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ORIGINAL ARTICLE

Preliminary investigations into nano-finishing of freeform surface (femoral) using inverse replica fixture

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Abstract

It is difficult to achieve nano-level surface finish on freeform surfaces. Femoral (knee joint) is one of such components which has freeform surface. Finishing operations are very costly and time consuming. Surface finish of femoral plays a major role in its functionality, efficiency, and life expectancy. To have uniform (or minimum variation) surface roughness value along its curvature, an inverse replica of the femoral component as a fixture has been designed and fabricated so that the magnetorheological (MR) fluid velocity is approximately constant in different areas of the femoral. In this work, an attempt has been made for achieving comparatively more uniform finish on different surfaces and reducing the time required for finishing femoral. For this, a special tooling is used in rotational-magnetorheological abrasive flow finishing (R-MRAFF) process. Different extrusion pressures have been used to examine the effect on percentage change in R_a, finishing rate, and final surface finish of the femoral in both directions, X and Y. Minimum surface roughness of 78 and 89 nm has been achieved on femoral from the initial surface roughness of 172 and 178 nm in X- and Y-directions, respectively.

Keywords Freeform surface · Nano-finishing · MR fluid · Femoral (knee joint) · Inverse replica · R-MRAFF

1 Introduction and literature survey

Freeform complex surfaces cannot be defined by any single mathematical equation. Freeform surfaces have become an inevitable part of various devices to efficiently perform specific functions such as implants (knee joint, hip joint, etc.) in medical science, dies of automotive body panels, turbine blades, impellers, artificial heart pumps, and so on [1]. It is very difficult to achieve nano-level surface finish especially in case of freeform surfaces. Finishing cost can be as high as 15% of the total production cost of the manufactured goods and it has been reported that 37–50% of the total production time is consumed in finishing of dies and molds [2]. Surface finish of femoral (knee joint implant) should be less than 100 nm as per ASTM requirements for its smooth functioning [3]. Abrasion of ultra-high molecular weight polyethylene (UHMWPE) tibial, infection, and aseptic loosening are also major issues of knee replacement [4–6]. Several traditional and advanced finishing processes (AFPs) have been developed for nano-finishing of simple and complex surfaces. Traditional finishing processes have been categorized such as rigid tool-based, floating abrasive-based, CNC-based, and robot-based finishing processes [7]. AFPs can be categorized as non-magnetic or polymer-based, magnetic field-assisted, and hybrid finishing processes. Many finishing processes such as belt finishing, vibratory finishing, and drag finishing processes have been developed, and they are often used in industries for finishing of freeform surfaces. By these processes also, uniform surface finish cannot be achieved because of the process limitations. Researchers are developing new finishing processes but still they are not able to efficiently achieve nano-level uniform surface finish with minimum variation in case of 3-D components, complex geometries, and freeform surfaces. The state-of-the-art related to the developments of the machining of freeform surfaces using CNC

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technology has been reported [8]. Path generation, tool identification, tool orientation, and tool geometry are the major issues which affect final surface finish achieved.

Sidpara and Jain [9] developed the magnetorheological fluid-based finishing (MRFF) process for nano-finishing of prosthetic knee implant and achieved surface finish as low as 28 nm. In this process, a fixture having a ring type magnet is coupled with tool head of three-axes CNC milling machine. Raster path is followed for covering the whole surface of the workpiece. Because of the curved surface at different locations of the femoral, a constant working gap between the tool and workpiece is not maintained and it leads to non-uniform surface finish. In the same way, Baghel et al. [10] used three-axes CNC milling machine for finishing of human teeth which has undefined curvature on its surface. Five-axes CNC milling machine could be a better choice for finishing operation because it can maintain uniform gap between the magnet and workpiece surface resulting in uniform finish.

Kumar et al. [11] developed the tooling as a cylindrical fixture made up of brass for R-MRAFF process for finishing of knee joint. High extrusion pressure tends to increase finishing rate as well as percentage change in surface roughness ($\%\Delta R_a$), but at very high extrusion pressure, the carbonyl iron particles (CIPs) chain structure tends to get destroyed resulting in lower finishing rate by the abrasive particles embedded between and within the CIPs chains. Uniform flow velocity of MR fluid and uniform magnetic field over the knee joint surface cannot be achieved in this process. In the same way, Sarkar and Jain [12] developed a fixture for finishing of femoral using abrasive flow finishing (AFF) process. The distinct medium was prepared by mixing silicon oil, boric acid, and polydimethylsiloxane (PDMS) including additional additives for finishing purposes. The surface roughness ranging values from 42.9 to 62.5 nm in various regions of different faces of the femoral achieved. The main drawback of the process is that it is not possible to control the medium properties on-line during the finishing process.

An attempt has been made by Nagdeve et al. [13] to get the uniform surface finish and uniform MR fluid velocity over the different faces of the knee joint by using a negative replica of freeform surfaces as a fixture. The minimum surface roughness of 26 nm was achieved using the negative replica of freeform surfaces. Yamaguchi and Graziano [14] developed the process for finishing of condyle surfaces. The required magnetic field which was desired to finish the condyle surfaces using MAF principle was obtained by controlling the material properties and geometry of the knee holder. The magnetic field so obtained permitted the magnetic particles to closely follow the pole tip rotation over the freeform condyle surface and hence there was a control over the surface lay by the combined results of kinematic behavior of the knee and pole tip.

Manufacturing industries are producing complicated components, but they are not able to deliver good quality components due to the limitations of the process employed. Industries, namely, Rosler and Otec have developed many finishing processes such as belt finishing, drag finishing, and vibratory finishing for complex-shaped components [15, 16]. Due to the process limitations, they are not able to achieve uniform surface finish.

It can be concluded from the literature survey that there is a need to develop the process with appropriate finishing tool which can provide the bulk contact area of workpiece with MR fluid and uniform medium flow velocity (almost constant velocity of MR fluid) throughout the curvature of the freeform surface, so that more uniform surface finish, higher productivity, higher finishing rate, and better surface finish can be achieved.

However, recent advancements in the finishing technologies (say, AFPs) have made it possible to achieve nano-level surface finish on the flat, cylindrical, spherical, as well as complex-shaped surfaces. The R-MRAFF process [17, 18] is one of the advanced finishing techniques which can be used to achieve surface finish in the nano-meter range using modified finishing fixture.

