Effect of counterface roughness on the wear of conventional and crosslinked ultrahigh molecular weight polyethylene studied with a multi-directional motion pin-on-disk device

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Abstract: The effect of counterface roughness on the wear of conventional γ-sterilized, and electron-beam-crosslinked ultrahigh molecular weight polyethylene was studied with a circularly translating pin-on-disk device. The counterfaces, CoCr disks, were either polished, or roughened so that they represented the type of roughening and the range of surface roughness values (R_a = 0.014–0.24 μm) observed in explanted femoral heads of total hip prostheses. The lubricant was diluted calf serum, and the test length 3 million cycles. A total of 24 tests were done. With both types of polyethylene, there was a strong correlation between R_a and wear factor k. The power equations were $k = 5.87 \times 10^{-5}(R_a)^{0.91}$ for conventional polyethylene (R^2 = 0.94), and $k = 7.87 \times 10^{-5}(R_a)^{2.49}$ for crosslinked polyethylene (R^2 = 0.82). Crosslinking improved wear resistance significantly. The wear of crosslinked polyethylene against the roughest counterfaces was lower than the wear of conventional polyethylene against the polished counterfaces. Against rough counterfaces, the wear of crosslinked polyethylene was an order of magnitude lower than that of conventional polyethylene. On the crosslinked polyethylene pins that were tested against polished counterfaces, remains of original machining marks were still visible after the test. The average size of wear particles produced by both types of polyethylene against rough counterfaces was similar, 0.4 μm, whereas that produced by conventional and crosslinked polyethylene against polished counterfaces was significantly smaller, 0.2 and 0.1 μm, respectively. © 2001 John Wiley & Sons, Inc. J Biomed Mater Res 57: 506–512, 2001

Key words: wear; surface roughness; crosslinking; ultrahigh molecular weight polyethylene; total hip prosthesis

INTRODUCTION

γ-irradiation has been used since 1971 to improve the wear resistance of ultrahigh molecular weight polyethylene acetabular cups of total hip prostheses.[1] In the sterilization of polyethylene components by γ-irradiation, free radicals are formed. If the irradiation is done in an oxygen-free environment, and if the free radicals are eliminated by subsequent thermal treatment, beneficial crosslinks of the molecule chains result instead of detrimental oxidation, which may lead to a collapse of strength and wear resistance. The wear of conventional polyethylene has caused serious clinical problems. The term conventional is used here to indicate a material for which γ-irradiation is used for sterilization, not for intentional crosslinking. Various new crosslinking techniques have been developed to overcome the wear problem, utilizing γ-irradiation, electron-beam-irradiation, or peroxides.[2] Typically, a crosslinked polyethylene shows minimal wear against a polished counterface in wear tests.[3] *In vivo,* however, the femoral heads often lose their original smoothness because of the abrasive action of bone, bone cement, or metal particles. The roughening of the heads has been found to increase the wear rate of conventional polyethylene acetabular cups *in vivo,*[4] and of conventional and γ-irradiation-crosslinked polyethylene cups *in vitro*.[5] Apparently, it is important to include the roughening factor in the wear simulation if realistic predictions of wear rate for new materials are to be produced.

In the present report, the wear behavior of conventional γ-irradiation-sterilized polyethylene is compared with that of electron-beam-crosslinked polyethylene. The wear tests were done with a circularly translating pin-on-disk (CTPOD) device, which has

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been shown to produce wear similar to that occurring in total hip prostheses *in vivo*.[6,7] The counterfaces, CoCr disks, were either polished or roughened so that they represented the type of roughening and the range of surface roughness observed in explanted femoral heads.[4,8–10]

MATERIALS AND METHODS

The 12-station CTPOD device is described in detail elsewhere.[6,7] The flat end of a polyethylene cylinder (pin) was pressed against the flat surface of a CoCr disk. The motion was such that the pin translated, without rotation, along a circular track of 10-mm diameter on the disk. Therefore, the direction of sliding relative to the pin changed continually. One complete revolution of the direction of sliding, which took 0.98 s, is called a cycle. The sliding speed was constant, 32 mm/s. The diameter of the polyethylene pin was 8.92 mm and the height 12 mm. The wear end of the pin was not chamfered. The CoCr disk had a diameter of 30 mm and a thickness of 10 mm. The normal load was constant 70.7 N, and nominal contact pressure therefore 1.1 MPa.

