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Effect of contact area on the wear of ultrahigh molecular weight polyethylene in noncyclic pin-on-disk tests

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Abstract

The 16-station RandomPOD pin-on-disk device with non-cyclic biaxial motion and load was used to study the effect of contact area on the wear of ultrahigh molecular weight polyethylene as used in total hip prostheses. The counterface was polished CoCr and the lubricant was diluted serum. The wear factor increased strongly and linearly with increasing contact area, which was in agreement with clinical findings for total hip prostheses. The coefficient of friction also increased strongly with increasing contact area. With small contact area the lumpy topography of the worn surface differed from the burnished appearance typical of retrieved acetabular cups. The nominal contact pressure should be kept below 2 MPa in pin-on-disk tests intended to simulate clinical wear mechanisms.

Keywords: biotribology, prosthetic joint, noncyclic pin-on-disk, UHMWPE

1 Introduction

In the field of orthopaedic tribology, it is common to perform basic research by utilizing the pin-on-disk (POD) simplification of the contact geometry [1]. The type of the relative motion and of the lubricant have been shown to be important in the reproduction of clinical wear mechanisms [2–6]. Usually, a test is run at 1 Hz for at least 3 million cycles (6 weeks). In POD testing, the efficiency can be readily increased by increasing either the number of test stations, up to 100 [7], or the test frequency, up to 25 Hz [8], provided that the velocity remains at a reasonable level. In full-scale hip and knee joint simulator studies, this is not similarly possible. If several materials are to be compared, the capacity problem, and consequently the need for valid pin-on-disk wear screening, become obvious.

The 16-station, non-cyclic RandomPOD wear test device was recently introduced [9,10]. The rationale for developing the RandomPOD was to completely avoid the simplified cyclic features of the wear test regarding the motion and load profiles, and still produce a realistic range of motion, velocity, acceleration and its derivative, and dynamic load. One important parameter in POD testing is the contact pressure [11]. In the present study, the effect of contact pressure on wear was studied in the RandomPOD for the first time by varying the contact area of the ultrahigh molecular weight polyethylene (UHMWPE) pin. It was shown in earlier circular translation pin-on-disk (CTPOD) studies that if the nominal contact pressure exceeds the critical limit of 2 MPa, the worn bearing surface topography differs from clinical observations, according to which burnishing is the predominant feature [12,13]. Above 2 MPa, protuberance formation is observed which is probably caused by thermal effects and plastic deformation. The lumpy topography was associated with considerable reduction of the wear factor and of the coefficient of friction, which is unlikely to be in agreement with the in vivo tribological behavior of UHMWPE. Based on the earlier CTPOD studies [11], it was hypothesized that to produce realistic RandomPOD hip wear simulation for UHMWPE, the average nominal contact pressure should not exceed the critical limit of 2 MPa.

2 Materials and Methods

The 16-station, computer-controlled RandomPOD wear test system has been described elsewhere [9,10]. Briefly, the pin translated biaxially and non-cyclically relative to the disk so that the slide track remained within a circle 10 mm diameter (Fig. 1). The sliding velocity varied between zero and 31.4 mm/s, with a mean of 15.5 mm/s. The acceleration varied from zero to 300 mm/s^2. Its derivative was continuous, and therefore the motion was smooth even in reversals. The direction of sliding changed continually (mean 500 °/s) relative to the pin, which has shown to be important in the simulation of UHMWPE wear mechanisms with respect to implant applications [2–6]. The load varied non-cyclically between zero and 142 N, with a mean of 73.5 N.

The type of UHMWPE was gamma-N_2-sterilized GUR 1020 (ISO 5834-1/-2). The contact surface diameters of cylindrical UHMWPE pins were 4.0 mm, 6.5 mm, 9.0 mm and 12 mm (n = 4 for each diameter). The counterfaces were polished CoCr disks (S_a = 0.01 µm, measured with a white light interferometry profilometer). 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 °C ± 0.5 °C with circulating cooling water that surrounded the test chambers [7]. The test duration was 37 days. The test was stopped at intervals of 147 hours (8.2 km) for the gravimetric wear measurement of the pins [7]. From the 6 wear values, the wear rate (mg/km) was obtained for each pin by linear regression. The first 147 h (origin) was omitted in the regression as running-in wear. The wear factor k (mm^3/Nm) was obtained by multiplying the wear rate by the sliding distance between the 1st and the 6th measurement points (41 km) and dividing by the density (0.935 mg/mm^3) and by the integral of the product of the instantaneous load and the incremental sliding distance between the 1st and the 6th measurement points (3.015×10^6 Nm). The product was numerically integrated at 100 Hz.