During knee implant, diseased femoral (Fig. 1a) is replaced by the artificial femoral as shown in Fig. 1b. An external surface which is introduced between the femoral and tibia is made up of as ultra-high molecular weight polyethylene (UHMWPE) (see in Fig. 1b). The femoral during its movement is constantly in contact with UHMWPE surface (Fig. 1b). Therefore, a femoral with high surface roughness will have low life of the implant because abrasion rate becomes high in the contact region. Such high abrasions lead to the disintegration of small particles from UHMWPE. Consequently, these particles affect immune system of the body. Thus, the femoral which moves over UHMWPE must be adequately smooth.[1] To maintain long life of the implant, one cardinal solution could be the use of nano-level uniform surface finish on knee joint which is the objective of this research work.

During selection of a process for finishing of freeform surfaces, two issues are important: (1) final surface roughness value (few tens of nanometer) and (2) uniformity of surface finish across the different faces and within a face of the freeform surface. For the first issue, preliminary studies using R-MRAFF indicate that it can give good results [11], but for the second issue, it has not proven to be successful in the present configuration used by researchers [11]. In R-MRAFF process, we get non-uniform surface roughness values because of (a) non-uniform magnetic field and (b) non-uniform MR polishing fluid velocity of flow.

[1] As per ASTM, its surface roughness should be less than 100 nm.

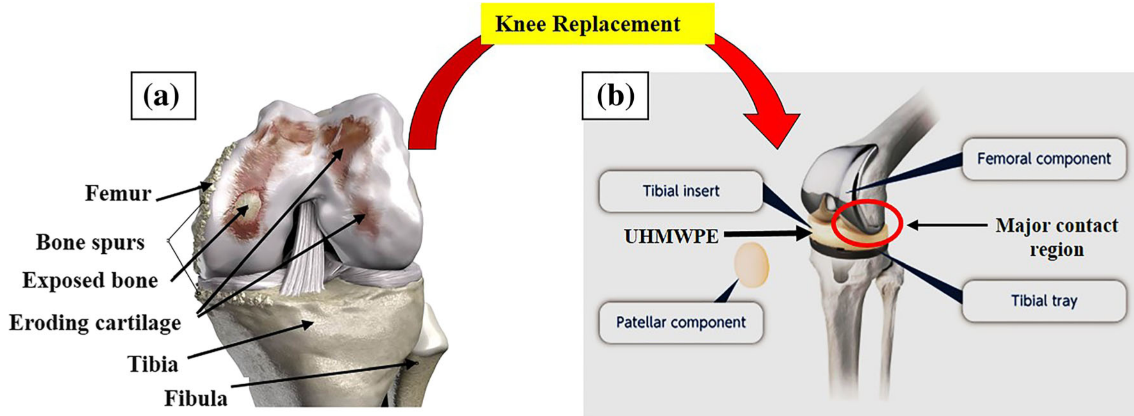


Fig. 1 Knee replacement. Courtesy of **a** diseased femoral component (health care center) and **b** AESCULAP implant system

To obtain the uniform surface finish on the freeform surface, the use of the inverse replica of freeform surface as a fixture seems to be appropriate.

In the present research work, an inverse replica as a novel finishing fixture for femoral has been designed and fabricated to achieve uniform surface finish. It is also expected to provide almost uniform fluid flow velocity along the curvature of femoral. The details about the developed novel finishing fixture are elaborated in the following section.

2 Development of novel finishing fixture

For R-MRAFF process, an inverse replica of femoral as a workpiece fixture has been designed and fabricated as shown in Fig. 2. Figures 2a, and 2b show the actual knee joint and solid model of the same knee joint, respectively. Solid model of knee joint was used for designing the fixture for the knee joint. Figures 2c, and 2d show the solid model of knee fixture and fabricated fixture for holding the knee joint. There are two parts of the finishing fixture as shown in Fig. 2d. The right hand side in Fig. 2d shows the inner surface of the femoral as a workpiece fixture, and the left hand side shows the inverse replica of the external surface of femoral (or finishing fixture). It can be clearly understood from Fig. 2e. It will help in maintaining approximately constant velocity of MR fluid flow during the finishing process. Finishing fixture is just an extended form of the femoral used in R-MRAFF process for maintaining almost uniform gap of 6 mm between the workpiece surface and internal surface of finishing fixture. MR fluid is flowing and

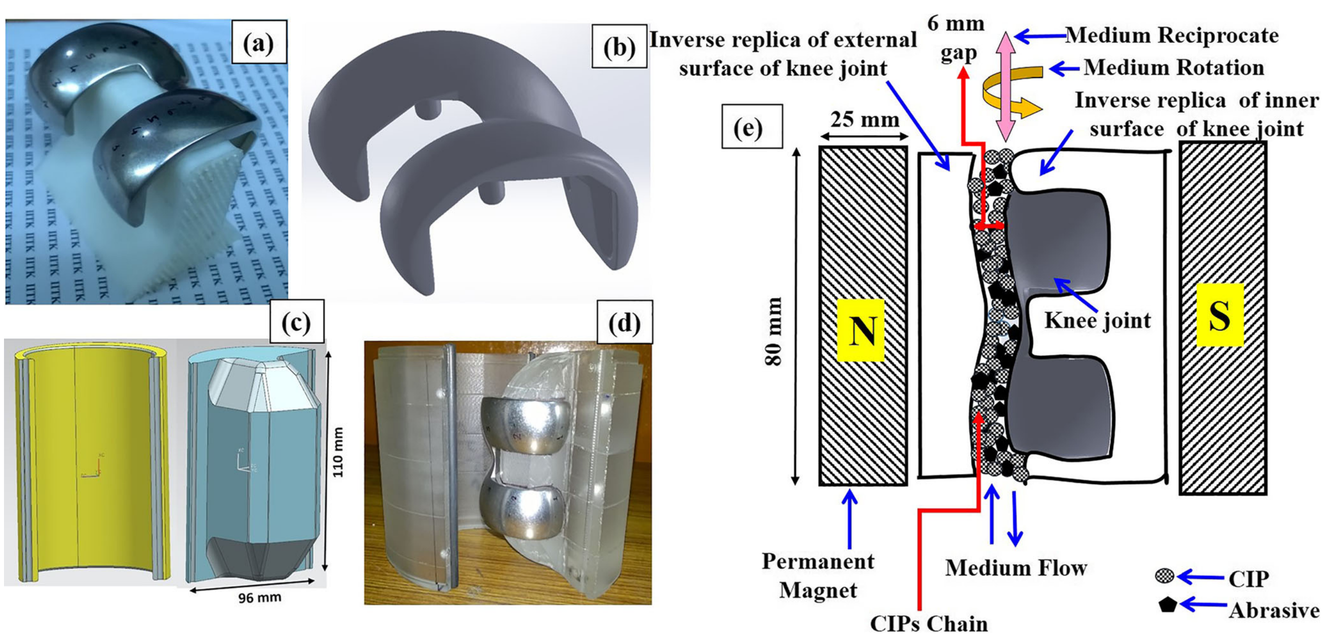


Fig. 2 **a** Actual knee joint. **b** Solid model of knee joint. **c** Replica fixture of knee joint. **d** Fabricated knee replica fixture where knee is kept. **e** MR fluid flow through the gap between the knee surface and internal surface of replica fixture (front view)