The pins and the disks were supplied by Sulzer Orthopedics Ltd. (Winterthur, Switzerland). The trade names of the conventional and crosslinked polyethylenes studied in the present report were Sulene-PE and Durasul, respectively. Sulene-PE was compression molded from GUR 1020 powder. After machining, the Sulene-PE pins were γ-irradiated by 25–40 kGy in nitrogen. Durasul was made from GUR 1050 powder by irradiating heated preforms with 10-MeV electron beam to 95 kGy. During irradiation, the material heated adiabatically. After irradiation, a thermal treatment at 150°C was applied to eliminate free radicals. The pins were then machined and sterilized using ethylene oxide. With both types of polyethylene, 12 tests were run.

The disks were made from CoCr alloy Protasul-20. The wear faces of the 24 disks used in the test program were first machined, ground, and polished. The arithmetical mean surface roughness values R_a of the polished disks were 0.014–0.027 μm. Both types of polyethylene were tested against three polished disks. The rest of the disks were artificially roughened before the tests using emery papers of various grit sizes. The roughening was done so that the resulting scratches went in all directions, as they do *in vivo*[9,10] (Fig. 1). The R_a values of the roughened disks were 0.028–0.24 μm. The range corresponded to that found in retrieved femoral heads.[4,8–10] The surface roughness was measured with a

