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Effect of CoCr counterface roughness on the wear of UHMWPE in the non-cyclic RandomPOD simulation

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Abstract

With the RandomPOD wear test system, conventional and highly crosslinked ultrahigh molecular weight polyethylenes (UHMWPE) were run against CoCr counterfaces with different surface roughnesses. The unique 16-station, computer-controlled pin-on-disk device produced non-cyclic motion and load. With appropriate specimen shapes, simulations of wear mechanisms of both hip and knee prostheses were performed. Against polished counterfaces, the crosslinked UHMWPE showed negligible wear. Its wear against severely roughened counterfaces was close to that of conventional UHMWPE against polished counterfaces. The reduction in wear with crosslinked vs. conventional UHMWPE was 80 to 86 per cent in the hip, and 87 to 96 per cent in the knee wear simulation. The wear particles were of clinically relevant size and shape which indicated realistic wear mechanisms.

Keywords: non-cyclic, randomness, abrasive wear, crosslinked UHMWPE

1 Introduction

It was shown in earlier RandomPOD (random motion and load pin-on-disk) studies that valid simulations of wear mechanisms of both the prosthetic hip and the prosthetic knee can be performed with the same motion and load input provided that the shapes of the specimens are designed appropriately [1–4]. The design principle of the RandomPOD was such that certain limits were set for the range of motion, velocity, acceleration and its derivative, and for the rate of change of the load so that instead of producing different activities sequentially, all biomechanically and tribologically relevant activities are produced at once. Within these limits, the motion and load are random (non-cyclic) so that the relative position of the pin and the disk and the magnitude of the load at a certain point of time cannot be predicted computationally. This took the design philosophy of tribosimulators to a new level which was made possible by advanced mechatronics. Many daily activities are not repetitious. Therefore it may be considered that tribosimulators with fixed motion and load inputs are presently reaching their end point of progress. In full-scale joint simulators however, randomness has not yet been incorporated.

The flat-on-flat and ball-on-flat test configurations (Fig. 1) were found to be suitable for the simulation of the wear mechanisms of ultra-high molecular weight polyethylene (UHMWPE) as used for the bearing surfaces of the total hip and the total knee prostheses, respectively [1–4]. The non-cyclic characteristics of the motion input signals that resulted in increased multidirectionality of the biaxial relative motion was shown to influence the wear behavior. Although the average sliding velocity in the RandomPOD, 15.5 mm/s, is relatively low, the cumulative change of the direction of sliding is high, 500°/s on the average. The wear factors were significantly higher compared with those obtained with cyclic input, while the wear mechanisms were largely similar [2,3,5]. The multidirectionality of the relative motion is known to be of fundamental importance with respect to the UHMWPE wear [6]. All earlier

RandomPOD tests were run with conventional UHMWPE sliding against polished CoCr counterfaces. The polished CoCr femoral bearing surfaces may roughen in vivo by abrasive metallic, ceramic, bone or bone cement particles, or by dislocation, which is likely to result in increased wear of the UHMWPE acetabular and tibial components [7–10]. Crosslinking of UHMWPE by high-dose irradiation and elimination of concomitant free radicals by various methods, including thermal treatments, has been shown to increase the clinical wear resistance significantly [11,12]. However, not only conventional but also crosslinked UHMWPEs may show substantial wear against rough counterfaces [13–18]. The principal motivation for the present study was to learn how roughening affects the wear of conventional and highly crosslinked UHMWPEs in the non-cyclic hip and knee wear simulation in comparison with earlier cyclic wear studies.

2 Materials and methods

The computer-controlled, 16-station RandomPOD wear test system, the test procedure and the test specimens for hip and knee wear simulation have been described elsewhere [1–4]. Briefly, the relative x-y-motion, implemented servo-electrically, and the z-axis load, implemented proportional-pneumatically, were non-cyclic. They were programmed so that the range of motion was a circle of 10 mm diameter, the average cumulative change of direction of sliding was 500°/s, the average sliding speed was 15.5 mm/s (range 0 to 31 mm/s), and the average load was 73 N (range 0 to 142 N).

