds in particular. The process was able to shear off the burrs of height up to $200 \mu\text{m}$ and thickness of $1 \mu\text{m}$ in two stages. First, the abrasive tool was used and then flexible magnetic abrasive brush (FMAB) was used for deburring and polishing of freeform surfaces, and three dimensional dies and moulds.



Source: Baghel et. al (2015)

Fig. 13. Surface finish of top cone: (a) before finishing and (d) after finishing, Surface finish of bottom cone: (b) before finishing and (e) after finishing, Surface finish of top rollers: (c) before finishing and (f) after finishing.

The final surface roughness achieved was 90 nm. Pa [93–95] investigated a super finishing module for freeform machining using magnetic assistance to help discharge the dregs from the gap between the electrodes and the workpiece during electrochemical finishing and burnishing. The super finishing module incorporating magnetic field assistance in electrochemical finishing and burnishing requires only a short time to make a freeform surface smooth and bright, and to eliminate the need for precise traditional polishing. A couple of limitations of this process, however, are as follows: It is difficult to scale up to mass production and, in some cases, it is not as easy as conventional finishing techniques.

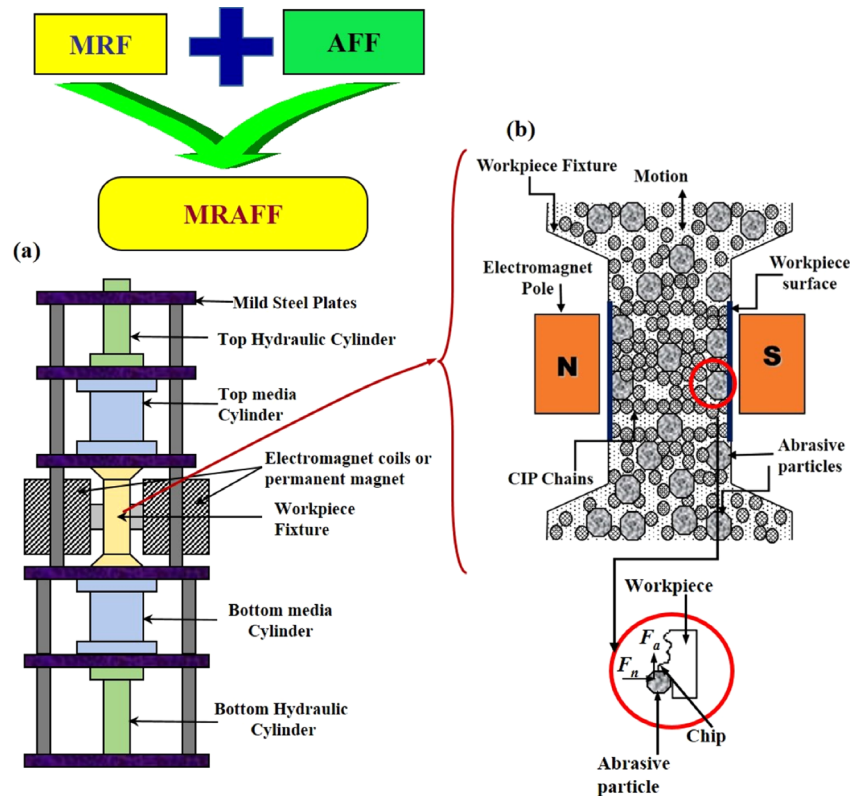
2.2.2.2 Magnetic abrasive finishing (MAF)

Fox et al. [96] discussed about the MAF of rollers. MAF is capable of producing highly finished surfaces with high accuracy and negligible surface damage. Surface finish up to 10 nm has been achieved by this process. Un-bonded magnetic abrasives particles give higher MRR and bonded magnetic abrasive particles give better surface finish. In this process, as the magnetic flux density increases the finishing rate increases up to a certain limit. Yamaguchi et al. [97] discussed the development of internal magnetic abrasive finishing process for non-ferromagnetic complex shaped tubes consisting of bent and straight sections. The setup consists of permanent magnetic poles rotation system. Magnetic field is produced for attracting magnetic abrasive particles to the finishing area and to apply magnetic force. The applied magnetic force is a function of the magnetic field intensity. When poles rotate around the workpiece, material is removed from the surface as a result of magnetic normal force and centrifugal force applied by the rotating ferro-magnetic abrasive particles. By manipulating the rotating pole, entire inner surface can be finished. The finishing experiments showed a nearly uniform internal finish of bent tubes by a single step. This process also shows the feasibility of applying flexible internal finishing process to an automated system. Yamaguchi and Graziano [98] reported nanofinishing of knee prosthesis