The friction tests were run after the wear tests for each pin with the friction measurement circular translation pin-on-disk (CTPOD) device [11], as the RandomPOD is purely a wear test device without friction measurement accessories. The disk was supported by low-friction ball bearings so that it could theoretically rotate freely about the vertical axis, but the rotation was prevented by a load cell, from the signal of which the frictional force was calculated. The load was constant, 73.5 N, which was the mean value of the wear tests. The lubricant environment was as in the wear tests, diluted Alpha Calf serum at 20 °C. The friction tests were run for 2 hours after which the steady state frictional force value was recorded.

3 Results

The wear factor k increased strongly and linearly with increasing contact area A (Fig. 2), and thus, with decreasing contact pressure. The correlation coefficient R^2 of the linear regression was as high as 0.9999. The variation of wear with sliding distance, from which the k values were calculated, was linear as well. The mean R^2 value of linear fit (wear rate) for the 16 pins was 0.9974 (range 0.9919 to 0.9998). The coefficient of friction μ also increased with increasing A, but the trend was not straightforward. Nevertheless, as A increased 9-fold, both k and μ increased 7-fold. With contact diameters of 4.0 mm and 6.5 mm, the bearing surface became lumpy, whereas with 9.0 mm and 12 mm, burnishing was conspicuous, and only a few protuberances appeared near the edge (Figs. 3 and 4). With the two smaller diameters, μ was on a lower level, 0.05, compared with the two larger diameters (~0.3). The CoCr surfaces remained virtually unchanged in the tests. No layers or scratches were observed.

4 Discussion

The observations of the increase of both k and μ with decreasing contact pressure, and the lumpy topography with high contact pressures were similar to the earlier findings with the circularly translating pin-on-disk (CTPOD), in which the pin diameter was 9.0 mm and the static load was varied [11]. Apparently, these phenomena were not sensitive to the type of multidirectional motion or to the type of load. The same type of gamma-inert-sterilized UHMWPE was used in these two studies. The main difference was in the magnitude of *k*. In the CTPOD, a value of 2.66 ± 0.16 × 10^{-6} mm^3/Nm was obtained with 1.1 MPa. A significantly higher value of 4.34 ± 0.20 × 10^{-6} mm^3/Nm was obtained in the present study with 9.0 mm diameter (p = 0.00007). This was likely to be attributable to the increased multidirectionality of the RandomPOD compared with the CTPOD, i.e., 500°/s vs. 360 °/s (accumulated change of direction of sliding per second). Particular attention may be drawn to the linearity of the *A* dependence of *k*, as the correlation coefficient *squared* was 0.9999 (Fig. 2).

It was not surprising that a polyethylene surface with protuberances here and there proved to be advantageous for lubrication, as indicated by the low μ values with 4.0 mm and 6.5 mm contact diameters. Between the contact spots, formed by the protuberances, lubrication was likely to be enhanced. Logically, this reduced wear. Alternatively, the high contact stresses on the contact spots caused heating that reduced the UHMWPE wear. It may be further speculated that the actual contact stresses were so high that they led to the formation of the protuberances by plastic deformation, contributed by the elevated contact temperatures. Contact diameters of 9.0 mm and 12 mm resulted in a nearly mirror-like surface, with which *k* and μ were significantly higher, probably due to a poorer lubrication (flat-on-flat contact between two polished surfaces), despite the fact that the contact pressures were low. The protuberances on the edge (Figs. 4C and 4D) can be explained by the fact that the true contact stresses were higher on the leading edge. The pin was guided by a precision shaft with a finite clearance (c. 0.01 mm) so that the true pin loading would not be affected by wear [9]. The frictional force slightly tilted the shaft together with the pin. As the direction of sliding relative to the pin changed continually (500°/s on the average), all locations on the edge acted as the leading edge at times. It should be noted that burnishing is the predominant feature on retrieved polyethylene acetabular cups of well-functioning total hip prostheses [12−14]. This is commonly considered to be an indication of adhesive wear to be the principal wear mechanism [12−14]. Therefore, the k and μ values obtained with the lumpy surfaces, that is, with excessive contact pressures, were likely to be underestimates, as the topography of the plastically deformed surface markedly differed from clinical observations. However, fine multidirectional scratches, seen on all pins (Fig. 4), are typical observations clinically [12−14], which indicates that the abrasive wear mechanism is also present.