The CoCr (ISO 5832-12) flat disks of 28 mm diameter and pins with a spherical bearing surface with a radius of 28 mm and a diameter of 9 mm were roughened manually by multidirectional abrasion with emery papers of 1000, 400, 240 and 120 grit sizes (Figs. 2 and 3) to represent the roughening observed in retrieved femoral components [7–10]. The relative motion of the specimen relative to the emery paper was circular translation in order to produce criss-cross scratching with no specific orientation. The roughness was measured with a Bruker white light interferometry profilometer. The scanned area was 1 mm^2 and three locations were measured on each specimen. The arithmetical mean surface roughness S_a varied from 0.07 µm to 0.89 µm, maximum peak height S_p from 0.7 µm to 5.3 µm, skewness S_{sk} from -1.1 to 0.03, and core roughness depth S_k from 0.2 µm to 2.5 µm (Tables 1 and 2). Because the flat and spherical forms required different roughening techniques, the resulting roughness values of the disks differed somewhat from those of the pins. Two types of UHMWPE were studied, conventional (GUR 1020, ISO 5834-1/-2, packed and 25 kGy gamma-sterilized in nitrogen) and highly crosslinked (GUR 1050, 95 kGy electron beam irradiated, after which thermally treated at 150 °C). They represented fresh material, i.e., they were neither shelf nor artificially aged. Both the hip wear simulations (flat-on-flat, 8 test stations) [1,2], and the knee wear simulations (ball-on-flat, 8 test stations) [3] were performed simultaneously.

Three similar, consecutive 18-day tests were run, and so the total number of UHMWPE specimens tested was 48. The wear was measured gravimetrically every six days. The sliding distance between the measurement points was 8 km on the average, and the integral of the product of instantaneous load and incremental sliding distance over this time period was 595 000 Nm on the average. The wear rate was evaluated from the three measurement points by linear regression. The wear factor k (mm^3/Nm) was calculated so that the wear rate (mg/km) was multiplied by the sliding distance between the first and the third measurement points (16 km) and divided by the density of UHMWPE (0.94 mg/mm^3) and by the above-mentioned integral between the first and the third measurement points (1.2×10^6 Nm). The first 8 km of the test was considered running-in. The roughenings of the CoCr specimens were redone for tests 2 and 3. In addition, crosslinked UHMWPE was run against polished counterfaces ($S_a = 0.01$ µm) for 18 days (1.8×10^6 Nm).

The lubricant was HyClone Alpha Calf serum SH30212.03 diluted 1:1 with Milli-Q grade ultrapure, deionized water. Its protein concentration was 20 mg/ml. No additives were used. To retard the degradation of the lubricant its temperature was kept at 20.0 ± 0.5 °C with circulating cooling water that surrounded the test chambers. Used serum samples were digested, and UHMWPE wear particles were isolated on polycarbonate membrane filters of 0.05 µm pore size and analyzed with a field emission scanning electron microscope (JEOL 6335 F FE-SEM) as described elsewhere [4,16,19].

3 Results

Crosslinked UHMWPE showed superior wear resistance (Fig. 4). Different relationships between k and S_a were found, that is, linear, exponential, and power, depending on the type of wear simulation and UHMWPE. The equations shown in Fig. 4 resulted in the highest correlation coefficient R^2 values. Since crosslinked UHMWPE did not show measurable wear against polished counterfaces, a k value of 6×10^{-9} mm^3/Nm was used for it in Fig. 4 (after a wear test of 1.8×10^6 Nm, wear could not be distinguished using a balance with a resolution of 0.01 mg, hence the highest possible k was taken to be 0.01 mg/(0.94 $mg/mm^3 \times 1.8 \times 10^6$ Nm) = 6×10^{-9} mm^3/Nm). The k values for conventional UHMWPE against polished counterfaces in Fig. 4 were taken from previous RandomPOD studies [2,3], as the material and the test conditions were the same, with the exception of the counterface roughness. High variation of wear was observed especially against the roughest counterfaces (Tables 1 and 2).

With increasing counterface roughness, the appearance of the worn UHMWPE surfaces gradually changed from burnished to mat. The surface topography showed no orientation due to the non-cyclic relative motion (Fig. 5). No pitting, delamination or cracking was observed. All specimens behaved in a ductile manner.

