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Polishing of artificial femoral head with coarse sisal fiber-based tool

Yahya Choopani[1,*], Mohsen Khajehzadeh[2], Mohammad Reza Razfar[3]

[1]Assist. Prof., Department of Mechanical Engineering, Meybod University, Meybod, Iran.
[2]Assoc. Prof., Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran
[3]Full Prof., Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

*Corresponding author: Choopani@meybod.ac.ir

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Abstract

In this study, fiber-assisted polishing is introduced as a method to eliminate the undesirable effects caused by abrasives on the surfaces of sensitive components such as prostheses, lenses, and turbine blades. To this end, a polishing tool based on coarse sisal fibers was first fabricated. The performance of this tool was then evaluated in terms of surface roughness ratio and polishing rate on an artificial femoral head made of 316L stainless steel. The results indicate that the coarse sisal fiber-based polishing tool performs effectively and efficiently in finishing the surface of the artificial femoral head. Microscopic observations revealed that the primary polishing mechanism involves the gradual fracture of sisal fibers and the formation of self-adaptive microfilaments that act as a soft abrasive. Over a period of 2.5 hours, transitioning from the rough machining phase to nano-polishing, this process produced a surface with an average roughness of 36.96 nm and mirror-like reflectivity on the femoral head. Accordingly, the sisal fiber-based polishing tool is proposed as an efficient method for surface modification of components with complex geometries in the medical, aerospace, and automotive industries.

Keywords: Polishing tool, Coarse sisal fiber, Artificial femoral head, Surface roughness ratio, Polishing rate.

1. Introduction

Total hip arthroplasty (THA) is one of the most successful and cost-effective orthopedic surgical techniques, in which a damaged hip joint is replaced with an artificial one [1]. In this procedure, to increase prosthesis durability and reduce component wear, the international standard ISO 7206-2 specifies surface roughness limits for the metallic femoral head (maximum 2 μm) and ultra-high molecular weight polyethylene (UHMWPE) cup (maximum 0.05 μm) [2]. Traditional manual polishing methods (such as buffing), used to meet these standards, are often non-uniform, operator-dependent, costly, and inefficient [3]. In pursuit of automation, methods such as abrasive flow finishing (AFF) have been developed. Although they have achieved some success in reducing roughness and preserving spherical geometry [4,5], they face challenges including residual abrasive particles embedded in the surface texture, collateral damage, biocompatibility concerns, and the need for multi-stage processing. Therefore, achieving simultaneous automated polishing, ideal surface smoothness, and damage-free finishing – particularly for 316L stainless steel femoral heads – remains a significant challenge [6].

To overcome this challenge, the present research focuses on the design and development of a fully automated and innovative fiber-assisted polishing process. In this method, the polishing tool is composed of styrene butadiene rubber (SBR), coarse sisal fibers, and naphthenic oil. To evaluate the performance of this novel tool, the effects of key process parameters – including hydraulic extrusion pressure and number of polishing cycles – on the surface roughness ratio and polishing rate of 316L stainless steel femoral head specimens were experimentally investigated. Furthermore, for deeper analysis, the surface morphology of the samples was examined and compared using scanning electron microscopy (SEM) images.

2. Materials and methods

Fig. 1 illustrates a schematic representation of the principles of fiber-assisted polishing for an artificial femoral head. The system consists of three main components:

1. The base machine
2. The femoral head reverse replica fixture
3. The coarse sisal fiber-based polishing tool

In the present study, a polishing tool composed of 25 wt.% SBR, 66 wt.% coarse sisal fibers, and 9 wt.% naphthenic oil was fabricated.

Artificial hip joint femoral head specimens made of grade 316L stainless steel with a diameter of 28 mm and hardness of 321 Brinell were used. The surface roughness ratio and polishing rate were calculated using Equations

(1) and (2), respectively. Based on preliminary experiments, the optimal conditions for achieving the best surface quality were determined as a hydraulic extrusion pressure of 12 MPa and 1000 polishing cycles. Surface roughness was measured at five different regions on the upper section of the artificial femoral head. All measurements were conducted under identical conditions and perpendicular to the machining flow direction using a SURFCOM 130A surface roughness tester.

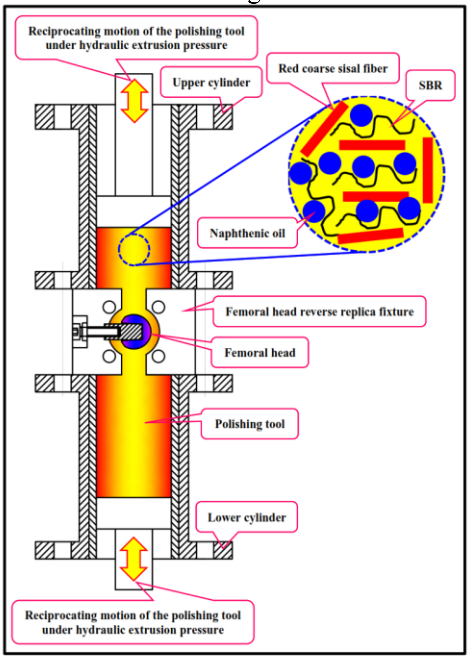


Figure. 1. Schematic and working principle of fiber-assisted polishing.

$$Surface\ roughness\ ratio\ (SRR) = \frac{Final_{Ra}}{Initial_{Ra}} \quad (1)$$

$$\text{Polishing rate } (\mu\text{m/min}) = \frac{\text{Initial}_{\text{Ra}} - \text{Final}_{\text{Ra}}}{\text{Total finishing time}} \quad (2)$$

3. Results and Discussion

The effect of hydraulic extrusion pressure on the surface roughness ratio and polishing rate under the optimal condition of 1000 polishing cycles is shown in Figs. 2-a and 2-b, respectively. The figures indicate that increasing hydraulic extrusion pressure results in a decreasing trend in surface roughness ratio (Fig. 2-a), while the polishing rate exhibits an increasing trend (Fig. 2-b). With increasing hydraulic extrusion pressure, the macro- and micro-filaments of sisal, in contact with the surface asperities of the femoral head, act as a soft micro-brush (or soft abrasive). This leads not only to a reduction in surface roughness but also to nano-scale polishing of the artificial femoral head.