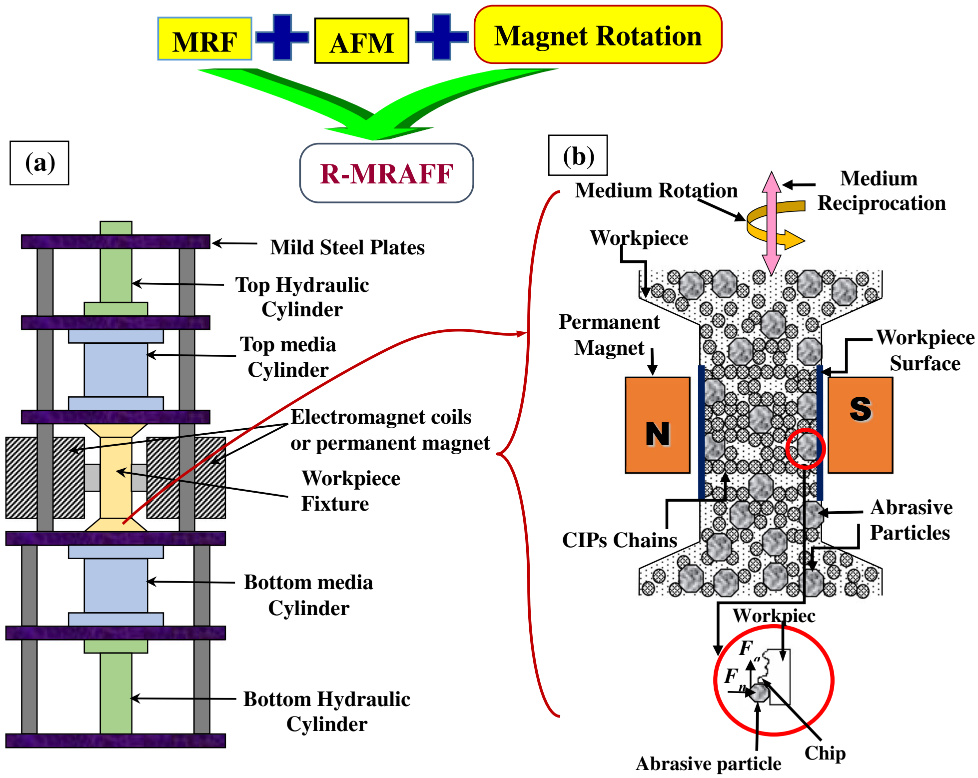


Fig. 3 **a** Schematic diagram of MRAFF process. **b** Mechanism of material removal in R-MRAFF process

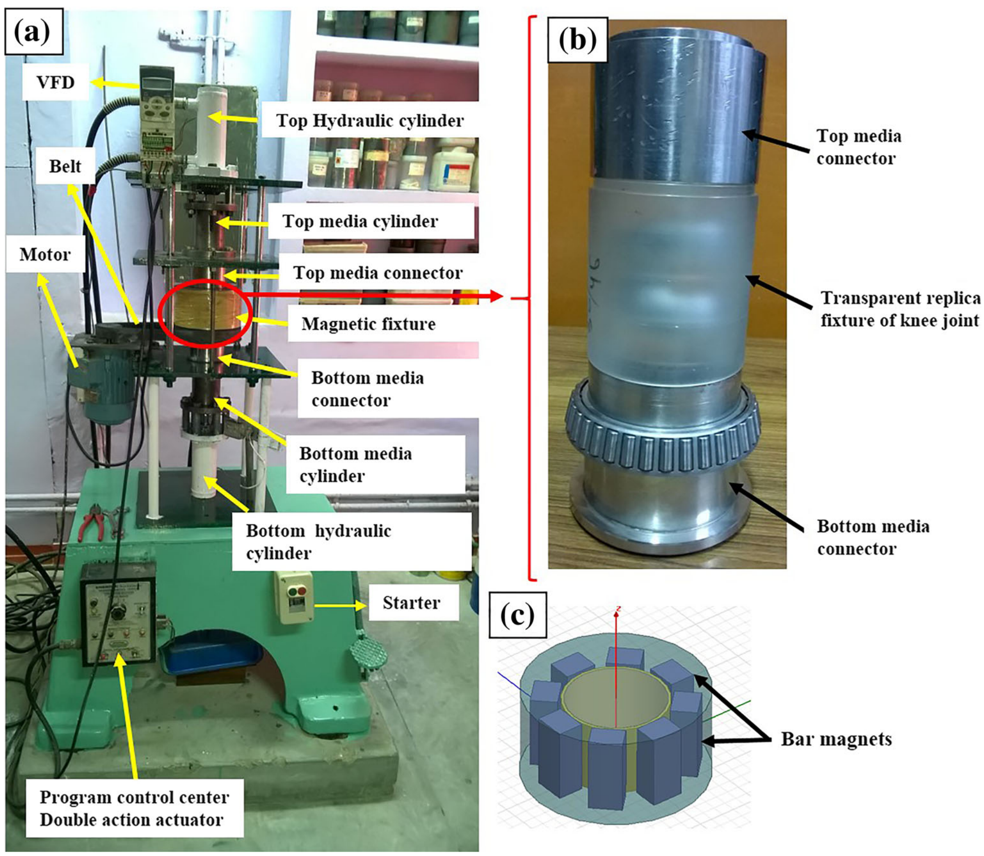


Fig. 4 **a** R-MRAFF setup. **b** Knee joint inside of magnet fixture. **c** Solid model of magnet fixture

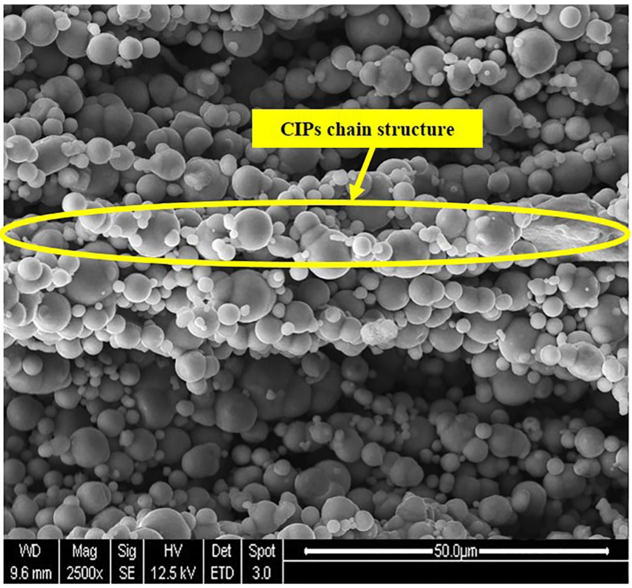


Fig. 5 CIPs chains formation in the presence of magnetic field

rotating in this gap as shown in Fig. 2e. An inverse replica of femoral is made up of acrylic block which has 96-mm outer diameter and 110-mm length (Fig. 2c).