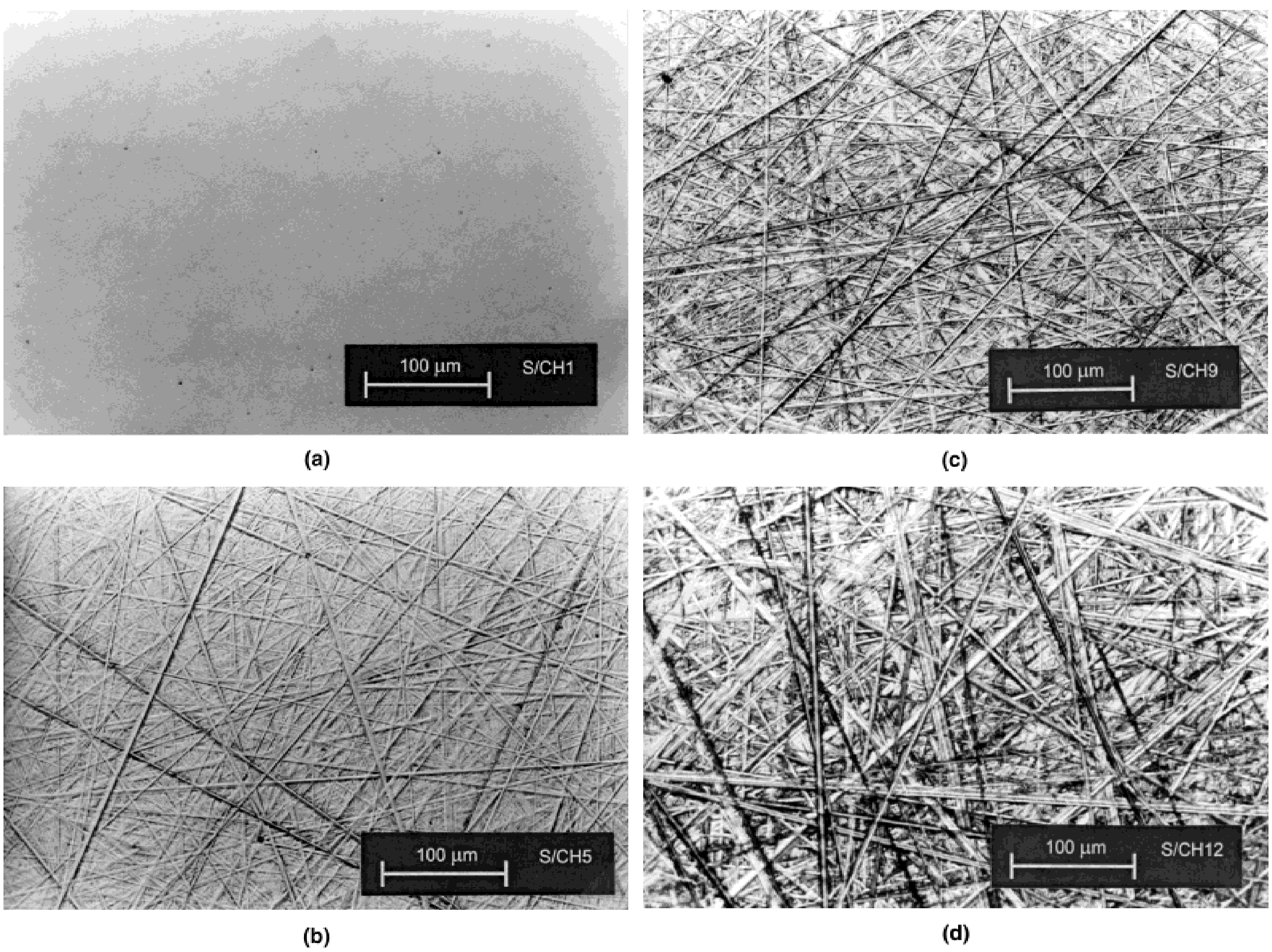

Figure 1. Optical micrographs from CoCr disks. (a) Polished, R_a = 0.022 μm; (b) roughened, R_a = 0.033 μm; (c) roughened, R_a = 0.080 μm; (d) roughened, R_a = 0.24 μm.

Taylor Hobson Surtronic 3+ diamond stylus instrument (Taylor Hobson, Leicester, UK) using 0.8-mm cut-off and 4-mm evaluation length. At least 10 measurements were made from each disk in different directions and locations. The mean values and standard deviations of R_a, root mean square roughness R_q, peak height R_p, and skewness R_{sk}, measured after the tests, are presented in Table I. The values did not significantly differ from those measured before the tests.

The lubricant was prepared so that triple 0.1-μm sterile filtered HyClone Alpha Calf Fraction serum (HyClone Laboratories, Inc., Logan, UT), catalog number SH30076.03, was diluted 1:1 with Milli-Q-grade distilled water. Hence, the protein content of the lubricant was 21 mg/mL. No additives were used in the lubricant. The pin and the disk were located in an open lubricant chamber, which contained 12 mL of lubricant. The tests were done at room temperature. In preliminary trials, the coefficient of friction against the roughest disks proved to be above 0.2, and so the frictional force exceeded the upper limit of the friction transducers. Therefore, the tests were done without friction measurement, using rigid fixation of the disks.

The amount of wear was measured by stopping the test and weighing the pins at intervals of half a million cycles. The amount of fluid absorption was corrected for by the use of soak control pins, four pins per test, immersed in lubricant similar to that used with the test pins. During a weighing stop, the specimens were carefully cleaned. Before the weighing, the pins were vacuum desiccated for 30 min. The weighing was done with a Mettler AT261 DeltaRange balance (Mettler-Toledo AG, Greifensee, Switzerland). After the weighing, the specimens were reassembled, and the test was continued with fresh lubricant. The total length of the tests was 3 million cycles. The wear rate was the slope of the linear regression line in the variation of gravimetric wear with the number of cycles (Fig. 2). Taking into account the density of polyethylene, the load, and the sliding distance per cycle, the wear factor k was calculated so that the wear rate, expressed as mg/10^6 cycles, was divided by ($10^6 \times 0.93$ mg/mm^3 $\times$ 70.7 N $\times$ 0.0314 m).

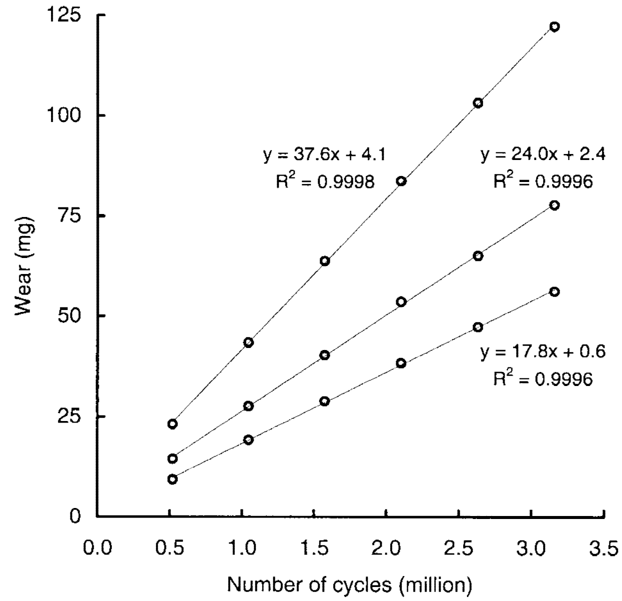

Figure 2. Examples of variation of polyethylene wear with number of cycles, illustrating the determination of wear rate. Conventional polyethylene pins against the three roughest disks.

