STATE OF THE ART OF SURFACE TEXTURING FOR BIOTRIBOLOGY APPLICATIONS

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Abstract: Surface texturing can be defined as a technique that consists of creating micro cavities in the surface of a material. There are different texturing techniques such as chemical etching, electromechanical micromachining, diamond embossing, electric discharge, pellet-pressing and laser surface, the last being the most common. For years, these surface texturing techniques have been used in tribological applications because microcavities can store oils or fluids and constantly lubricate the surfaces that are subjected to wear; they can also be used to trap wear particles (debris) that would otherwise act as abrasive particles (three body abrasive wear). This literature review seeks to analyse and compare the advantages that the use of surface texturing techniques can offer in reducing the wear of prosthetic components and therefore lengthening their useful life, to provide a better quality of life to patients. The results of this review showed a growing interest in the scientific community in the use of surface texturing for biotribological applications, using to a greater extent the Laser Surface Texturing (LST) technique and the surface pattern composed by dimples.

Key words: surface texturing, biomedical applications, prosthesis, lubrication, COF, cavities, tribology, wear.

1. INTRODUCTION

For years, efforts have been made to enhance the useful life of tools, pieces, and devices in different industries, and biomedicine is not the exception. The main problem of joint prostheses is their short useful life of approximately 15 years [1,2], after this period patients need to undergo to a revision surgery where one or more components of the implant must be replaced. In some cases, the revision surgeries are caused by the constant fatigue to which the prostheses are subjected, which can even cause a fracture of the implant; likewise, the wear of materials can also produce the deterioration of the implant components.

The constant friction between the components of the prosthesis tends to manifest in the form of wear particles, the size of these can vary, depending mainly on the constituent materials of the implant. With the use of a Scanning Electron Microscope (SEM) for the characterization of different implant samples, it has been shown that the average size of the wear particles is 0.5 μm ; furthermore, it is ensured that almost 90% of them are smaller than 1 μm . Like the size of the wear particles, the materials used for the manufacture of each prosthesis can vary, these two factors are very important to determine the type of response the tissues will produce; for example, titanium particles generally do not affect cell viability [3]. On the other hand, there is evidence that the wear particles of a Cobalt-Chromium (CoCr) alloy can cause hypersensitivity of the hip, due to the inflammation of the tissues adjacent to the prosthesis [4]. Over time, the use of the metal-on-metal friction couple has been reduced, since there is evidence that it tends to produce ions and particles that can cause diseases in the body [5,6]. The generation of metallic particles tends to be characterized by producing a very aggressive reaction; however, even though polyethylene debris generate a lower response than metallic particles, the contribution to the general biological response in vivo is usually greater than that of metallic particles, since the polymeric ones are produced to a greater extent [3]. In addition to this, the production of Ultra High Molecular Weight Polyethylene (UHMWPE) wear particles can cause implant loosening in the medium and long term, which translates into a surgical reintervention [7]. In some cases, the enhancement in useful life has been obtained with the development of new

materials; however, for biomedical applications the formulation of new materials is supervised by strict regulations, since both the chemical composition and the mechanical properties of the biomaterials must have certain specifications to avoid secondary effects. That is why the interest arises to extend the useful life of materials without altering their chemical composition. An effective alternative is the use of surface engineering techniques, such as Coatings, Thermochemical Treatments, or Surface Texturing. Surface Texturing is a technique that is defined as a selective material removal process, where micro or nano cavities are created on the surface of a material. There are different texturing techniques such as

Fig. 1. Schematic representation of the tribological effect of surface texturing: a) Storage of lubricant; b) Debris trapped inside the cavities

In some cases, the benefits of texturing have been used for biotribological applications with the aim of reducing wear between components of joint prostheses, where positive results have been obtained; an example of this is the work of Ito et al., where concave dimples (diameter of 0.5 mm, pitch of 1.2 mm, and depth of 0.1mm) were textured on the surface of a Co-Cr alloy femoral head using the electrical discharge etching technique. Wear tests were carried out using a hip joint simulator with a metal-on-polyethylene configuration, the results showed that dimples reduced COF and wear by 35% and 68%, respectively [13]. Another example is the work of Sawano et al., where CoCrMo alloy plates were textured with dimples using an abrasive waterjet and then tested using a pin-on-plate tribotester with UHMWPE pins to simulate a joint prosthesis. The results showed a wear reduction of 0.2 mg in UHMWPE when 1 μ m deep dimples were textured in the sliding surface of the CoCrMo plates. The reduction in wear is attributed to the fact that dimples acted as micro traps for the wear particles. With their findings, the authors suggest that the useful life of joint prostheses can be increased to approximately 33 years if the proposed micro-dimple in metal surfaces are used [2].