3 Experimental setup

3.1 R-MRAFF process

R-MRAFF is a deterministic process and has the potential to finish any complex geometry up to nano-level surface finish. In this process, magnetorheological (MR) fluid makes to and fro motion and at the same time rotates due to the rotation of the magnetic field. Figures 3a and 4a show a schematic diagram and photographic view of R-MRAFF setup, respectively. Figure 3b illustrates the mechanism of material removal in R-MRAFF process. In the R-MRAFF setup, top hydraulic cylinder, top medium cylinder, and top medium connector are co-axially connected to the bottom hydraulic cylinder, bottom medium cylinder, and bottom medium connector. R-MRAFF process works on the principle of abrasive action performed by the abrasive particles and aided by the magnetic field. In the magnet fixture, eight Nd-Fe-B bar magnets (size, 80 mm length × 25 mm width × 20 mm thickness) are kept in the slots made in aluminum cylindrical block on its outer periphery as shown in Fig. 4c.

In the R-MRAFF process, the workpiece on which finishing operation is to be performed, is kept inside the replica fixture as shown in Fig. 4b. This whole system is placed inside the magnet fixture. The MR fluid is filled inside the bottom medium cylinder, and bottom medium connector and then filled in the workpiece fixture. In this process, the MR fluid comprises of non-colloidal magnetic particles of micron-sized such as CIPs and very fine abrasive particles suspended in the viscoplastic carrier medium of mineral oil or water and grease. In the presence of external magnetic field, MR fluid exhibits non-Newtonian behavior, while in the absence of magnetic field, it behaves as Newtonian fluid and the phenomenon is known as MR effect observed by Rabinow [19]. MR fluid forms a multiple flexible brush in the presence of external magnetic field which works as a flexible polishing tool, and hence, it can polish simple as well as 3-D complex-shaped components including freeform surfaces.

During the experiments, MR fluid reciprocates with the help of pistons operated by a hydraulic unit, and rotates at the same time with the help of a mechanical cum electrical system developed to rotate the magnet fixture [18, 20]. On the application of magnetic field, CIPs are aligned along the magnetic field lines and form the chain-like structure. Figure 5

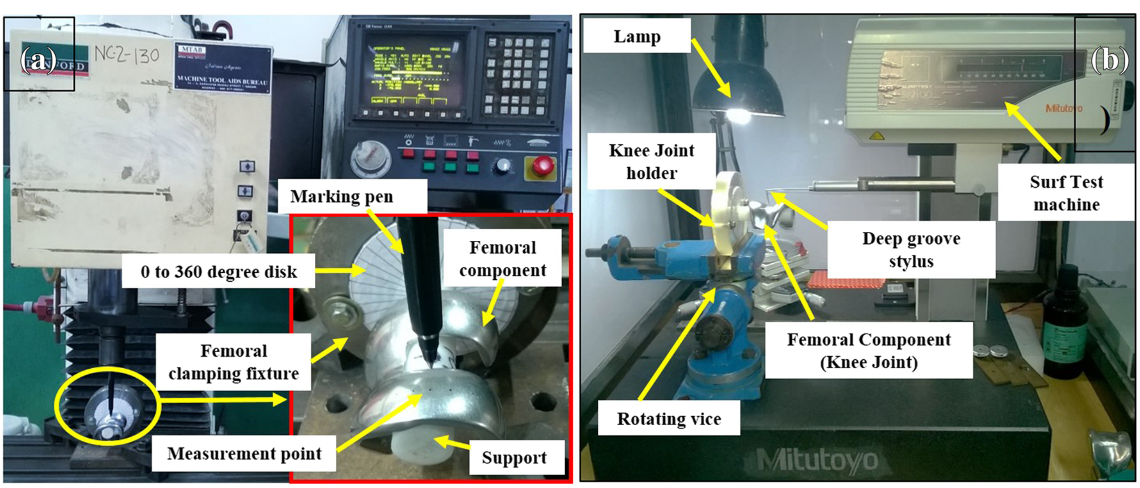


Fig. 6 **a** Locating points on femoral for maintaining accuracy using CNC machine. **b** Roughness Tester Surf Test SV2100M4 (Mitutoyo, Japan)

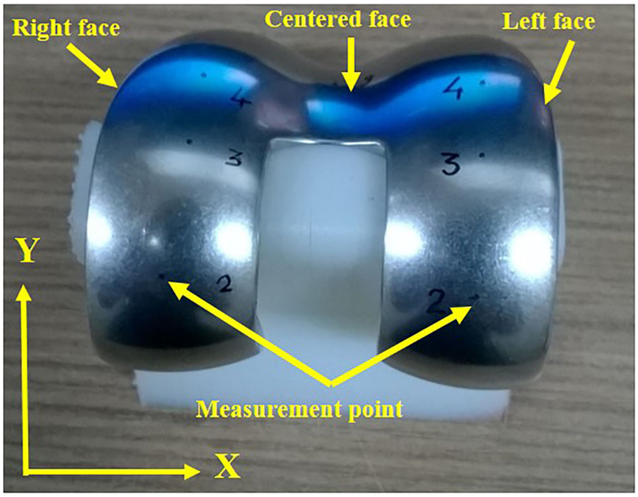


Fig. 7 Femoral component consisting left face, right face, and central face

shows the SEM image of CIPs chain structure formation during the finishing operation.

When the magnetic field is removed, the MR fluid acts as the Newtonian fluid. Due to the abrasive action of the non-magnetic abrasive particles, the finishing operation is performed. The surface finish is obtained due to the onset of two forces, i.e., indentation force and cutting force [19]. The indentation force ($F_{indention}$) and cutting force ($F_{cutting}$) are given by Eqs. (1) and (2), respectively.

$$F_{indentation} = F_m + F_r + F_{cen} \quad (1)$$

where

F_m magnetic force
F_r radial force
F_{cen} centrifugal force.