Against moderately roughened counterfaces, both the conventional and crosslinked UHMWPE generated a mean wear particle size of 0.3 to 0.4 µm in both the hip and knee wear simulation (Fig. 6). Conventional UHMWPE wear particle size increased with increasing counterface roughness in both the hip and knee simulation. From the agglomerations of strips of several µm length, individual particles were difficult to distinguish. Crosslinked UHMWPE particle size on the other hand decreased with increasing counterface roughness to a level of 0.2 µm in the knee wear simulation, whereas in the hip wear simulation the mean size remained unchanged.

4 Discussion

Simulations of wear mechanisms of total hip and knee prostheses were simultaneously performed for two types of UHMWPE and with four different roughnesses of the flat and spherical CoCr counterfaces using the unique 16-station, non-cyclic RandomPOD wear test system. The wear factors of crosslinked UHMWPE against the roughest counterfaces were of the same order of magnitude as the wear factors of conventional UHMWPE against the polished counterfaces, or lower. This observation is in agreement with an earlier cyclic pin-on-disk study that was restricted to hip wear [16]. The size and shape of the wear particles, which are important from the point of view of adverse clinical reactions [20], were also close to those analyzed earlier [4,16,19] and in agreement with clinical findings [21]. The wear factor of crosslinked UHMWPE was 80 to 86 per cent lower than that of conventional UHMWPE in the hip wear simulation, and 87 to 96 per cent lower in the knee wear simulation. These percentages are close to those observed in cyclic hip and knee joint simulator studies using actual prosthetic components [14,17,18].

In earlier tests with the circularly translating pin-on-disk (CTPOD) device, which utilizes the same flat-on-flat specimen geometry for the hip wear simulation as the RandomPOD, power relationships between k and R_a were found for conventional and crosslinked UHMWPE [16]. In the present study, power relationships were found for crosslinked UHMWPE, whereas conventional UHMWPE showed either linear (hip) or exponential (knee) relationships. In the CTPOD hip wear simulation [16], the wear factor was proportional to R_a raised to the power of 2.49, whereas in the present RandomPOD hip wear simulation the exponent was 1.38. The dependence was not necessarily weaker in the present study as indicated by the lower exponent. The contact stylus instruments such as that used earlier in R_a (two-dimensional) measurements [16] are known to produce systematically lower values compared with the S_a (three-dimensional) measurements obtained by non-contact methods such as the white light interferometry profilometer used in the present study [7]. With crosslinked UHMWPE, the exponent in the present knee wear simulation was equal to that in the hip wear simulation, but the constant term was lower. Hence the knee wear factor of crosslinked UHMWPE was lower than its hip wear factor over the range of S_a values studied. The knee wear factor of conventional UHMWPE clearly exceeded its hip wear factor with the roughest counterfaces. When a power relationship was applied to the hip wear simulation of conventional UHMWPE, the exponent was 0.30 ($R^2 = 0.87$), whereas in the CTPOD study it was 0.91. The reason for the difference is likely to be similar to that observed with the crosslinked UHMWPE. Interestingly, the wear factor values of both types of UHMWPE in the RandomPOD hip wear simulation against the roughest counterfaces were close to those obtained earlier by the cyclic CTPOD device [16]. Against polished counterfaces, the wear factors produced by the RandomPOD for conventional UHMWPE were significantly higher [2,3]. In hip joint simulator studies, linear relationships between k and R_a were observed for conventional UHMWPE [9,13], which is in agreement with the finding of the present study.

The wear factor of conventional UHMWPE ranged from 3.41 to 26.9 × 10^{-6} mm^3/Nm in the hip wear simulation (Table 1) and from 2.06 to 66.1 × 10^{-6} mm^3/Nm in the knee wear simulation (Table 2). In earlier RandomPOD tests against polished CoCr counterfaces, the wear factor of conventional UHMWPE was 3.92 ± 0.26 × 10^{-6} mm^3/Nm (n = 16) in the hip wear simulation [2] and 2.04 ± 0.06 × 10^{-6} mm^3/Nm (n = 16) in the knee wear simulation [3]. Compared with these low standard deviations that were 6.6 % and 2.9 % of the mean values, respectively, both the conventional and crosslinked UHMWPE showed high variation of wear against roughened counterfaces (Tables 1 and 2). The high variation was likely to be attributable to the variation of the peak height S_p of the roughened CoCr surfaces which proved to be difficult to reduce especially for the pins with the spherical (radius = 28 mm) bearing surface of only 9 mm diameter. The hard CoCr peaks ploughed the soft UHMWPE vehemently and their height undoubtedly had a strong influence on the rate of material removal by the abrasive wear mechanism. The S_p values were nevertheless close to those obtained from retrieved, roughened CoCr femoral components, 1.9 to 10 µm [8].