made of Cobalt-chromium molybdenum (Co–Cr–Mo alloy) using MAF process. They designed and fabricated knee holder and used 6-axes robot arm where they placed the knee implant. A conical pole tip was attached to an electromagnetic coil and kept it in front of the knee joint and maintained the clearance of 1 mm. Iron particles and diamond particles were used as a polishing tool. They also applied finite element method for magnetic field analysis. Houshi [99] reviewed the state-of-the-art of MAF process taking into consideration about the recent research and challenges in the relevant finishing processes. It has been reported that there is no mathematical model available which could show the influence of all the finishing parameters on MRR and SR. It has also been reported that there is no model available which could describe the mechanism of material removal from the freeform surfaces in the existing process which are the notable area to fill the gap. Basera and Jain [100,101] used MAF process to finish the curved surfaces of the helicopter bearings, Figure 13. The experimental work was also focused on reducing cycle time of finishing of taper roller bearing. Earlier the finishing time was observed as 6–20 h depending on the level of damage of the bearing surface. By implementing the method and process described in this paper, the authors were able to achieve surface finish as low as $R_a = 36.5$ nm from the initial $R_a = 271.5$ nm without any surface damage. Jain et al. [102–105] revived various nanofinishing techniques for complex geometries including AFM, MRF, MRAFF, MAF and other processes for nano finishing. Magnetic abrasive finishing was used to finish flat surface, internal and external surfaces of tubes and some of freeform surfaces. Analytical model is developed Shanbhag et al. [106] and the responses were found in good agreement with the experimental results.

2.2.3 Hybrid finishing processes

Hybrid finishing process is a combination of more than one finishing process to take advantage of the constituent finishing processes involved. Jha and Jain [107] developed the magnetorheological abrasive flow finishing (MRAFF)



Source: Jha and Jain (2004)

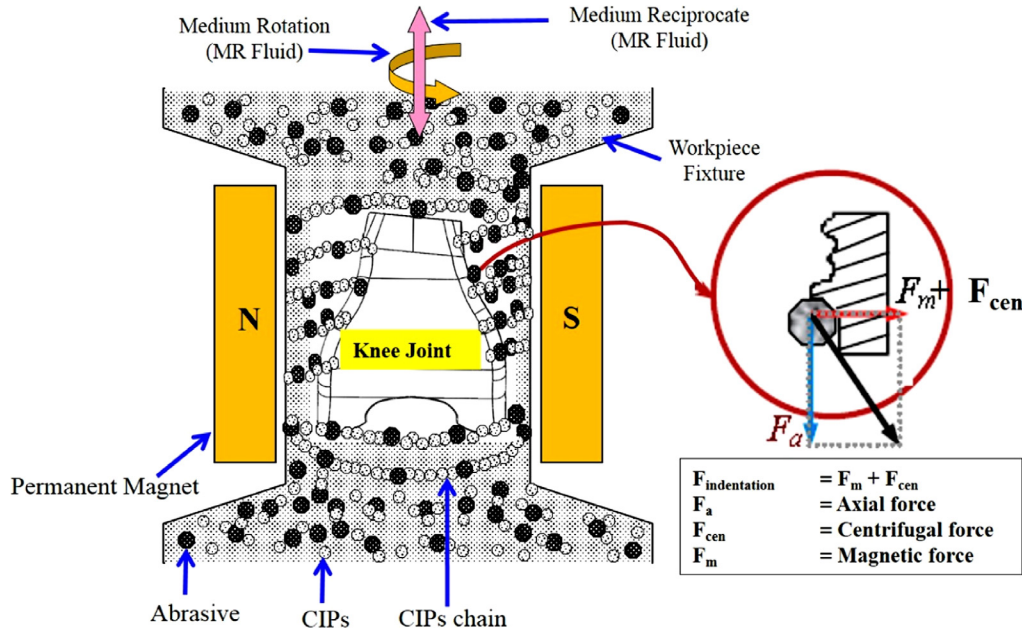
Fig. 14. (a) Schematic diagram of MRAFF process, and (b) Mechanism of material removal in MRAFF process.

process by combining AFF and MRF processes. The MRAFF setup is shown in Figure 14a and the mechanism of material removal in MRAFF process is shown in Figure 14b. AFF is not a deterministic process but MRF is a deterministic process where some of the process parameters can be externally changed, say, by changing the current to the electromagnet, the magnetic field can be changed during the process.