The cutting force comprises of two forces:

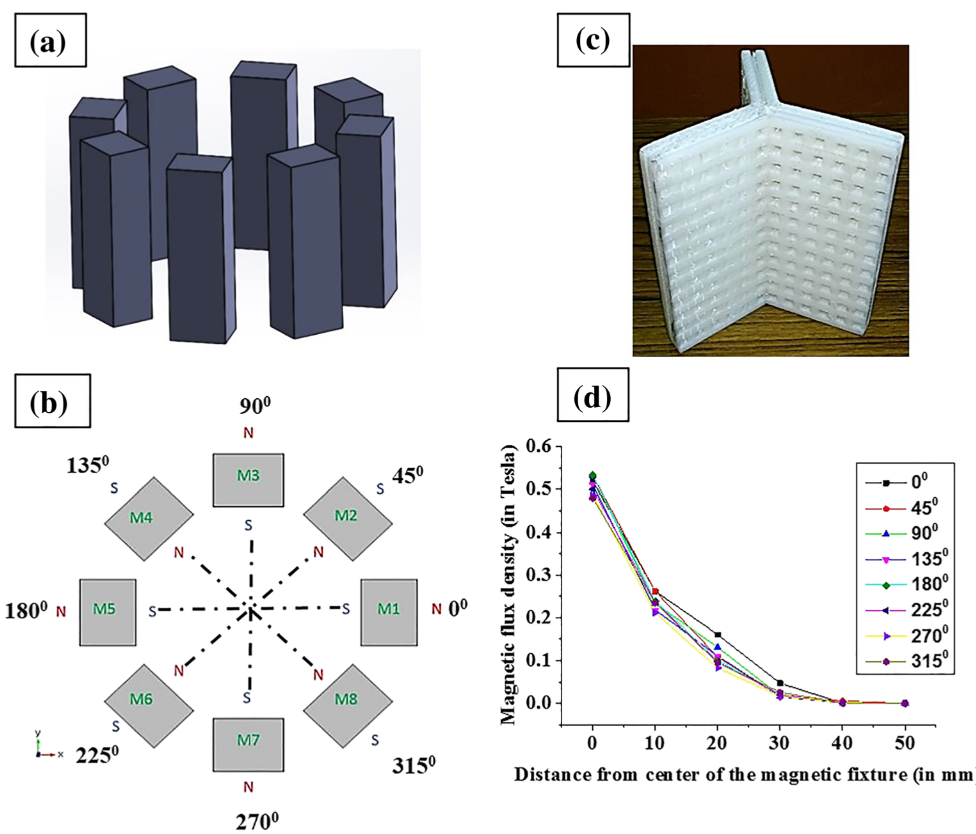
$$F_{cutting} = (F_t + F_a) \quad (2)$$

where

F_t tangential force
F_a axial force.

Experiments were conducted on femoral made of Co-Cr-Mo alloy. Roughness Tester Surf Test SV2100M4 (Mitutoyo, Japan) with a least count of 0.1 nm (Fig. 6b) was used for measuring R_a values on different locations of femoral. Measurement of surface finish along the curved surface of a femoral is a difficult task. For this purpose, a knee holder and a knee holder vice (shown in Fig. 6a) were designed and

Fig. 8 **a** Solid model of arrangement of eight magnets. **b** Top view of magnet fixture (M, magnets; N, north pole; S, south pole). **c** Three-pin stand. **d** Relationship between magnetic field and radial distance



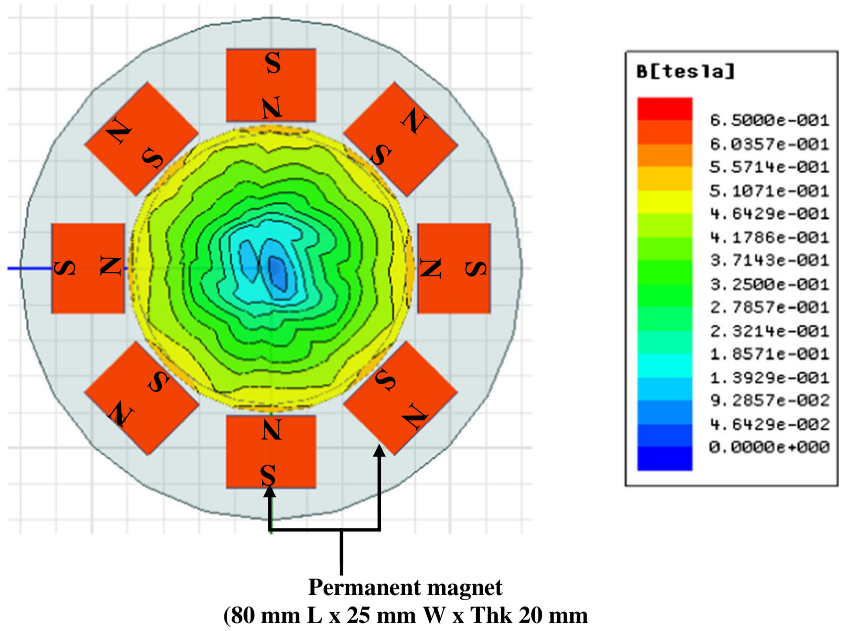


Fig. 9 Magnetic field (B) contour plot of R-MRAFF process

fabricated which made it possible to measure surface roughness along the curvature. To measure surface roughness repeatedly at the same place, before and after finishing was a difficult task. For that, three-axes CNC machine as shown in Fig. 6a was used. The coordinates (*X*-*Y*-*Z*) of all the points on which surface finish was to be measured were recorded. It helped in exactly locating the points every time where surface finish is to be measured. Some parameters were fixed during the measurement of R_a value because of non-uniformity of surface. Sampling length = 0.08 mm, number of samples = 5, and speed of stylus = 0.05 mm/s were selected during all the measurements before and after finishing. Surface roughness was measured in both *X*- and *Y*-directions, respectively, as shown in Fig. 7. It is also very important to analyze the topography of workpiece surface before and after finishing for which 3-D optical profilometer was used.

It has been observed that initial surface roughness of femoral varies on different faces starting from 146 to 178 nm in *X*-direction and 136 to 172 nm in *Y*-direction. It was observed that the initial area roughness was varying from 230 to 242 nm on the left and right face of the femoral.