TABLE I
Surface Roughness Values of the Disks

Test	Disk	R_a (μm)		R_q (μm)		R_p (μm)		R_{sk}	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Conventional polyethylene	1	0.022	0.003	0.032	0.005	0.087	0.032	−1.0	2.0
	2	0.023	0.003	0.032	0.005	0.081	0.024	−0.8	1.9
	3	0.027	0.004	0.037	0.006	0.095	0.048	−0.7	0.8
	4	0.031	0.002	0.043	0.002	0.114	0.011	−0.6	0.3
	5	0.033	0.003	0.045	0.004	0.128	0.013	−0.5	0.4
	6	0.054	0.004	0.074	0.006	0.179	0.013	−1.0	0.6
	7	0.058	0.004	0.078	0.005	0.196	0.015	−0.8	0.2
	8	0.075	0.008	0.099	0.009	0.292	0.043	−0.2	0.3
	9	0.080	0.007	0.104	0.009	0.307	0.038	−0.4	0.3
	10	0.135	0.021	0.193	0.049	0.438	0.089	−2.8	3.2
	11	0.166	0.009	0.220	0.014	0.555	0.054	−0.8	0.4
	12	0.237	0.023	0.308	0.029	0.862	0.194	−0.6	0.3
Crosslinked polyethylene	1	0.014	0.002	0.022	0.003	0.075	0.041	0.6	2.8
	2	0.021	0.003	0.030	0.004	0.101	0.041	0.4	1.3
	3	0.023	0.002	0.032	0.004	0.091	0.034	−0.1	1.2
	4	0.028	0.001	0.039	0.002	0.106	0.009	−0.5	0.2
	5	0.032	0.002	0.044	0.002	0.131	0.011	−0.5	0.1
	6	0.054	0.003	0.073	0.005	0.190	0.022	−0.8	0.5
	7	0.055	0.003	0.075	0.004	0.194	0.020	−0.8	0.3
	8	0.087	0.012	0.120	0.022	0.256	0.034	−1.3	0.9
	9	0.096	0.009	0.129	0.011	0.273	0.024	−1.1	0.7
	10	0.130	0.015	0.170	0.020	0.452	0.097	−0.3	0.3
	11	0.165	0.017	0.210	0.019	0.552	0.057	0.0	0.3
	12	0.215	0.017	0.274	0.022	0.729	0.073	−0.2	0.3

Polyethylene wear particles were isolated from samples of used serum lubricant by NaOH digestion and filtration on 0.05-μm pore size Nucleopore filters (Millipore, Bedford, MA), photographed with a scanning electron microscope, and examined using image analysis software as described in detail in a previous article.[11] The samples represented conventional and crosslinked polyethylene against polished disks and against the roughest disks.

RESULTS

The variation of wear factor with counterface surface roughness is shown in Figure 3. Note that each one of the 24 points in the diagram represents an independent wear test of 5 weeks' duration and six periodic wear measurements. With both types of polyethylene, the wear factor showed a strong correlation with the counterface R_a value. With conventional polyethylene, the power equation was $k = 5.87 \times 10^{-5}(R_a)^{0.91}$, the R^2 value being 0.94. With crosslinked polyethylene, the correlation was somewhat weaker ($R^2 = 0.82$), but the regression line was steeper, $k = 7.87 \times 10^{-5}(R_a)^{2.49}$. The steepness was clearly affected by the fact that, against the polished disks, the total weight loss of the crosslinked polyethylene pins was below the detection limit, 0.01 mg, set by the readability of the balance used. These pins were assigned a k value of $0.01 \text{ mg}/(3 \times 10^6 \times 0.93 \text{ mg/mm}^3 \times 70.7 \text{ N} \times 0.0314 \text{ m}) = 1.6 \times 10^{-9} \text{ mm}^3/\text{N m}$.

Optical micrographs from pin wear faces after 3 million cycles are shown in Figure 4. In general, the smoother the counterface, the more burnished the pin. On the crosslinked polyethylene pins that were tested against polished disks, remains of original machining marks were still visible [Fig. 4(c)]. The wear particles produced by conventional and crosslinked polyethylene pins against the roughest disks were similar, the mean equivalent circle diameters (ECD), their standard deviations, and number of particles analyzed being 0.37 ± 0.23 μm (n = 149) and 0.39 ± 0.22 μm (n = 194), respectively [Fig. 5(b,d)]. The wear particles produced by a conventional polyethylene pin against a polished disk were smaller (ECD = 0.21 ± 0.09 μm, n = 340) and more rounded [Fig. 5(a)]. The smallest particles in size (ECD = 0.10 ± 0.04 μm, n = 71) and number were those produced by a crosslinked polyethylene pin against a polished disk [Fig. 5(c)]. When these four categories were compared in pairs (Wilcoxon's ranked sum test), all p values were = 0, except for (b) versus (d) (p = 0.44). The amount of polyethylene on the filters was optimized for the image analysis, so the number of particles seen in Figure 5(a–d) is not directly proportional to the wear rate [especially (b) versus (d)].