The fact that the wear factor strongly increased with increasing contact area (Fig. 2) was in agreement with clinical findings that the wear rate of UHMWPE acetabular cups increase with increasing femoral head diameter [12]. The wear rate against 32 mm femoral heads was twice that against 22 mm heads in the revision group. In other words, and increase of the head diameter by 45 per cent resulted in an increase of wear rate by 100 per cent. If the two largest pin diameters of the present study, 9.0 mm and 12 mm, are compared, an increase of the pin diameter by 33 per cent resulted in an increase of the wear factor (and wear rate) by 76 per cent (Fig. 2). This diametral dependence was very close to the clinical finding [12]. The above indicates that a larger contact area results in a higher wear rate simply because the surface that releases wear particles is larger. The lower contact stresses do not seem to efficiently counteract this detrimental tendency so that the rate of particle release would be lower. Laboratory tests actually showed the opposite [11]. The wear rate increased as the nominal contact pressure decreased from 11 MPa to 2 MPa. However, in the use of contemporary crosslinked polyethylene materials with improved wear resistance, large femoral heads are currently favored because of a lower risk of dislocation. This unfortunately leads to a lower cup thickness and therefore to an increased risk of cup fracture. A large femoral head also leads to a higher frictional torque due to a larger moment arm, irrespective of the type of UHMWPE. Note that with respect to the wear rate, the sliding distance per cycle, that increases with increasing head diameter, has been shown to be unimportant [15].

A mean clinical wear factor, 2.1×10^{-6} mm^3/Nm, for the UHMWPE acetabular cup of the Charnley design with 22 mm femoral head diameter can be found from literature [16]. The range was wide, covering nearly two orders of magnitude, from slightly above 1×10^{-7} mm^3/Nm to almost 1×10^{-5} mm^3/Nm. Compared with this, the present range was much more narrow, from 1.0×10^{-6} mm^3/Nm to 8.1×10^{-6} mm^3/Nm. There are many clinical variables, which were absent from the strictly controlled laboratory wear test, that may explain the difference in the range, such as bone cement ingress and patient activity.

The fact that the wear and friction tests were run with two different devices may be considered a limitation of the study. The procedure can be justified as follows. First, both devices were nevertheless multidirectional, and the lubrication environment was uniform. Second, the observed difference in the frictional behavior between the two very different types of polyethylene bearing surface topographies formed in the wear test, lumpy ($\mu \approx 0.05$) and mirror-like ($\mu \approx 0.3$), was indisputable.

5 Conclusions

In multidirectional pin-on-disk hip wear simulation of UHMWPE, the nominal contact pressure should not exceed 2 MPa in order not to produce unrealistically low wear and friction values, or bearing surface topographies which indicate wear mechanisms that do not occur clinically. Particularly, the protuberance formation appears to be a phenomenon related to the flat-on-flat tests conditions and augmented by frictional heating and plastic deformation. With conventional UHMWPE, the wear factor should rather be substantially above 2.0×10^{-6} mm^3/Nm than substantially below this value.

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References

[1] Baykal D, Siskey RS, Haider H, Saikko V, Ahlroos T, Kurtz SM. Advances in tribological testing of artificial joint biomaterials using multidirectional pin-on-disk testers. J Mech Behav Biomed Mater 2014;31:117–34.

[2] Wang A, Stark C, Dumbleton JH. Mechanistic and morphological origins of ultra-high molecular weight polyethylene wear debris in total joint replacement prostheses. Proc Inst Mech Eng H: J Eng Med 1996;210:141–55.

[3] Bragdon CR, O'Connor DO, Lowenstein JD, Jasty M, Syniuta WD. The importance of multidirectional motion on the wear of polyethylene. Proc Inst Mech Eng H: J Eng Med 1996;210:157–65.