In this review, a comparison will be made of some of the most important surface texturing techniques used in biomedical applications, especially in those whose

sandblasting, ion beam texturing, etching technique, machining, and laser texturing, being the last one the most innovative in recent years [8,9].

Surface texturing has been used successfully in tribological applications where it is sought to reduce wear between sliding surfaces, since there is evidence that the cavities that are created with this technique can be used to store lubricant (Figure 1(a)) and keep the sliding surfaces constantly lubricated; furthermore, the cavities can also be used to trap wear particles (debris) that would otherwise produce third-body abrasive wear [9–12], as can be seen in Figure 1(b).

reduce the friction and wear on materials used for the manufacture of joint prostheses.

2. SURFACE TEXTURING TECHNIQUES

As can be seen in Figure 2, Surface Texturing research has risen in recent years, reaching up to 2400 publications in 2020, according to scientific search engine "sciencedirect.com" and keyword *surface texturing for biomedical applications*. A trend and a clear increase in the number of published works can be shown over the 15 years, which can be translated into an interest of the scientific community in exploring the effect that surface texturing has in biotribology applications.

Fig. 2. Number of publications with "surface texturing for biomedical applications" as search topic, according to Sciencedirect.com

As mentioned above, there are different surface texturing techniques, each with different advantages and disadvantages; likewise, different parameters can be manipulated in each one to produce the cavities, in this section some of the most popular techniques will be described.

The complexity of the surface texturing techniques can vary, there are investigations where different techniques are combined to obtain a texturing pattern, such as the work of Zhang et al., where samples of SS316 and UHMWPE were textured using combinations of lithography-electrolytic etching and lithography-moulding, respectively. In the case of the SS316, a photo-resist mask was manufactured according to a standard lithography process using a spin-coater, then the pattern was transferred to the surface of the sample using an electrolytic etching technique, finally a solvent was used to remove the photo-resist mask. On the other hand, for the UHMWPE texturing the photo-resist mask was coated on the surface of a copper mould according to a standard lithography process, then UHMWPE powder was emptied inside a hot-press mould with the copper mould and pressed with 48MPa at 200 °C for 90 min, the last step is the mould remotion after being cooled to room temperature [14].

Laser surface texturing (LST) is a technique used to modify the surface and, in some cases, the chemical composition of some materials. The operating principle of the LST is based on focusing a direct laser beam to the surface of a material, after the laser radiation is absorbed by the outermost layer, the optical energy from the laser produces an increase in the temperature of the material, reaching to reach vaporization temperatures and may even melt a portion of the surface. The modification of the chemical composition can occur when the photons of the laser beam have enough energy to break the chemical bonds of the material [15]. This highly adaptable technique uses a computer-controlled laser to generate cavities on the surface of a material, some of the parameters that can be manipulated for the generation of these cavities are the dimensions of the geometry, laser power, frequency,

pulse duration and scanning speed [16,17]. There is a variant of the LST, named Masked Laser Surface Texturing (MLST), where a mask is placed and fixed on top of the surface of the material to be textured, the mask acts as a filter preventing the passage of a portion of the laser beam on the sample, in order to draw the texturized patterns [18]. Figure 3 shows a schematic representation of the MLST operating principle.

Fig. 3. Schematic representation of MLST

There are different machining surface texturing techniques, for example, some authors such as Dong et al., use mechanical indenter machines (Rockwell roller indenter) for the fabrication of cavities [19], in other cases a micromachining centre is used for the machining texturing, like the work of Pratap, et al., where a Mikrottools DT-110 was used for micro-dimpled generation in Ti6Al4V samples. In this investigation different machining tools were used to obtain different geometries such as micro flat-end mill, micro ball-end mill, and micro drill. The spindle speed and feed were set to 60000 rpm and 120 mm/min, respectively, to minimize the cutting forces exerted in the surface of the material where the dimples were generated [20]. In some cases, a diamond drill bit is used in order to reduce the possibility of forming wear debris in the micromachining process [21]. It is important to mention that if a strict control in the manipulation of the machining input parameters to generate texturing cavities is obtained, it is possible to even machine ceramic samples, proof of this is the investigation of Roy, et al., where a CNC micro machine (Mikrottools DT110) with a solid carbide drill bit (400 µm diameter) was used to fabricate micro-dimples in Al₂O₃ samples, the spindle speed and feed rate were maintained at 55,000 rpm and 334 mm/min, respectively [22]. Table 1 shows a comparison of the input parameters of LST and Machining Surface Texturing used in different biotribology publications.