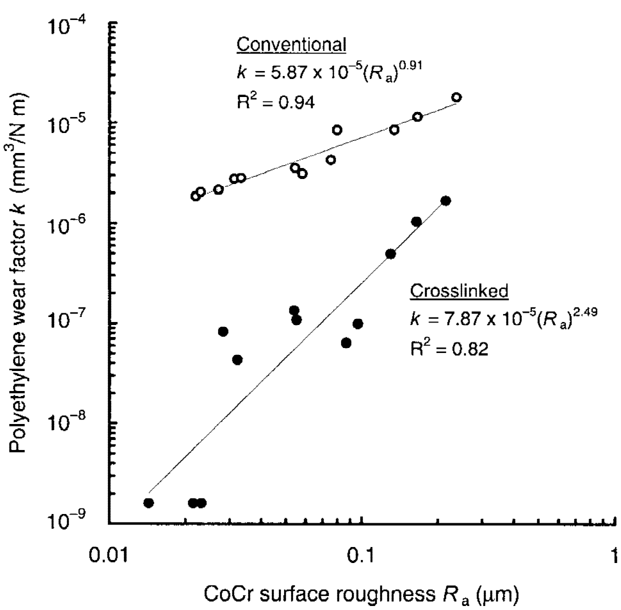

Figure 3. Variation of polyethylene wear factor with counterface surface roughness.

DISCUSSION

The present wear test results indicate that significant improvement in the wear resistance of ultrahigh molecular weight polyethylene is achieved by electron-beam-irradiation and subsequent thermal treatment. Against polished counterfaces, the wear factor of crosslinked polyethylene was of the order of 2×10^{-9} mm^3/N m, whereas that of conventional polyethylene was 2×10^{-6} mm^3/N m, which is a typical clinical value.[4] Against a rough counterface of around 0.2 μm R_a, electron-beam-irradiation resulted in tenfold improvement in wear resistance, the wear factors being 1×10^{-6} versus 1×10^{-5} mm^3/N m. Particular significance is given to these findings by the fact that the surface topography of the counterfaces (Table I) corresponded with the type of roughening, and the range of surface roughness observed in explanted femoral heads.[4,8–10]

In a retrieval study,[4] a weak correlation ($R^2 = 0.14$) was found between the wear factor of conventional polyethylene acetabular cups and femoral head roughness, $k = 9.7 \times 10^{-6}(R_a)^{0.54}$. Apparently, there are several factors that affect the wear *in vivo* and weaken the correlation, which are absent in strictly controlled laboratory wear tests. For instance, the time when the roughening occurred,[12] the locations of roughened areas,[9] and the composition of joint fluid may vary *in vivo*. In the calculation of clinical wear factors, the activity of the patients is naturally taken into account, but the activity varies considerably and its estimation is a potential source of large errors. Elfick et al.,[12] in their hip simulator tests using explanted femoral heads which had roughened *in vivo*, observed that the *in vitro* wear rate was five times higher than the *in vivo* wear rate measured from the corresponding retrieved