The effect of the number of polishing cycles on surface roughness ratio and polishing rate under the optimal hydraulic extrusion pressure of 12 MPa is shown in Figs. 3-a and 3-b, respectively. The figures demonstrate that increasing the number of polishing cycles decreases the surface roughness ratio (Fig. 3-a), while increasing the polishing rate (Fig. 3-b). As the number of polishing cycles increases, the number of macro- and micro-sisal filaments impacting the surface asperities per second also increases, resulting in a significant reduction in the surface peaks of the femoral head. This effect plays a major role in reducing the surface roughness ratio and enhancing the polishing rate.

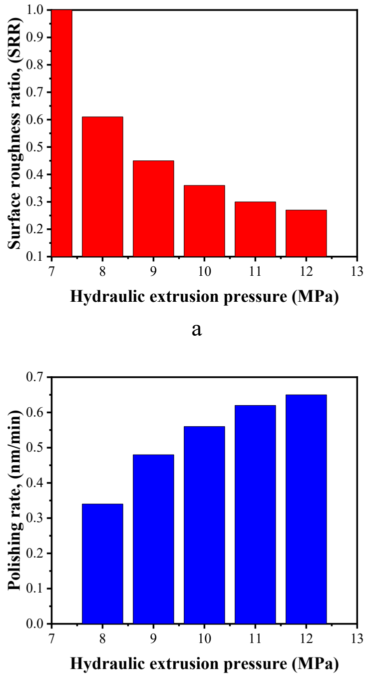


Figure. 2. Effect of hydraulic extrusion pressure on (a) surface roughness ratio (SRR) and (b) polishing rate (µm/min).

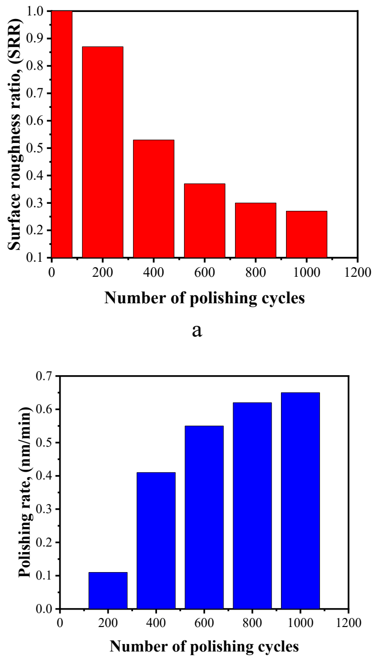
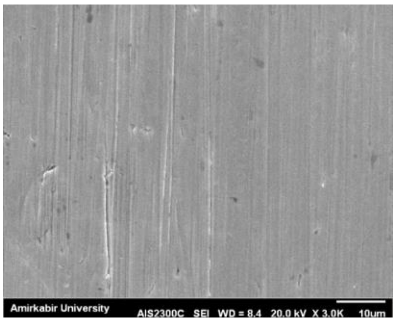
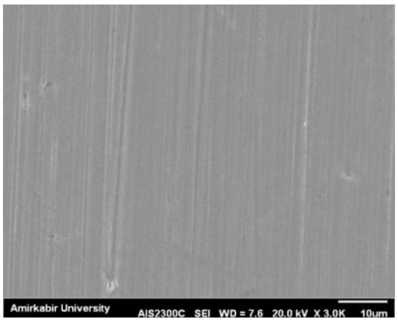


Figure. 3. Effect of number of polishing cycles on (a) surface roughness ratio (SRR) and (b) polishing rate (µm/min).

For a clearer understanding of the effect of polishing cycles, the surface morphology of the samples is examined in Fig. 4. As shown in Fig. 4-a, up to 200 cycles, no noticeable improvement in surface roughness is observed, and initial machining marks remain visible. This indicates weak interfacial bonding between the SBR matrix and the sisal fibers, leading to insufficient fiber penetration depth and ineffective removal of surface irregularities. Besides, during the initial cycles, energy is mainly dissipated through frictional phenomena and mechanical degradation (fibrillation), resulting in no significant change in surface roughness ratio or polishing rate. In contrast, at 1000 cycles (Fig. 4-b), surface irregularities are completely eliminated, yielding a uniform and polished surface. This improvement may be attributed to enhanced adhesion between composite components (SBR, naphthenic oil, and sisal fibers) due to chemical interactions. Stronger interfacial bonding restricts fiber movement and orientation, allowing them to function effectively as a soft abrasive (similar to a micro-brush). Consequently, at 1000 cycles, optimal surface modification is achieved, resulting in minimum surface roughness ratio and maximum polishing rate.



a



b

Figure. 4. SEM images of the polished surface morphology after (a) 200 and (b) 1000 polishing cycles.

4.Conclusions

The findings confirm the effectiveness and efficiency of the proposed sisal fiber-assisted polishing method for artificial femoral heads. Microscopic observations indicate that during the process, fibers undergo simultaneous mechanical degradation and structural refinement, transforming into fine macro- and micro-filaments that function as soft, uniform abrasives. This mechanism leads to the gradual and complete removal of surface irregularities and produces, within 2.5 hours, a mirror-like, uniform surface free of surface damage.

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