Table 1. Surface texturing techniques and parameters

Texturing technique	Textured material	Wavelength [nm]	Power [W]	Scanning speed [mm/s]	Frequency [Hz]	Pulse duration [ns]	Spindle speed [rpm]	Feed rate [mm/min]	Ref.
LST	Al ₂ O ₃ /TiC	1064	16.2	5	6000	10	NA	NA	[23]
LST	Al ₂ O ₃ /TiC	1064	-	5	6000	10	NA	NA	[24]
LST	CoCr	1064	6000	2	4.5	7e+6	NA	NA	[16]
LST	CoCrMo	532	0.05	-	100000	0.01	NA	NA	[12]
LST	CoCrMo	1064	20	50-200	3000-5500	-	NA	NA	[25]
LST	PEEK	1064	10	5	10000	4	NA	NA	[26]
LST	PEEK	1030	0.22	-	50000	4e-4	NA	NA	[27]
LST	Ti6Al4V	1064	1.2	400	20000	35	NA	NA	[28]
LST	Ti6Al4V	610	70	0.5-10	60	-	NA	NA	[29]
LST	Ti6Al4V	1064	-	5	2000	20	NA	NA	[30]
LST	Ti6Al4V	1064	10	5	10000	-	NA	NA	[8,31]
LST	Ti6Al4V	-	21	1	5000	-	NA	NA	[32]

LST	Ti6Al4V	193	-	-	200	5	NA	NA	[10]
LST	Ti6Al4V	1060	9.1	-	100000	26	NA	NA	[33]
LST	Ti6Al4V	355	5	500-1500	30000	-	NA	NA	[34]
LST	Ti6Al4V	1064	10	5	10000	-	NA	NA	[35]
LST	Ti6Al4V	800	0.1	1	1000	3.5e-5	NA	NA	[36]
LST	Ti6Al4V	1064	-	-	-	450	NA	NA	[37]
LST	Ti6Al4V	1064	-	1.2	10000	0.01	NA	NA	[38]
LST	UHMWPE	1024	-	25-40	20e+6-30e+6	-	NA	NA	[39]
MLST	Ti6Al4V	1064	-	20	-	10	NA	NA	[40]
Machining	Al ₂ O ₃	NA	NA	NA	NA	NA	55000	334	[22,41]
Machining	Ti6Al4V	NA	NA	NA	NA	NA	60000	120	[20,42]

3. GEOMETRIES OF SURFACE TEXTURING

Just as there are different texturing techniques, there are also different geometries that can be implemented to generate texturing patterns. Some commonly used geometries are dimples, triangles, squares, diamonds; in other cases, linear grooves, wavy grooves, crosshatch are also used. In Figure 4, an illustration of some of the most common texturing patterns used is presented.

Figure 5 shows a pie chart where the most used texturing patterns in the publications consulted in this review are illustrated. There is a clear trend in the use of Dimples, Crosshatch and Lines with 51%, 16% and 14%, respectively. The preference for the use of dimples can be attributed to the fact that it is a relatively easy geometry to texturize, in addition to this, dimple textures have proven to be effective in tribological applications, reaching COF reductions of up to 80% compared to non-textured sliding surfaces [8].

Fig. 4. Surface texturing patterns. a) Dimple; b) Triangle; c) Square; d) Diamond; e) Wavy groove; f) Linear groove; g) Diamond crosshatch; h) and i) Square crosshatch

Fig. 5. Surface texturing patterns pie chart

Some of the most important characteristics of the geometries are the texture density, which can be defined as the portion of the surface that the cavities

occupy, some authors affirm that the optimum density for tribology applications is 16% [17].