Das et al. [108,109] designed and developed the R-MRAFF setup and carried out experiments on the stainless steel tubes and flat surfaces. The medium has been rotated by rotating the magnetic fixture in the existing MRAFF setup. Therefore, rotation of the medium is attained in the existing setup by rotation of the magnetic field, and hence, the process is known as rotating MRAFF (R-MRAFF) process. Kumar et al. [110] developed a fixture for femoral component (Fig. 15) which is one of the examples of freeform surfaces and carried out the experiments on it. Magnetic fixture having 8 magnets was used in the setup. Mesh size and extrusion pressure were selected as variable parameters to study their effects on the final outcome. It has been observed that the process was useful for any complicated profile, but separate tooling is needed for each workpiece. It has also been noted that surface roughness was not uniform. They concluded that there is a need of augmentation in the workpiece fixture for getting uniform surface finish by the existing set-up.

Hybrid finishing process is developed by combining elastic emission machining (EEM) and MRF process to achieve atomic level of surface finish. In this finishing process, high MMR is achieved. In this hybrid process, time and errors (placement, alignment, handling, etc.) can be minimized up to a great extent. Sidpara et al. [111] studied the fabrication and finishing processes (MRF and EMM) of mirrors such as flat, cylindrical, elliptical and toroidal followed by various steps as grinding, etching, lapping, and polishing. These processes are able to achieve surface roughness of a few Angstrom (below 1 nm) which is required in Synchrotron beam line for good focusing properties and good reflectivity of X-rays. However, there are few challenging issues related to the metrology because the measurement of surface roughness and slope errors require specialized instruments on the specified level of measurement.

Electrochemical honing is a hybrid super finishing process that associates advantages of both the processes that is electrochemical machining and mechanical honing. Jain et al. [112] reported the state-of-the-art of ECH in which more than 90% of material is removed by electrolytic action and remaining 10% is removed by abrasive honing action. Pathak et al. [113] reported the mechanism of gear finishing by pulse electrochemical honing (PECH). More research areas can be found to finish and explore the ECH process in herringbone, hypoid, worm and worm gear.



Source: Satish et al. (2015)

Fig. 15. Schematic of R-MRAFF process.

Table 1. Comparisons of abrasive-based finishing processes, Jain and Jain [110].

S. No	Finishing process	Work-piece	Ra (nm)
1	Grinding	–	25–6250
2	Honing	–	25–1500
3	Lapping	–	13–750
4	Abrasive flow machining (AFM) with SiC abrasives	Hardened steel	50
5	Magnetic abrasive finishing (MAF) with diamond abrasives	Stainless steel rods	7.6
6	Magnetic float polishing (MFP) with CeO ₂ abrasives	Si ₃ N ₄	4.0
7	Magnetorheological finishing (MRF) with CeO ₂	Flat BK7 glass	0.8
8	Elastic emission machining (EEM) with ZrO ₂ abrasives	Silicon	<0.5
9	Ion beam machining (IBM)	Cemented carbide	0.1

Efforts are being made to develop new finishing processes in order to incorporate the merits of the individual processes into the new processes. In this way, Jain et al. [114] developed the chemo-mechanical magnetorheological finishing (CMMRAFF) process as a super finishing process by combining three different finishing processes namely, chemo mechanical polishing, MRF and abrasive flow finishing processes. Minimum surface roughness of 0.486 nm was achieved on a single crystal silicon wafer surface. The main characteristic of CMMRAFF process is that this process can be employed for all engineering material by optimizing chemical composition of MRP fluid. Table 1 and Table 2 shows the overall comparison of all the traditional and advanced finishing processes with different characteristics employed for finishing of freeform surfaces.