[4] Saikko V, Ahlroos T. Type of motion and lubricant in wear simulation of polyethylene acetabular cup. Proc Inst Mech Eng H: J Eng Med 1999;213:301–10.

[5] Joyce TJ, Monk D, Scholes SC, Unsworth A. A multi-directional wear screening device and preliminary results of UHMWPE articulating against stainless steel. Bio-Med Mater Eng 2000;10:241–9.

[6] Hua Z, Zhang H, Fan Y, Jin Z. Development of a BiotriboPOD testing methodology for the wear evaluation of orthopaedic biomaterials. RSC Adv 2014;4:19987–91.

[7] Saikko V. A hip wear simulator with 100 test stations. Proc Inst Mech Eng H: J Eng Med 2005;219:309–18.

[8] Saikko V. High frequency circular translation pin-on-disk method for accelerated wear testing of ultrahigh molecular weight polyethylene as a bearing material in total hip arthroplasty. J Biomech 2015;48:401–4.

[9] Saikko V., Kostamo J. RandomPOD—A new method and device for advanced wear simulation of orthopaedic biomaterials. J Biomech 2011;44:810–4.

[10] Saikko V. In vitro wear simulation on the RandomPOD wear testing system as a screening method for bearing materials intended for total knee arthroplasty. J Biomech 2014;47:2774–8.

[11] Saikko V. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multi-directional sliding. Proc Inst Mech Eng H: J Eng Med 2006;220:723–31.

[12] Jasty M, Goetz DD, Bragdon CR, Lee KR, Hanson AE, Elder JR, Harris WH. Wear of polyethylene acetabular components in total hip arthroplasty. An analysis of one hundred and twenty-eight components retrieved at autopsy or revision operations. J Bone Jt Surg Am 1997;79:349–58.

[13] Pourzal R, Knowlton CB, Hall DJ, Laurent MP, Urban RM, Wimmer MA,. How does wear rate compare in well-functioning total hip and knee replacements? A postmortem polyethylene liner study. Clin Orthop Relat Res 2016;474:1867–75.

[14] Edidin AA, Rimnac CM, Goldberg VM, Kurtz SM. Mechanical behavior, wear surface morphology, and clinical performance of UHMWPE acetabular components after 10 years of implantation. Wear 2001;250:152–8.

[15] Saikko V, Calonius O, Keränen J. Effect of extent of motion and type of load on the wear of polyethylene in a biaxial hip simulator. J Biomed Mater Res Part B: Appl Biomater 2003;65B:186–92.

[16] Hall RM, Unsworth A, Siney P, Wroblewski BM. Wear in retrieved Charnley acetabular sockets. Proc Inst Mech Eng H: J Eng Med 1996;210:197–207.

Figure captions

Figure 1. Schematic of RandomPOD.

Figure 2. Variation of wear factor k (filled circles) and coefficient of friction μ (open circles) with contact surface area A of gamma-inert-sterilized UHMWPE against polished CoCr in diluted serum lubricant at 20 °C, mean and standard deviation. Wear tests were run with RandomPOD and friction tests with CTPOD. In the latter, load was constant 73.5 N (mean value of RandomPOD tests) and hence the nominal contact pressure values were 5.9 MPa, 2.2 MPa, 1.2 MPa, and 0.65 MPa. With $A = 12.6\ mm^2$, SD was so low that circular symbols cover the limits.

Figure 3. UHMWPE pins after RandomPOD wear test, representing four different contact diameters. Note lumpy topography of 4.0 mm and 6.5 mm pins, and burnishing of 9.0 mm and 12 mm pins.

Figure 4. Optical micrographs from edge of UHMWPE pins after RandomPOD wear test. Contact surface diameter was (A) 4.0 mm, (B) 6.5 mm, (C) 9.0 mm and (D) 12 mm. Protuberances were typical of the entire bearing surface in (A) and (B), whereas only few of them were formed near edge in (C) and (D) and the predominant feature was burnishing.

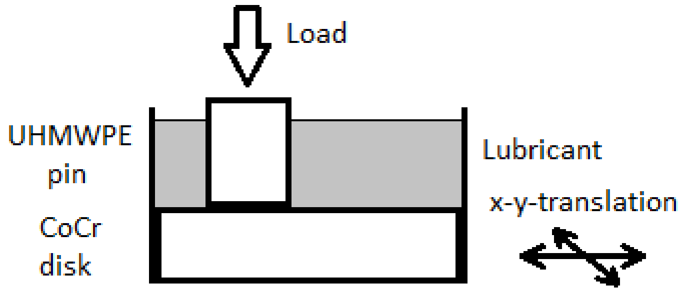

Figure 1.