4 Magnetic flux density measurement

Sometimes, it becomes very difficult to measure magnetic field in the finishing zone having freeform geometries. Hence, a small fixture (three pins stand, Fig. 8c) was made using 3-D printing machine by taking care of the requirements for measuring flux density in the entire zone of magnet fixture. The arrangement of magnets in the fixture is shown in Fig. 8a. Before the flux density measurement, angles at 45° were marked on the top face of the fixture (Fig. 8b). Three-pins stand (Fig. 8c) was inserted inside the magnet fixture. Gauss meter and other devices were used to measure the magnetic flux density in the finishing zone. The probe of Gauss meter is inserted into the grid of the three-pins stand. Magnetic flux density was measured in the radial direction of the magnet

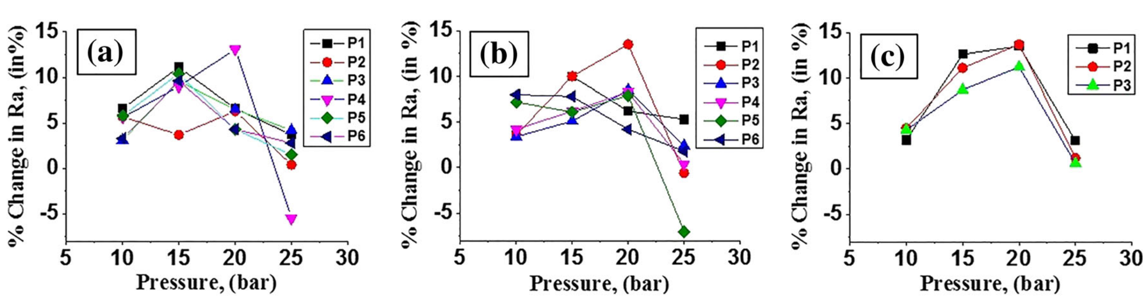


Fig. 10 Relationship between % change in R_a and pressure in *X*-direction. **a** Left face. **b** Right face. **c** Center face. (P1, point 1; P2, point 2; P3, point 3; P4, point 4; P5, point 5; P6, point 6)

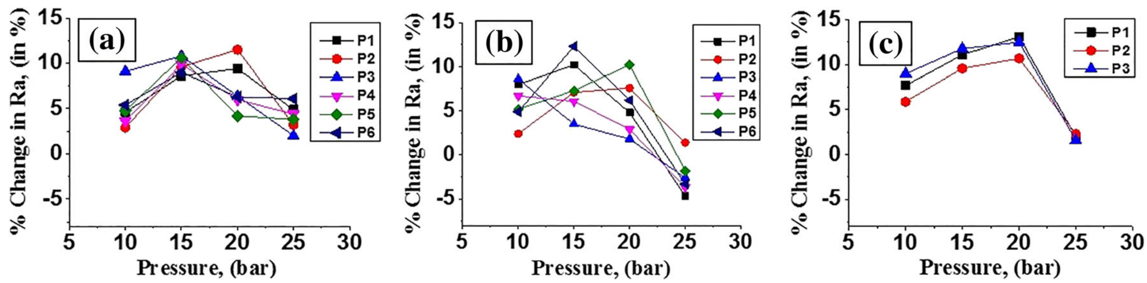


Fig. 11 Relationship between percent changes in R_a and pressure in *Y*-direction. **a** Left face. **b** Right face. **c** Center face. (P1, point 1; P2, point 2; P3, point 3; P4, point 4; P5, point 5; P6, point 6)

fixture starting from 0° to 360°. Figure 8d shows the relationship between the magnetic flux density and redial distance of the fixture.

From the experimental results, it was concluded that at an angle 0° and also the radial distance being 0 mm (near to the magnet), the flux density was found to be maximum value of 0.53 T, but when the radial distance from the magnet was increased to 10 mm (towards the center of magnet fixture), then the flux density decreased to the value of 0.19 T. Variations of the flux density with the radial distance and angle are shown in Fig. 8d. From the above experimental results, it is concluded that as the radial distance from the magnets increases, the magnetic flux density decreases.

5 Magnetic field simulation

Externally applied magnetic field applied the workpiece surface plays a significant role. To understand the distribution of magnetic flux density over the workpiece surface is very important. Finite element analysis (FEA) was done using ANSYS Maxwell V14. All the major and necessary components mentioned in the experimental setup have been modeled into Maxwell 14. The boundary conditions were applied by providing the coercive field force Hc (− 836 kA/m) and residual flux density Br (1.42 T) of the bar magnet (N52 grad of Nd-Fe-B) to the solver along with the direction of magnetization.

Vibrating sample magnetometer (VSM) was used to measure the magnetic properties of MR fluid such as non-linear permeability from BH curve, coercive magnetic field, saturation magnetization, and residual flux density. All the input parameters related to MR fluid, magnets, and workpiece are given to the FEA solver for simulation purposes. Using the convergence criterion as ten passes with 30% refinement per pass are given to the adaptive setup. Software computes the vector potential (A) of bar magnet at each point in the space based on the following Maxwell's equation:

$$\nabla \times \left(\frac{1}{2\mu_0 \mu_r} \nabla \times A \right) = J \quad (3)$$

where μ_0 is the permeability of free space, μ_r is the relative permeability of material and J is the current density field. Magnetic flux density (B) and magnetic field (H) can be computed after getting A using the relationship of the following Eqs. 4 and 5.

$$B = \nabla \times A \quad (4)$$

$$B = \mu_0 H \quad (5)$$

Figure 9 shows the magnetic field in the entire finishing zone. Results are in agreement with the experimental results (Fig. 8d).

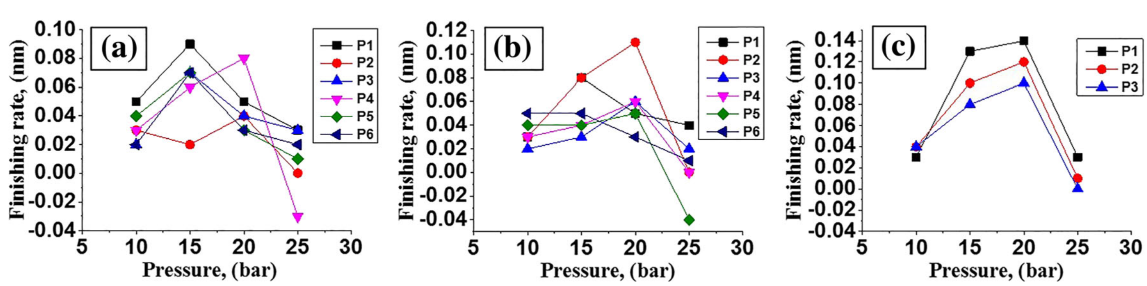


Fig. 12 Relationship between finishing rate and pressure in *X*-direction. **a** Left face. **b** Right face. **c** Center face. (P1, point 1; P2, point 2; P3, point 3; P4, point 4; P5, point 5; P6, point 6)