3 Issues to be addressed in nano-finishing of freeform surfaces

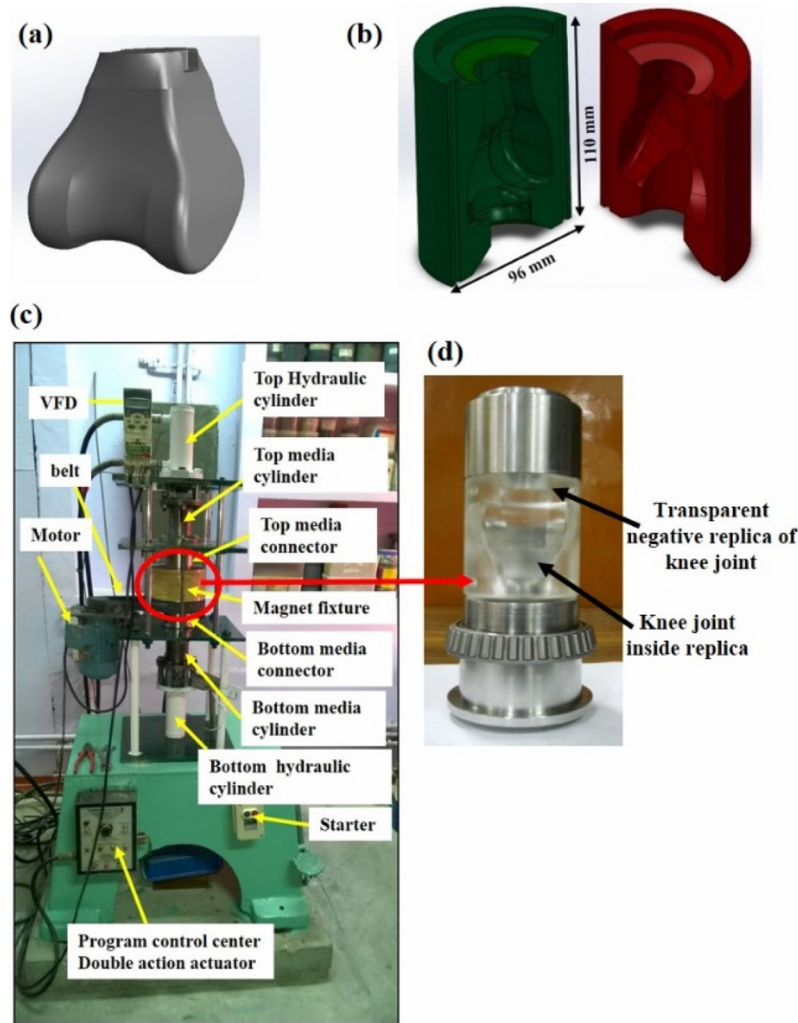
3.1 Existing challenges

The following areas are identified to be ones that would need attention for further research:

- design and development of a fixture as the extended replica of the component with freeform surface and online monitoring of input process parameters, namely, magnetic field, medium flow velocity or medium pressure, etc;
- 3-D CFD simulation of MR polishing fluid, comprehensive modeling by coupling different physical phenomena to estimate velocities and forces in the fluid flow channel;

Table 2. Comparison of different advanced nano-finishing techniques used for freeform surfaces.

Characteristics	AFM	MAF	MRFF	MRAFF	R-MRAFF	Advanced R-MRAFF
Base medium and abrasive	Polymer as a viscoelastic base medium mixed with fine abrasives	non-magnetic abrasive particles and ferromagnetic particles and additives	Water based or Oil based medium mixed with cerium oxide abrasives	Mineral oil and grease as viscoplastic medium with CIPs and different types of abrasives depending upon requirement	Same as in MRAFF	Same as in MRAFF
Workpiece fixture	Cylindrical	Flat, holding devices depending on workpiece	Workpiece is fixed by an device and pendulum motion is given to workpiece	Cylindrical	Cylindrical	Negative replica of workpiece
Working principle	To and fro flow of abrasive laden viscoelastic medium through the restricted passage	Relative motion of medium (FMAB) with workpiece	To and fro magnetically stiffened MR polishing fluid in the vicinity of workpiece surface	To and fro extrusion of magnetically stiffened MR polishing fluid over workpiece surface	Rotation as well as to and fro extrusion of magnetically stiffened MR polishing fluid over workpiece surface through uniform channel	Rotation as well as to and fro extrusion of magnetically stiffened MR polishing fluid over workpiece surface through uniform channel
Mechanism of material removal	Indentation & shearing of material in the form of microchips	Indentation and removal of material due to rotation of brush	Shearing and material removal in the form of microchips	Shearing and material removal in the form of microchips	Shearing and material removal in the form of microchips	Shearing and material removal in the form of microchips
Minimum surface roughness	46.6 nm Sarakar and Jain [Sarakar and Jain]	36.5 nm [Basera and Jain]	28 nm [Sidpara and Jain]	36 nm [Kumar and Jain]	36 nm [Kumar and Jain]	26 nm [Nagdeve et al.]
Applications	Small holes in micro-range, internal, and external 3D complex shaped surfaces	Flat, cylindrical, helical geometry, internal and external surfaces of cylindrical geometry	Flat, spherical, concave, convex and aspherical external surfaces. Brittle component etc.	Non-magnetic internal closed surfaces and external surfaces irrespective of material type	Internal and external surface of any complex geometrical shapes of non-magnetic material irrespective of hardness	Internal and external surface of any complex geometrical shapes of non-magnetic material irrespective of hardness
Limitations	Not deterministic	Deterministic	Deterministic	Deterministic	Deterministic	Deterministic
Challenges	To control the medium properties during experiments	Finishing of complex features in minimum time	Reducing finishing time	3-D CFD simulation of MR polishing fluid	Use of Magnetic replica of freeform surface to generate the uniform magnetic fixture	Use of Magnetic replica of freeform surface to generate the uniform magnetic fixture
			Finishing of complex features	Reducing finishing time	3-D CFD simulation of MR polishing fluid	3-D CFD simulation of MR polishing fluid
				To archive uniform surface finish	Reducing finishing time	Reducing finishing time
					To archive uniform surface finish	To archive uniform surface finish