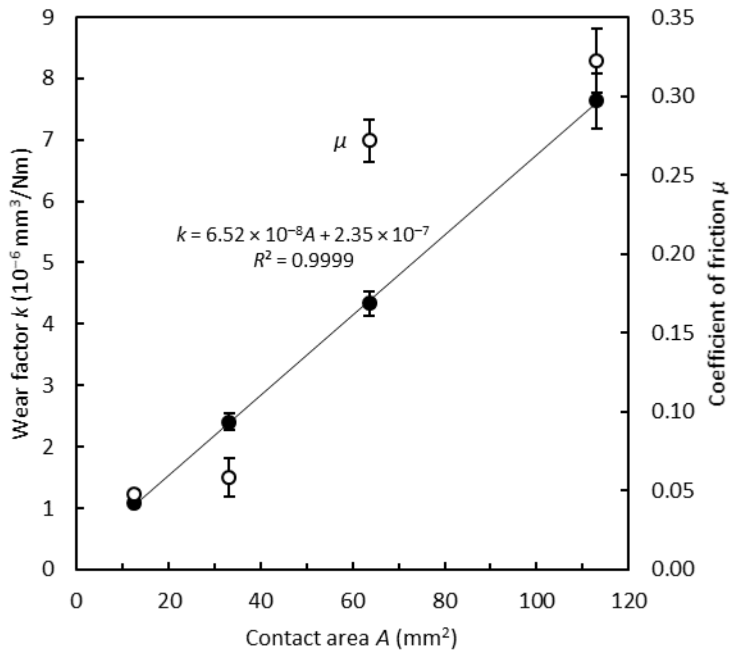

Figure 2.

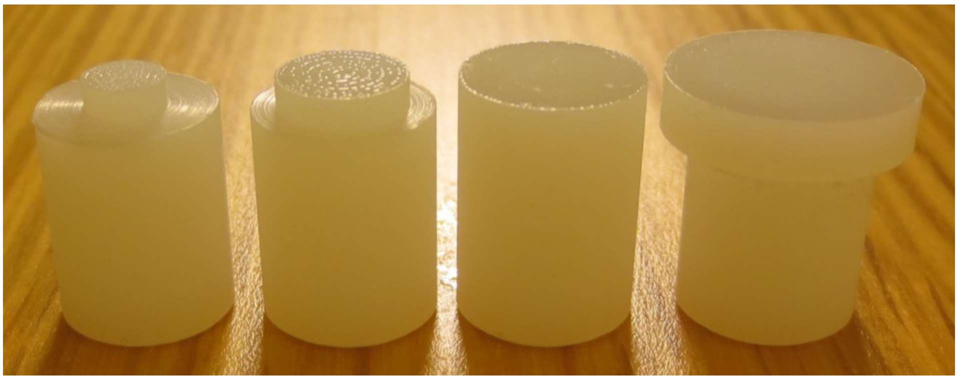

Figure 3.