While the conventional gamma-inert-sterilized UHMWPE that was studied is the most widely used bearing material in arthroplasty, it should be noted that the present crosslinked UHMWPE that showed excellent wear resistance represents only one of the many different types of commercial highly crosslinked UHMWPEs, between which large differences in wear behavior may exist [22]. There are indications that any type of UHMWPE that has been irradiated, including the two studied in the present paper, may show oxidation in vivo, which is known to be detrimental for the strength and the wear resistance [23]. Therefore the fact that only fresh UHMWPE specimens were tested may be considered a limitation of the study. However, it was shown in an earlier paper that the contemporary methods of artificial, accelerated aging [24], i.e., oxygen bomb and air convection oven aging, do not lead to the clinically relevant type of oxidation manifested as subsurface embrittlement and delamination wear (in subsequent knee wear tests) that are known to take place in vivo [25]. The paper dealt with conventional gamma-air-sterilized UHMWPE that is specifically susceptible to oxidation [26]. Hence, there is little reason to assume that accelerated aging by contemporary methods of other types of UHMWPE would simulate their in vivo oxidation in a realistic way from the point of view of their wear resistance. Another limitation naturally was that a pin-on-disk simplification was used instead of testing real prosthetic components with hip and knee joint simulators.

5 Conclusions

In the non-cyclic RandomPOD hip and knee wear simulation, highly crosslinked UHMWPE showed negligible wear against polished counterfaces, and it was less vulnerable to the roughening of the counterface than conventional UHMWPE. The reduction in wear achieved with crosslinked vs. conventional UHMWPE was 80 to 86 per cent in the hip, and 87 to 96 per cent in the knee wear simulation. The wear factors of crosslinked UHMWPE against the roughest counterfaces were of the same order of magnitude as the wear factors of conventional UHMWPE against the polished counterfaces. Especially the similarity of the wear particle size and shape of the present study to clinical wear particles indicated that the wear mechanisms were realistic. For the first time a pin-on-disk device simultaneously produced hip and knee wear simulations using the same motion and load input.

Acknowledgements

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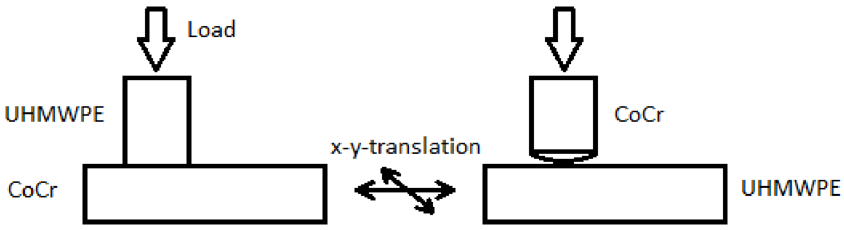
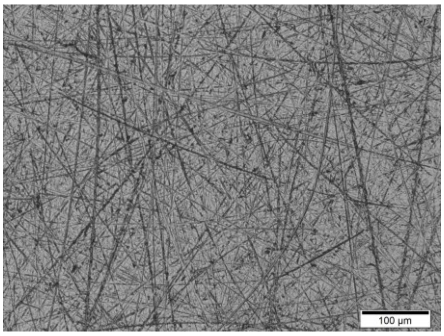
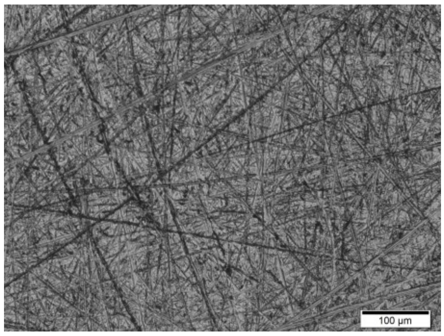


Figure 1. Schematic of pin-on-disk test configurations, (left) flat-on-flat hip wear simulation, (right) ball-on-flat knee wear simulation.