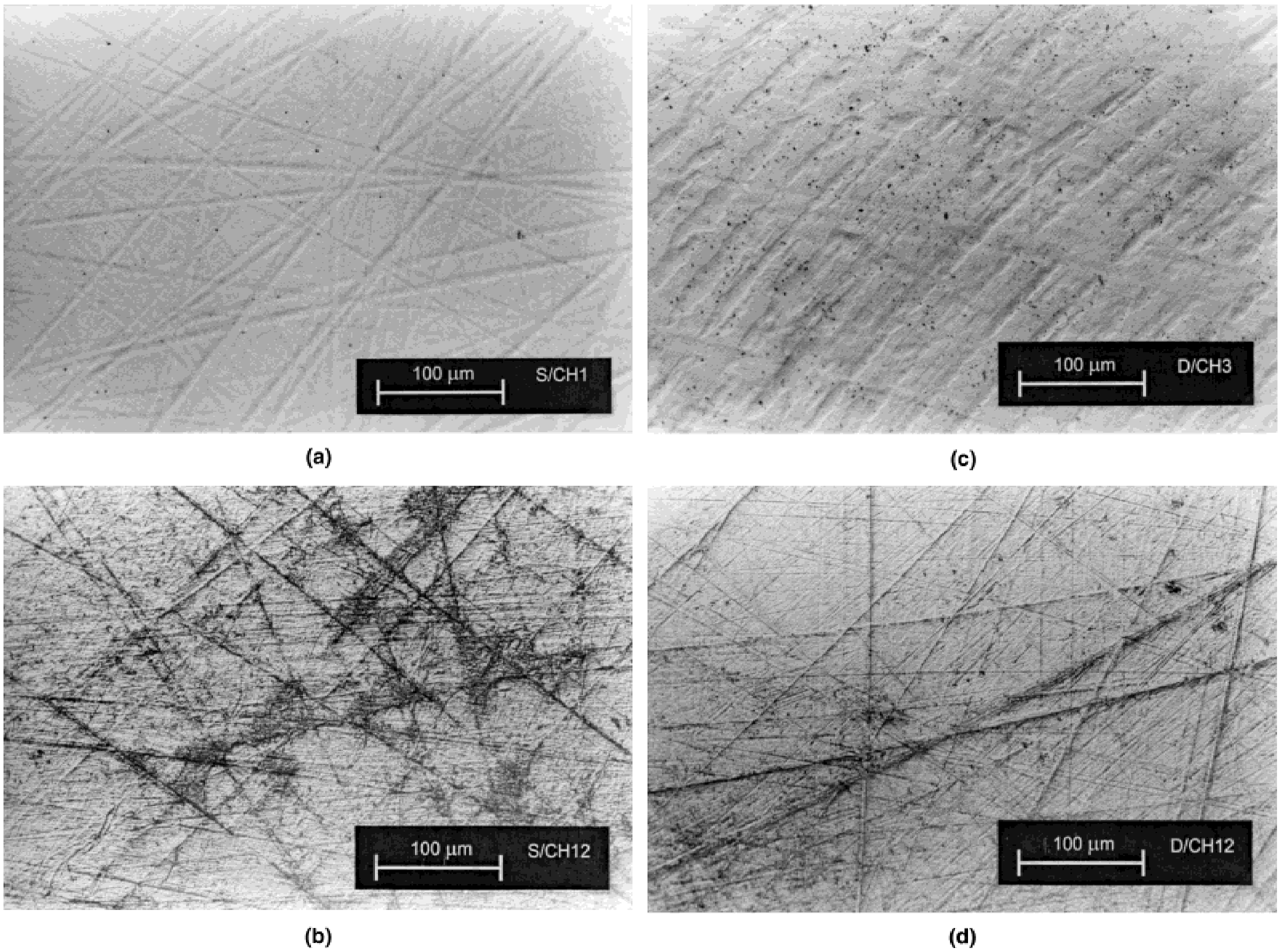

Figure 4. Optical micrographs from polyethylene wear faces after the tests. (a) Conventional polyethylene, counterface R_a = 0.022 µm; (b) conventional polyethylene, counterface R_a = 0.24 µm; (c) crosslinked polyethylene, counterface R_a = 0.023 µm; (d) crosslinked polyethylene, counterface R_a = 0.22 µm. Note the remains of machining grooves in (c).

cups. This was likely because of the fact that the roughening occurred at a late stage of the implant duration, and the consequent period of rapid wear soon resulted in osteolysis and revision. Therefore, it is logical that against roughened counterfaces, the *in vitro* wear factors are higher than the *in vivo* ones, because abrasive wear tests are usually done so that the counterfaces are rough from the very beginning of the tests, and the roughness remains fairly unchanged during the tests, as in the present study.

The dependence of the wear of conventional polyethylene on counterface roughness has been studied extensively with pin-on-disk devices.[13–15] From water-lubricated reciprocating pin-on-disk tests, Dowson et al.[13] derived the classical expression $k = 4.0 \times 10^{-5}(R_a)^{1.2}$. It was later observed that reciprocating motion and water lubrication exaggerate the roughness dependence, and underestimate the wear against a polished counterface.[16] Even with serum lubrication, linear motion results in very low wear, as shown by Weightman and Light,[14] who studied RCH 1000 type of polyethylene, and by Lancaster et al.,[15] who found a relationship $k = 4.9 \times 10^{-8}(R_a)^{0.37}$ (D. Dowson, personal communication) for non-irradiated GUR 415. Serum-lubricated biaxial hip simulator tests by Wang et al.[16] yielded $k = 7.21 \times 10^{-6}(R_a)^{0.42}$ for γ-irradiated GUR 4150. For comparison, the equation obtained in the present study together with those mentioned above are shown in the same diagram (Fig. 6). In addition to the fact that the wear conditions greatly differed, the type of polyethylene was not the same in all studies, which may also partly explain the differences in wear. Moreover, different types of contacting and noncontacting instruments were used in surface roughness measurement. In studies of retrieved femoral heads,[9,17] it was found that laser profilometry gives values that may be as much as 4 to 6 times higher than those given by contact profilometry! Note also that the calculated equations only are illustrated, although the R^2 values of fit varied considerably. In the present study, the R^2 values of linear regression between k and R_a were even slightly higher than those of power regression, but power regression is used here to facilitate comparison with other studies. Perhaps the most surprising difference is that of the exponents when comparing the study by Wang et al.[16] with the present