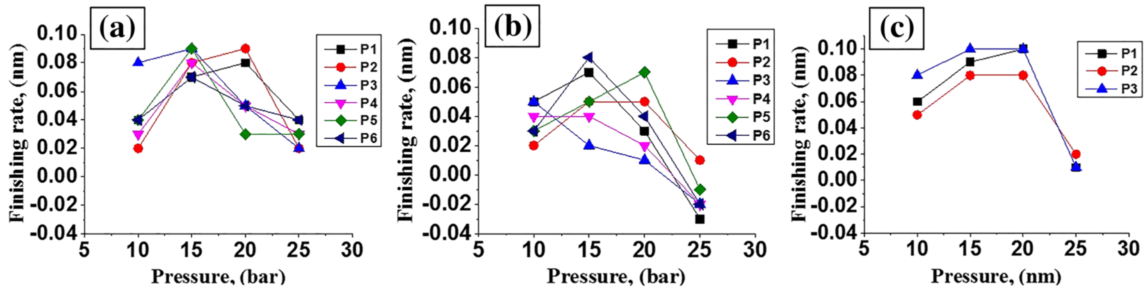


Fig. 13 Relationship between finishing rate and pressure in *Y*-direction. **a** Left face. **b** Right face. **c** Center face. (P1, point 1; P2, point 2; P3, point 3; P4, point 4; P5, point 5; P6, point 6)

6 Results and discussion

6.1 Percentage change in R_a

6.1.1 Percentage change in R_a (% ΔR_a) in *X*-direction

Percentage change in surface roughness was calculated using Eq. 6.

$$\% \Delta Ra = \frac{(Initial\ Ra - Final\ Ra)}{(Initial\ Ra)} \times 100 \tag{6}$$

Experiments were carried out to see the effect of pressure on the initial surface finish improvement. Figure 10a–c shows the relationship between percentage change in R_a (% ΔR_a) and pressure on all the three faces (Fig. 7). It has been observed that % ΔR_a varies with a change in pressure. Initially, the experiments were conducted at 10 bar and positive % ΔR_a results have been observed at 10 bar, 15 bar, as well as at 20 bar. Later on, at 25 bar, it was noted that % ΔR_a became negative or close to zero because the surface finish started deteriorating except at some points on left face and right face. Depth of indentation increases on all the faces of femoral due to an increase in extrusion pressure as applied on the abrasive particles. It also results in an increase in the number of active abrasive particles on all the faces except center face. Beyond a particular value of the pressure (> 20 bar), % ΔR_a decreases on all the faces. It was also observed that at a few points on left face and right face, % ΔR_a became negative as shown in Figs. 10a, and 10b. Here, finishing conditions and few modifications in the fixture need to be incorporated for better improvement in finishing.

6.1.2 Percentage change in R_a (% ΔR_a) in *Y*-direction

Surface roughness was also measured in *Y*-direction to check the differences in roughness values achieved in both directions *X* and *Y* on the knee joint (Fig. 7). Percent change in R_a was calculated using Eq. 6. It has been observed that percentage change in R_a is not same on the same point on the surface in *Y*-direction compared to *X*-direction as shown in Figs. 11a-c because of the initial non-uniformity in surface roughness in both directions.

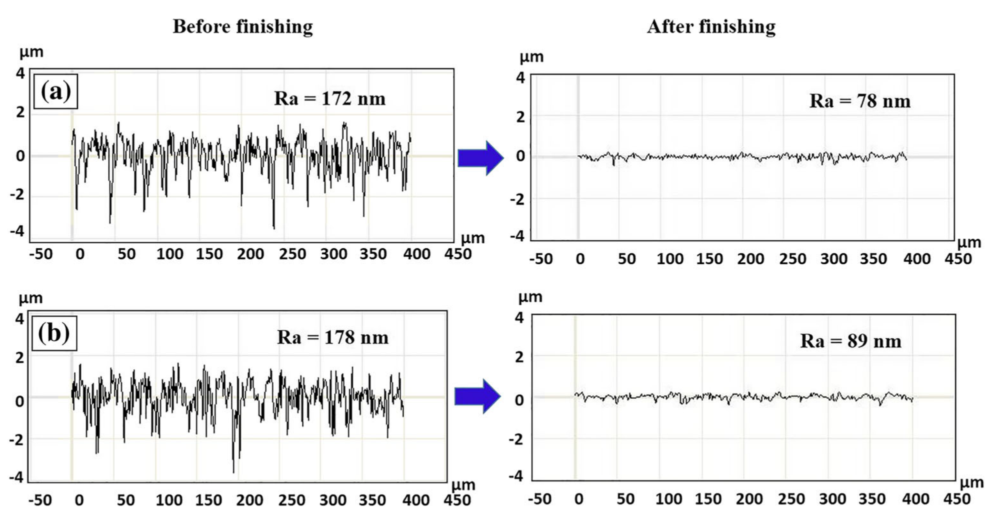


Fig. 14 Surface roughness before and after finishing. **a** *X*-direction. **b** *Y*-direction