(a)



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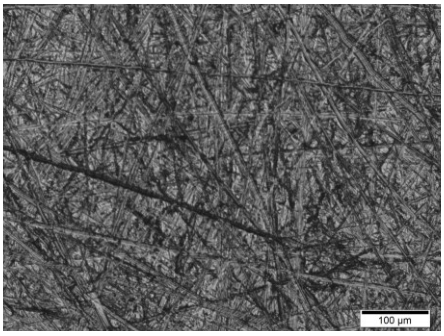

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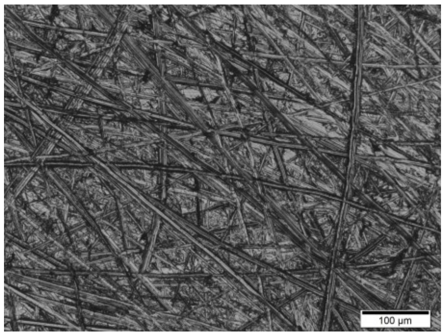

(d)

Figure 2. Optical micrographs from center of spherical (radius = 28 mm) bearing surfaces of CoCr pins for abrasive knee wear tests. Pins have been roughened so that their mean S_a values are (a) 0.21 µm, (b) 0.30 µm, (c) 0.42 µm, and (d) 0.67 µm.

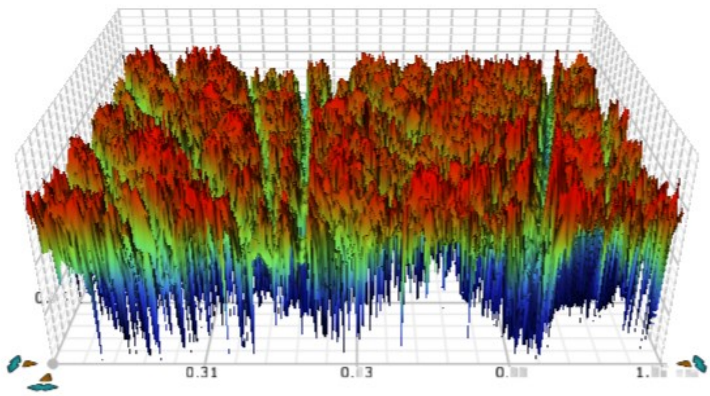

Figure 3. White light interferometry scan of the roughests disk with surface roughness S_a = 0.92 µm, S_p = 4.4 µm, S_{sk} = -1.1, and S_k = 2.6 µm.