Source: Nagdeve et al. (2016)

Fig. 16. (a) Solid model of the Knee Joint, (b) Solid model of negative replica of a Knee Joint, (c) Photographic view of R-MRAFF setup and (d) Fabricate and assembly of replica fixture where knee joint is kept.

- reducing finishing time and obtaining uniform surface finish. It requires improvement in MR polishing fluid and design of a fixture for the workpiece;
- on-line control of fluid properties in the presence of magnetic field is required to control the forces acting on the workpiece surface.

For achieving uniform desired surface roughness on the workpiece, proper arrangement of the poles of the magnets is required so that the uniform magnetic field could be achieved at the outer surface of the workpiece to be finished. In this direction, Nagdeve et al. [115] designed and developed the negative replica or cavity of the freeform surface (knee joint) for uniform distribution of MR polishing fluid and to generate uniform pulsating magnetic field in the finishing region. Figure 16b shows a proposed workpiece fixture design for R-MRAFF process. The objective of this design was to produce a constant velocity of MR fluid in the finishing region and to reduce the total finishing time.

Figure 16a shows the solid model of a knee joint which is placed inside the replica (see Fig. 16d). Figure 16c shows the photographic view of R-MRAFF setup. Minimum surface roughness of 26 nm was achieved using this system.

3.2 Future scope

3.2.1 Experimental work

The following are some exploratory areas in which further experimental research would be needed to enhance the performance of the finishing processes:

- for providing uniform magnetic field in different areas of the freeform surfaces, the negative replica can be used as a magnet fixture keeping in view that the radial distance between the freeform surface to be finished and the magnet surface is maintained almost constant. It will be able to produce almost constant magnetic field in different areas where finishing is to be done;

- the arrangement of magnets in the fixture can be made such that it produces pulsating magnetic field of the desired frequency and strength along the freeform surfaces;
- rheological study of the MR fluid can be done for getting appropriate yield stress and viscosity which play a major role in the finishing of freeform surfaces;
- experiments can be conducted by maintaining different gaps between the workpiece surface and replica of freeform surfaces and then analyzing the results for optimizing the gap.

3.2.2 Theoretical work

- 2D-CFD simulation would be needed to analyze the exact velocity profile along the curvature of all the surfaces of the freeform surfaces.
- Numerical analysis and correlation among material removal and surface finish should be conducted.
- A mathematical model of physical phenomenon of material removal and forces involved during the finishing process should be developed.
- Parametric analysis of the employed processes while creating a freeform surface should be performed. Also, a predictive surface finish model should be developed.
- Molecular dynamics simulations of CIPs and abrasive particle chains should be conducted to model the actual forces applied by abrasive particles on the surfaces to be finished.

4 Conclusion

Several configurations of conventional and non-conventional finishing processes such as grinding, buffing, honing, ball burnishing, soft and elastic abrasive tool and MR fluid based finishing processes have been presented for finishing of freeform/sculptured surfaces. It is a challenging task to obtain a uniform surface finish in case of freeform surfaces. The review conducted leads to the following conclusions:

- 5 or 7 axes CNC machines are capable to produce even surface finish, but in case of freeform surfaces in the nanometer range, it is still not satisfactory;
- due to complex geometry, finishing time required is very high. Although, drag finishing and belt finishing have been extensively used in the industries, but they are not able to produce the uniform surface finish;
- finishing of freeform surfaces using abrasive flow finishing process is possible but external control of the forces acting on the freeform surfaces is not feasible;
- finishing of freeform surfaces is feasible through deploying a flexible magnetic abrasive brush concept, involving magnetic field assisted nanometer finishing processes such as MAF, MRF and MRAFF;
- for achieving uniform surface finish in the case of freeform surfaces using a magnetorheological-fluid based finishing process, negative replica seems to be a potential solution.

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