Table 2. Surface texturing geometries

Geometry	Textured material	Bearing	Density (%)	Cavity length (μm)	Cavity depth (μm)	Distance between cavities (μm)	COF reduction (%) *	Ref.
Crosshatch	UHMWPE	Ceramic	43.4-51	500-600	110-120	650-850	53.47	[39]
Crosshatch	UHMWPE	Si ₃ N ₄	-	-	1	-	40	[43]
Crosshatch	Ti6Al4V	Bovine bone	-	40-140	15.2-49	0-100	-83.33	[28]
Crosshatch	Ti6Al4V	UHMWPE	9.75-10.38	50-200	10	853-2458	13.51	[36]
Cross groove	Ti6Al4V	Ti6Al4V	18-64	43	4.5	171-378	79.56	[38]
Diamond, Dimple	CoCrMo	UHMWPE	37-58	55-190	1.5-9.5	80-500	45	[19]
Dimple	Al ₂ O ₃	Al ₂ O ₃	5.84-9.78	400	20	1500-2000	15.15	[22]
Dimple	Al ₂ O ₃	Al ₂ O ₃	15	300-400	30	400-1800	23.03	[41]
Dimple	CCM+	CCM+	-	80-100	6-10	250	4.28	[44]
Dimple, Line, Net, Surf	CoCr	Al ₂ O ₃	9.86-100	450	40.8-235.9	1000-1300	40	[16]
Dimple, triangle, square	CoCrMo	Ti6Al4V	-	50-150	8-16	100-300	20.51	[25]
Dimple	PEEK	SS316L	15-30	300	100	-	3.22	[26]
Dimple	PEEK	Al ₂ O ₃	10-48	30	2-21	79-156	27.58	[27]
Dimple	SS316	UHMWPE	5-40	50	15	-	66.66	[14]
Dimple	Ti6Al4V	Zirconium	6.5-42.6	186-267	3-6.2	120-600	27.05	[29]
Dimple	Ti6Al4V	GCr15 steel	-	70	50	200	41.39	[30]
Dimple	Ti6Al4V	AISI 52100	28-44	45-300	25	100	79.82	[8]
Dimple	Ti6Al4V	AISI 52100	13-44	150	40	-	64.46	[31]
Dimple	Ti6Al4V	GCr15 steel	-	450	13	-	36.61	[40]
Dimple	Ti6Al4V	AISI 52100	44	36	25	52	15.73	[35]
Dimple	Ti6Al4V	GCr15 steel	21.20	260	-	500	-8.96	[37]
Dimple	Ti6Al4V	Ti6Al4V	16.20	410	30	950	31.89	[21]
Dimple	Ti6Al4V	Ti6Al4V	-	122.66-410	19.61-30	298.76-950	22.41	[20]
Dimple, Linear	Ti6Al4V	AISI E-52100 steel	-	25-60	-	20	54.13	[10]
Linear groove	Al ₂ O ₃	AISI 1045 steel	-	40-50	40-50	150-250	78.08	[24]
Linear groove, Wavy groove	Al ₂ O ₃ /TiC	AISI 1045 steel	-	40-50	40-50	100-250	-5.16	[23]
Linear channel	Ti6Al4V	100 Cr6 steel	-	30	10	-	23.07	[33]
Microgroove	Ti6Al4V	Si ₃ N ₄	-	25-65	10.4-12.3	100	71.15	[34]
Parallel micro-dimpled, Staged micro-dimpled, Micro grid	Ti6Al4V	Ti6Al4V	-	87-142	20-30	200	34.44	[42]
Petaloid	CoCrMo	CoCrMo	44.1	90	5	150	30.04	[12]
Square	Ti6Al4V	-	72-81	30-150	71.15-87.15	-	81.39	[32]

* In some publications wear tests were carried out with different geometries or varying the characteristics of the cavities, the COF difference presented is the one obtained from the best performer of each investigation.

Other characteristics that are commonly modified are the length and depth of the cavities, since as mentioned previously the cavities can be used to store lubricant and debris. Table 2 presents a comparison of different geometries, specifying their characteristics (density, length, depth) and the difference in COF obtained when using these patterns in different tribology tests (pin on disc, ball on disc, ring on disc, etc.) in comparison to non-textured surfaces.