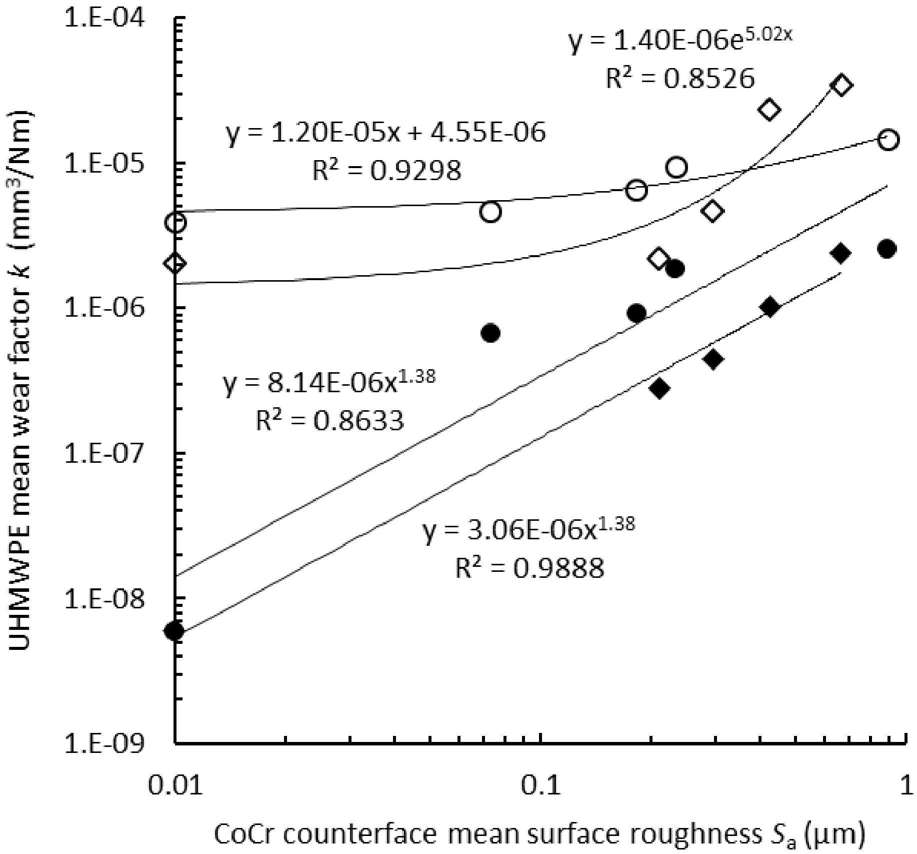

Figure 4. Variation of UHMWPE wear factor k with counterface surface roughness S_a and best-fit equations. Open symbols represent conventional UHMWPE, filled symbols crosslinked UHMWPE. Circles represent hip wear simulation, diamonds knee wear simulation.

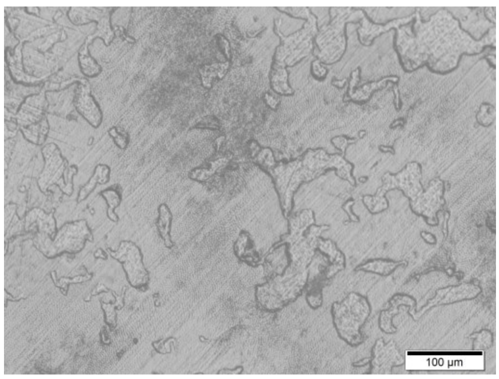

Figure 5. Optical micrograph from conventional UHMWPE disk worn against spherical CoCr pin with surface roughness S_a value of 0.21 µm in knee wear simulation. Lumps of rolled wear debris show no orientation due to non-cyclic relative motion.