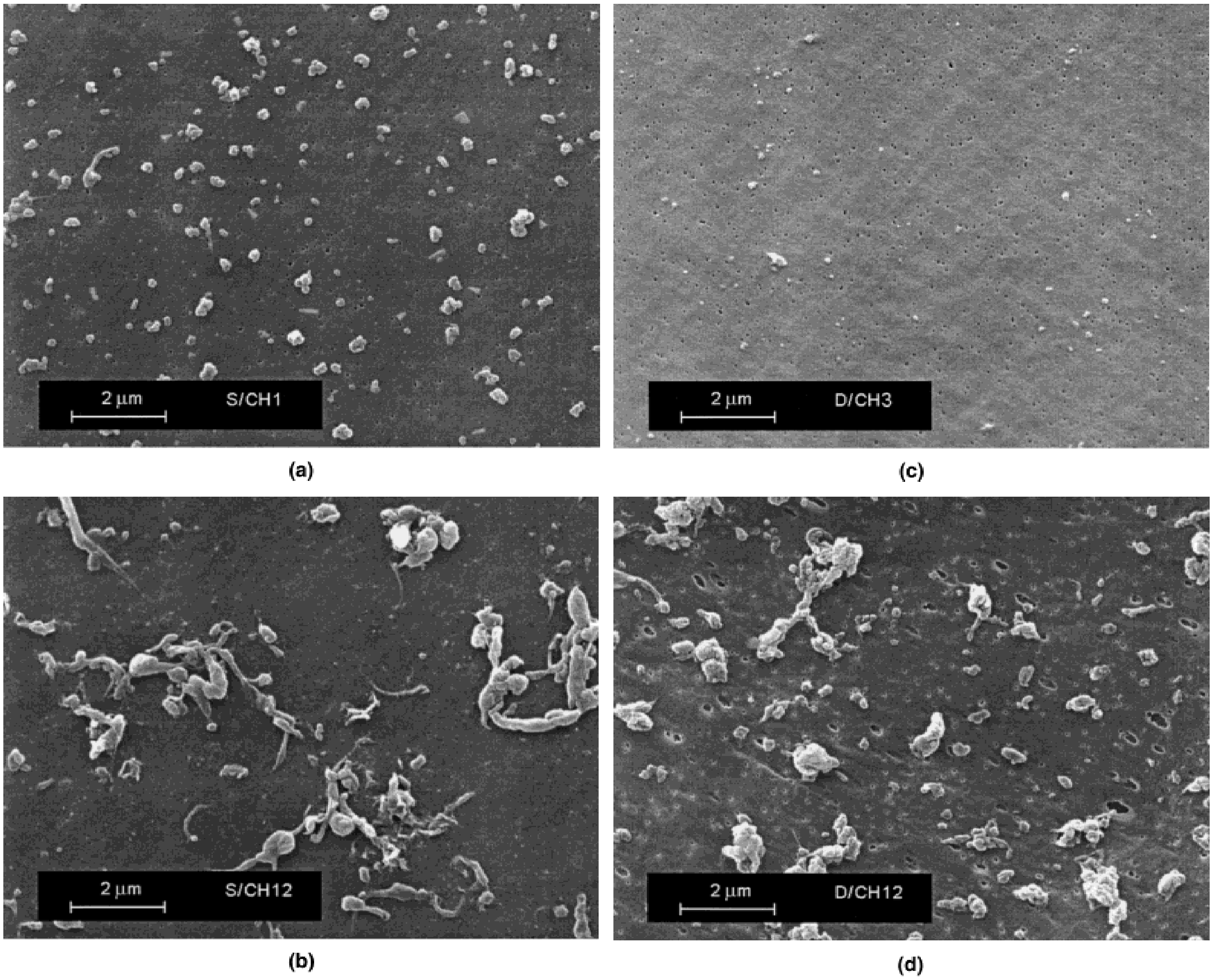

Figure 5. Scanning electron micrographs from 0.05-μm pore size Nucleopore membranes, through which the digested samples of serum lubricant were filtered, showing polyethylene wear particles. (a) Conventional polyethylene, counterface R_a = 0.022 μm; (b) conventional polyethylene, counterface R_a = 0.24 μm; (c) crosslinked polyethylene, counterface R_a = 0.023 μm; (d) crosslinked polyethylene, counterface R_a = 0.22 μm.