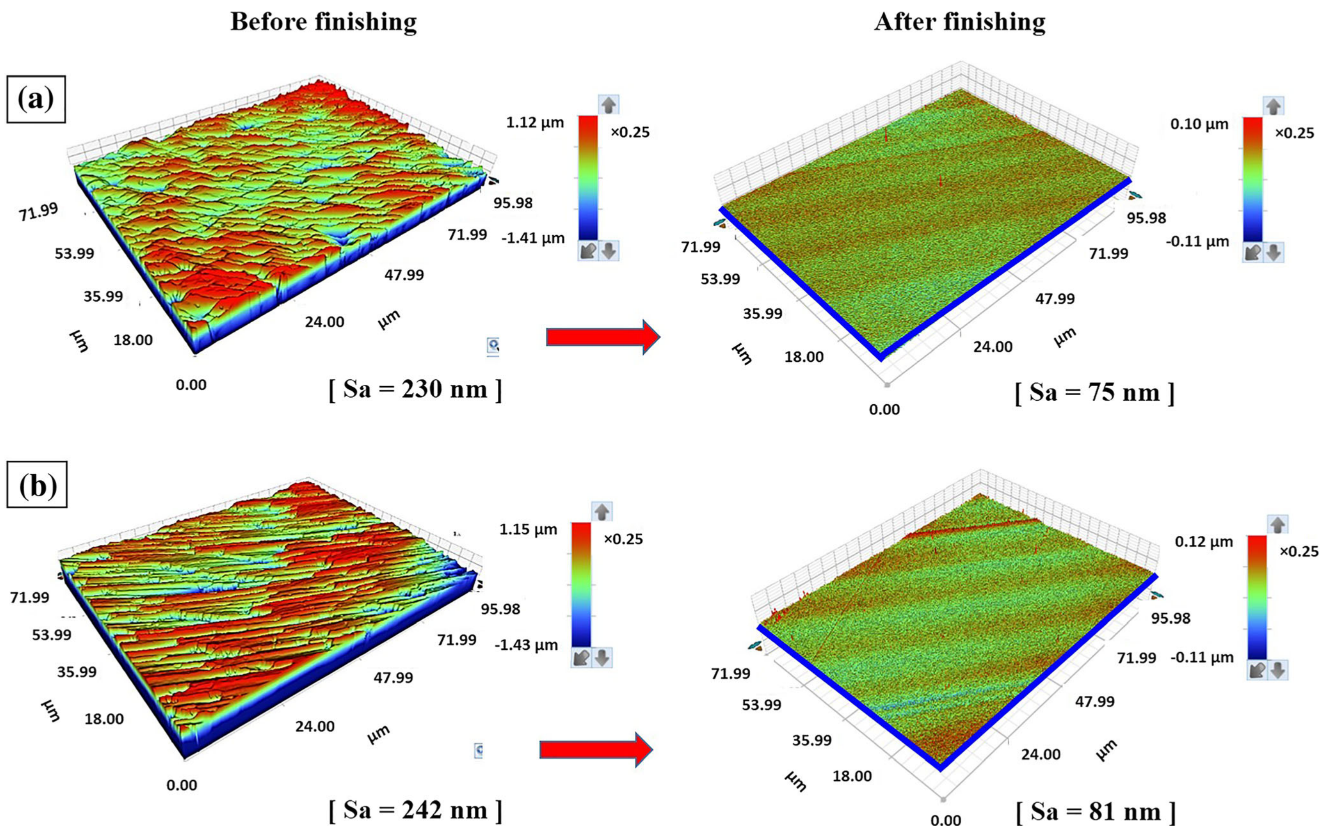


Fig. 15 3-D area roughness plot before and after finishing; **a** Right face. **b** Left face

6.2 Finishing rate

6.2.1 Finishing rate in *X*-direction and *Y*-direction

Finishing rate was calculated in both directions *X* and *Y* using Eq. 7. Figure 12 shows the relationship between finishing rate (nm) and extrusion pressure (bar) in *X*-direction.

$$\textit{Finishing rate}\ (\text{nm/min}) = \frac{\textit{Initial}\ \text{Ra}-\textit{Final}\ \text{Ra}}{\textit{Total finishing time}} \quad (7)$$

During the experiments, it was found that finishing rate (FR) in *X*-direction increases as pressure increases up to a certain value beyond which it starts decreasing (Fig. 12a–c) on all the faces of the femoral except at point P4 on the left face at 15 bar. Initially, finishing operation was started at 10 bar of extrusion pressure and continued till 25 bar. It was observed that FR increases up to 20 bar except at few points on left and right faces. Beyond this pressure, FR started decreasing and deteriorating the surface finish. It even attained negative value as shown in Fig. 12a on left face on point P4, and P5 on right face in Fig. 12b. During finishing operation, indentation of the abrasive particles becomes more as applied extrusion pressure becomes higher. It may leave the scratch marks deeper than the preceding scratch marks. Hence, FR decreases.

Finishing rate was calculated in the *Y*-direction also to see the differences in FR in different directions. It was observed that FR was different in *Y*-direction on all the faces of femoral (Fig. 13a–c) because of difference in the initial surface roughness and direction of the scratches formed. Hence, it gave different FR in different directions. Negative values of FR are also achieved on the right face of the femoral for which the reasons have been explained in the preceding sections.

Minimum surface roughness obtained on the femoral was 78 nm in X-direction and 89 nm in *Y*-direction as shown in Fig. 14.

Surface finish in *X*- and *Y*-directions can be further improved (that is reducing the minimum R_a value) by modifying the finishing fixture and by optimizing the process parameters (magnetic field, abrasive particles size and, volume fraction, etc.).

Figure 15 shows 3-D area roughness before and after finishing on right face and left face of the femoral. In Fig. 15, machining marks can be seen before finishing which have been removed by the finishing operation shown in the same figure after finishing.

It has been reported that total finishing time for all the faces of femoral made up of titanium alloy (Ti-6Al-4V) was 64.7 h in MRFF process using diamond abrasive [21]. It has been found that the surface roughness range was 28–97 nm with standard deviation of 25.50–27.12 on all the faces.

In the present research work, R-MRAFF process with inverse replica fixture as a finishing tool was used to finish the femoral. It has been observed that the total finishing time for all the faces (right face, left face, and centered face) achieved was 10.35 h using boron carbide (B_4C) abrasive which is the 15.99 % of the total finishing time used by Sidpara and Jain (2012). Surface roughness range was 78–95 nm with minimum standard deviation 2.32–3.67 on all the faces. Surface roughness can be further reduced by changing the input parameters (abrasive hardness, size of abrasive particles, etc.). Further optimization can be carried out to optimize the finishing time as well as surface roughness. Comparing above both the processes employed for finishing of femoral, R-MRAFF with inverse replica is better in terms of finishing time, finishing rate, and standard deviation.

From the discussion in the preceding section, this new concept is helpful in achieving more uniform surface finish on any kind of irregular shapes, 3-D components, and freeform surfaces having different curvature at different locations. For achieving still better surface finish than the one obtained in this paper, inversed replica fixture diameter can be reduced. Reduced diameter of the inverse replica fixture would increase the strength of the magnetic field inside the finishing zone. Computational fluid dynamics (CFD) can be employed to study the flow behavior of MR fluid within the gap maintained between the inverse replica fixture and outer surface of the femoral.

7 Conclusions

Preliminary experiments were conducted to study the effect of pressure on the percentage change in surface roughness and finishing rate while finishing a femoral (or knee joint implant) made up of Co-Cr-Mo alloy, by the R-MRAFF process with a new finishing fixture. Following conclusions can be drawn based on the results and discussion:

1. Based on the results and discussion, R-MRAFF process can be recommended for finishing of freeform surfaces up to nano-level of surface roughness with special design of tooling for the workpiece.
2. Inverse replica of the workpiece as a finishing fixture is recommended for finishing of freeform surfaces up to nano-level of R_a value.
3. Percentage change in R_a (% ΔR_a) in both X-direction and the *Y*-direction is found to increase as the extrusion pressure increases up to a certain limit. It requires optimization of the process parameters so that no negative % ΔR_a is achieved.
4. Lowest surface roughness of 78 and 89 nm on femoral has been achieved from the initial surface roughness of 172 and 178 nm in *X*-direction and *Y*-direction, respectively.
5. Area roughness of 75 and 81 nm has been achieved from the initial area roughness of 230 and 242 nm on the left face and right face of femoral, respectively.
6. Comparing with the previous studies, it is observed that the process leads to a better uniformity in surface roughness on all the faces in a comparatively lesser time.

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