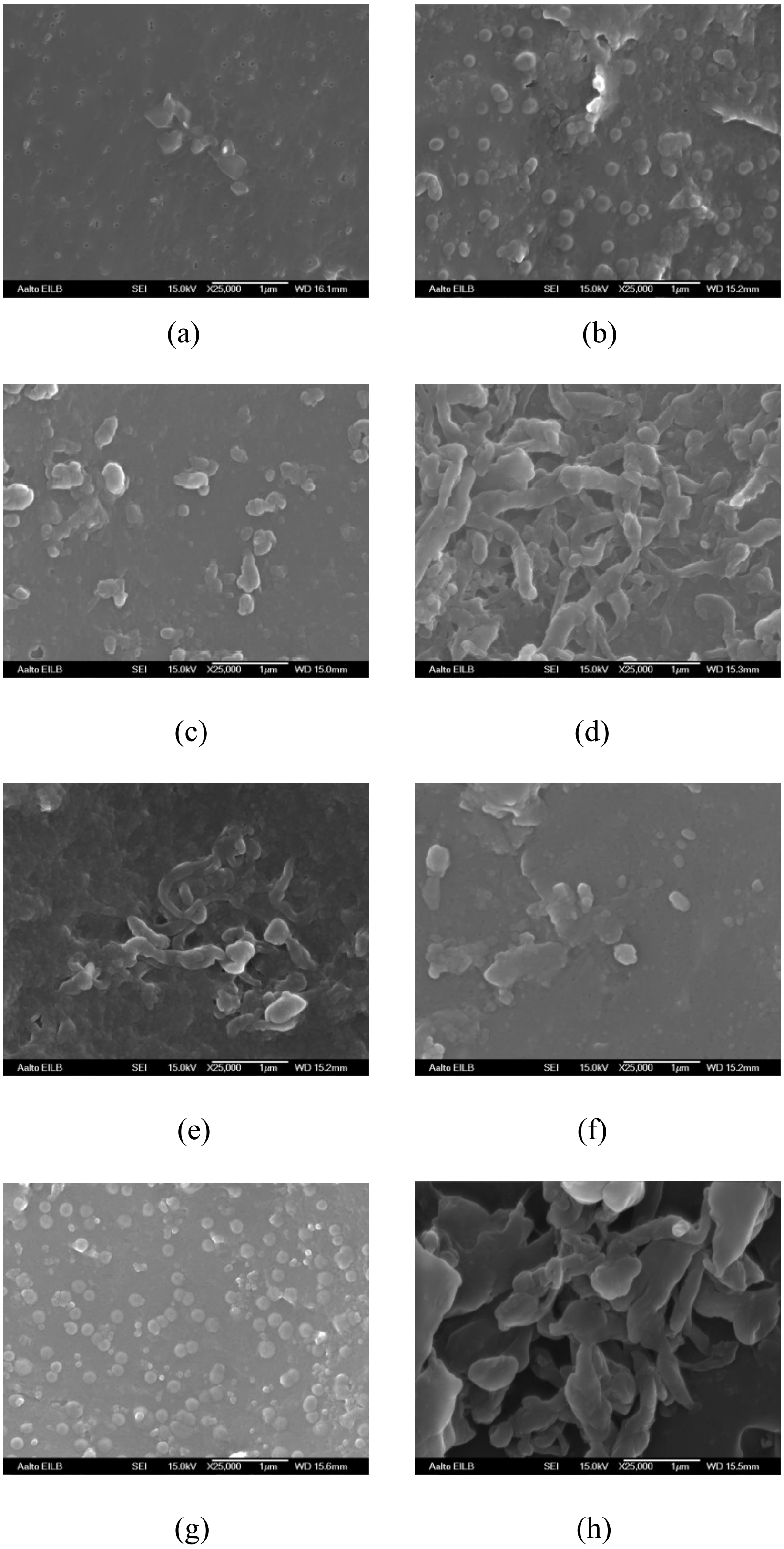

Figure 6. Scanning electron micrographs of UHMWPE wear particles, (a) crosslinked UHMWPE, hip wear simulation, counterface surface roughness S_a = 0.07 µm, (b) conventional, hip, S_a = 0.07 µm, (c) crosslinked, hip, S_a = 0.89 µm, (d) conventional, hip, S_a = 0.89 µm, (e) crosslinked, knee, S_a = 0.21 µm, (f) conventional, knee, S_a = 0.21 µm, (g) crosslinked, knee, S_a = 0.67 µm, (h) conventional, knee, S_a = 0.67 µm.

Table 1. Surface roughness values of roughened CoCr disks and wear factors of UHMWPE pins (minimum, median, and maximum) in hip wear simulation.

CoCr disk surface roughness				UHMWPE pin wear factor (10^{-6} mm^3/Nm)					
S_a (µm)	S_p (µm)	S_{sk}	S_k (µm)	Conventional			Crosslinked		
				min.	med.	max.	min.	med.	max.
0.073 ± 0.002	0.704 ± 0.134	0.025 ± 0.166	0.217 ± 0.005	3.41	3.69	6.96	0.61	0.67	0.75
0.183 ± 0.004	1.247 ± 0.111	-0.287 ± 0.041	0.553 ± 0.014	5.48	6.09	8.37	0.23	0.50	2.06
0.234 ± 0.018	1.575 ± 0.068	-0.354 ± 0.023	0.722 ± 0.064	8.13	9.77	10.2	1.51	1.89	2.28
0.888 ± 0.061	4.061 ± 0.325	-1.094 ± 0.018	2.512 ± 0.066	7.10	10.2	26.9	1.42	2.24	3.97

Table 2. Surface roughness values of roughened CoCr pins and wear factors of UHMWPE disks in knee wear simulation.

CoCr pin surface roughness				UHMWPE disk wear factor (10^{-6} mm^3/Nm)					
S_a (µm)	S_p (µm)	S_{sk}	S_k (µm)	Conventional			Crosslinked		
				min.	med.	max.	min.	med.	max.
0.211 ± 0.021	1.651 ± 0.827	-0.278 ± 0.163	0.637 ± 0.071	2.06	2.06	2.47	0.18	0.23	0.42
0.295 ± 0.020	2.250 ± 1.214	-0.616 ± 0.257	0.920 ± 0.035	3.06	4.02	7.05	0.31	0.48	0.56
0.423 ± 0.018	2.485 ± 0.601	-0.634 ± 0.094	1.322 ± 0.054	5.22	26.2	38.5	0.67	1.05	1.34
0.665 ± 0.058	5.304 ± 1.702	-0.585 ± 0.154	2.058 ± 0.087	16.3	21.9	66.1	0.80	0.92	5.41