one, especially because the simulator used by Wang et al. is analogous with the CTPOD device (direction of sliding rotates with constant angular velocity), and the lubricants were identical.

The wear particles produced by conventional polyethylene against a polished counterface were significantly smaller than those produced against a roughened counterface. Quite the opposite was observed by Hailey et al.,[18] who used a unidirectional pin-on-disk device, which is fundamentally different from the circularly translating pin-on-disk device used in the present study. In the CTPOD device, the direction of sliding relative to the polyethylene component changes continually, which is also the case in the hip joint in walking. The continual change of the direction of sliding has been shown to be a crucial factor in the realistic wear simulation of the total hip prosthesis.[6,16] It is interesting that the average size of particles produced by conventional polyethylene against a polished counterface in the present study was close to a value of 0.2 μm, which has been found to be the lower limit for biological activity,[19] the critical size range being 0.2–8 μm. The average size of particles produced by crosslinked polyethylene against a polished counterface, 0.1 μm, is clearly below the limit. Filter size 0.05 μm was used in the present study. If size 0.2 or 0.4 μm was used, as in some previously published studies, particles in the 0.1–0.2-μm size range, produced against polished counterfaces through an adhesive wear mechanism, would probably not be caught on the filter.

It is possible that the wear against a damaged counterface *in vivo* is detrimental, not necessarily because the number of particles produced is higher than against an undamaged counterface, but because the particles are biologically more active because of their larger size. In the abrasive wear against rough counterfaces, the wear particles produced by conventional

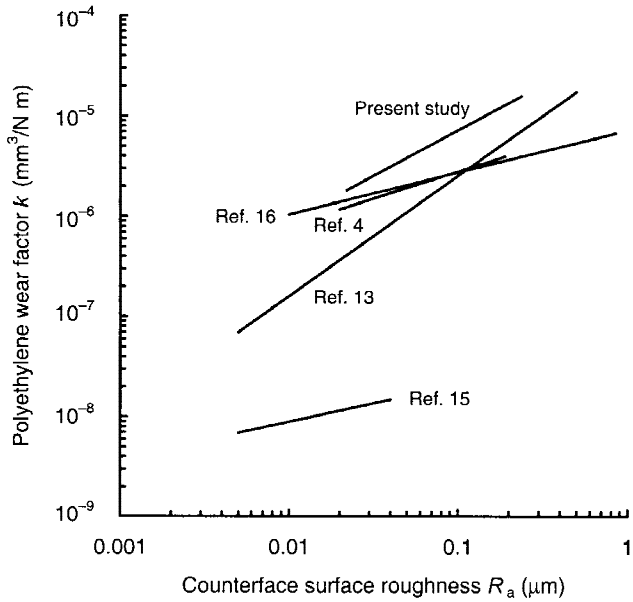

Figure 6. Present k versus R_a power relationship for conventional polyethylene compared with those found from the literature.

and crosslinked polyethylenes were of similar shape and average size, 0.37 and 0.39 μm, respectively, corresponding well with those isolated from periprosthetic tissues.[20] In the case of a damaged femoral head, it is reasonable to assume that the tissue reaction would be less severe if electron-beam-crosslinked polyethylene was used as the cup material instead of conventional polyethylene, because the number of particles would be much lower. Further, it can be assumed that if the head remained smooth, the size, and probably also the number of particles removed from an electron-beam-crosslinked polyethylene cup would be so small that the incidence of osteolysis would be reduced. In the published articles on clinical wear particles, the surface roughness of the femoral heads has not been studied. Hence, it is still unknown whether damaged counterfaces produce larger polyethylene wear particles than undamaged ones *in vivo,* as was the case in the present study. It would be most interesting if future studies on clinical wear particles were to include the surface roughness measurement of the corresponding femoral heads, and to examine the possible correlation between counterface roughness and size of polyethylene particles.

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