4. DISCUSSION

In general, the use of mesh-shaped texturing patterns has proven to have favourable results in tribological

tests, different works where UHMWPE and Ti6Al4V samples were textured with crosshatch patterns and subjected to wear against sliding surfaces (UHMWPE, Ti6Al4V, Si₃N₄) obtained COF reductions in the range of 13-80% [36,38,39,43]. On the other hand, in the work of Tiainen et al., crosshatch arrays were textured on Ti6Al4V samples and then tribological tested against bovine bone plates. The results were not as expected, since an increase in COF was observed in the textured samples compared to grit-blasted surfaces. The authors attribute this phenomenon to the fact that the bone debris adhered to the Ti6Al4V surface creating a layer, so the COF was not measured between the

bone and the metallic surface but between compacted bone and bone bulk [28].

The use of ceramic materials for the manufacture of joint prostheses has been of great importance in recent years, since it has been shown that prostheses composed of a ceramic-on-ceramic friction pair present a considerably lower wear rate, compared to prostheses with metal-on-metal, metal-on-polymer and ceramic-on-polymer bearings [45]. With the implementation of surface texturing, the wear rate of ceramic-on-ceramic bearings can be further reduced, as in Roy et al., investigations, where Al_2O_3 discs were textured with dimple arrays, then pin-on-disc tests were carried out using Al_2O_3 pins. A 15% COF reduction was achieved using a micro-dimple array with density of 9.78%, diameter and dept of 400 μm and 20 μm , respectively [22]. On the other hand, when the dimple array had a density of 15% (400 μm diameter and 20 μm depth), the COF difference raised up to 23% [41]. In both cases, the textured samples were compared to untextured Al_2O_3 discs with the same testing conditions. Similarly, in the work by Xing et al., $\text{Al}_2\text{O}_3/\text{TiC}$ samples with linear grooves were textured, with length and depth of 40-50 μm and then a WS_2/Zr coating was added. The samples were subjected to ball on disc tests using AISI 1045 steel ball as bearing, in the results a COF reduction of 78% was reached [24].

As mentioned above, the use of dimples as texturing patterns is widely used with the aim of reducing wear in biotribology applications. These circles can be fabricated using different texturing techniques varying the characteristics of the cavities, obtaining positive results as in the investigations of Zhang et al., and Hu et al., where dimpled textured SS316 (diameter 50 μm and depth 15 μm) and Ti6Al4V (diameter 150 μm and depth 40 μm) samples were subjected to wear testing, obtaining COF reductions of approximately 65% [14,31]. In contrast, there are publications where the use of dimples is not favourable, even obtaining a COF difference of $\sim -9\%$, when Ti6Al4V samples were textured with dimple arrays with 260 μm diameter [37]. The greatest difference between the works where a COF reduction was obtained and the one where the COF difference increased is the contact pressure that was applied in the tribological tests, since in those that had a positive difference, pressure ranges of 0.05 - 0.239 MPa were used., while in the work of Qin et al., a pressure of approximately 984 MPa was applied.

5. CONCLUSIONS

A review of the literature related to the use of surface texturing to reduce the wear of materials used for the manufacture of joint prostheses was carried out,

emphasizing the impact that different texturing techniques, characteristics of cavities, and texturing patterns geometries had in the COF reduction in tribological tests. The number of publications related to the use of surface texturing for biomedical applications has increased considerably in the last 15 years, so it can be assumed that the scientific community has a rising interest in studying the effects that these selective material removal techniques have on the tribological behaviour of the friction pairs that make up joint prostheses.

After analysing different publications in this review, it can be concluded that LST is the most widely used technique in research that seeks to reduce wear in biotribology applications through surface texturing techniques. One of the main advantages of using LST is its adaptability, different geometries such as dimples, squares, triangles, grooves, and crosshatch can be fabricated. It is important to mention that if strict control of the input parameters of surface texturing is achieved, patterns with very complex geometries can be obtained, as in the work of Zhang et al., where CoCrMo samples were textured with petaloid geometries, it should be emphasized that in addition to using a complex pattern, a 30% COF reduction was obtained in tribological tests, when compared to untextured CoCrMo samples [12]. Different texturing patterns such as linear grooves, squares and crosshatch have been used obtaining COF reductions of $\sim 80\%$ [24,32,38]; however, there is a marked preference in the use of dimples, which can be attributed to their easy manufacture and favourable results in tribological tests.

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