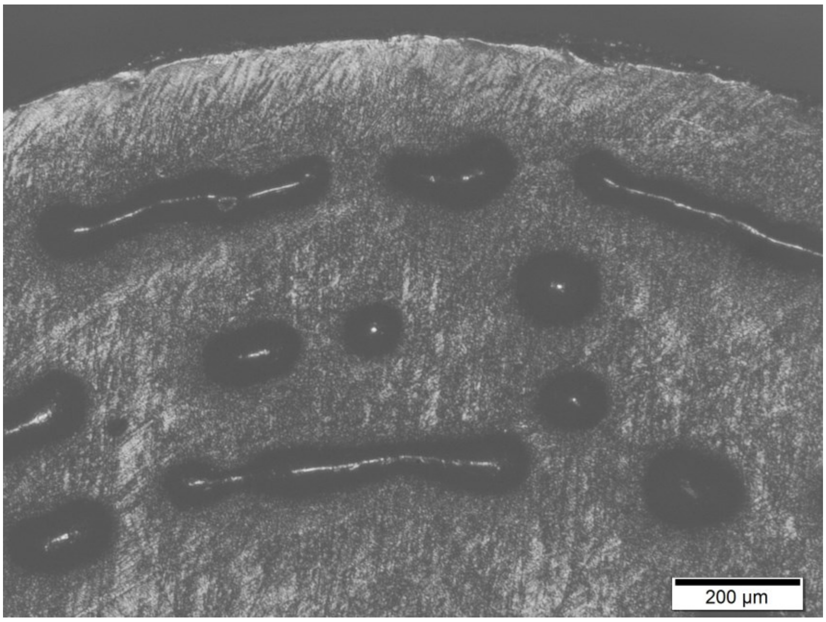

Figure 4A.

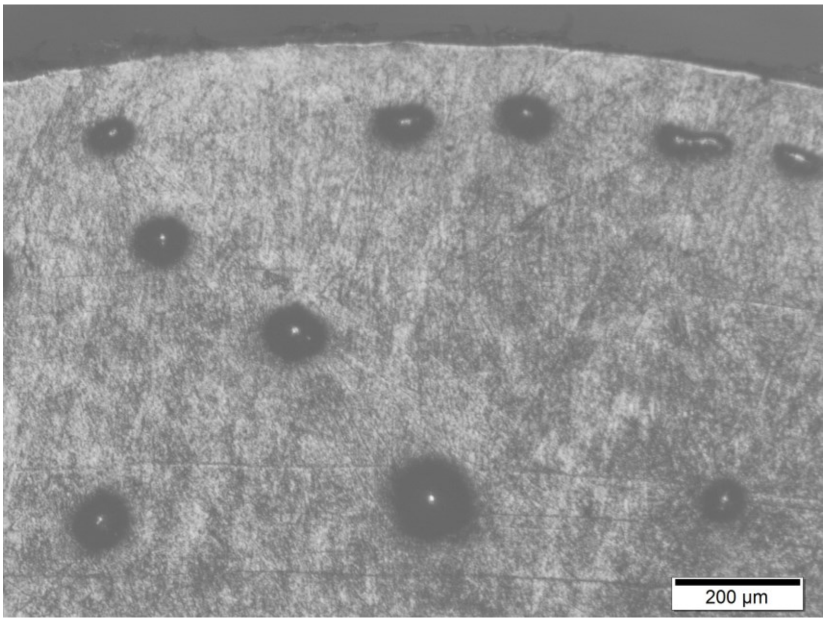

Figure 4B.

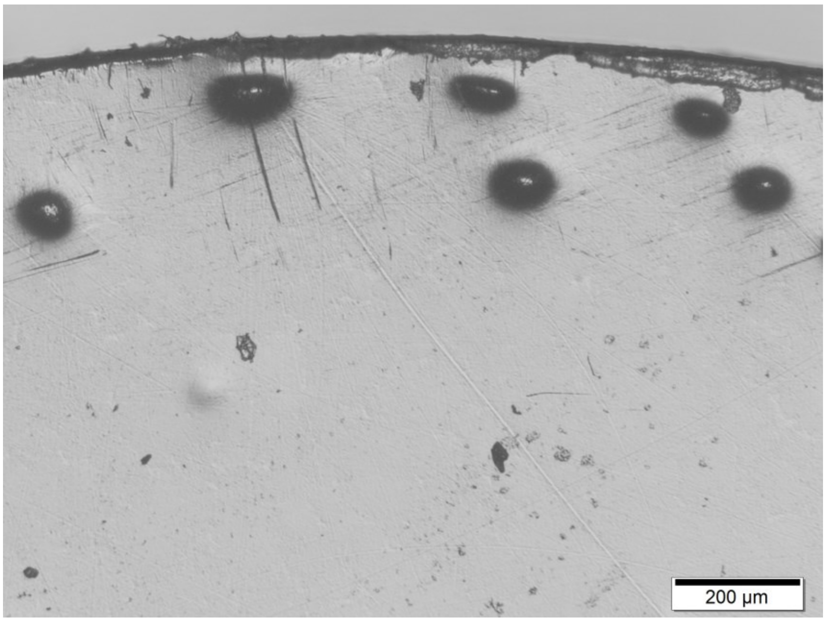

Figure 4C.

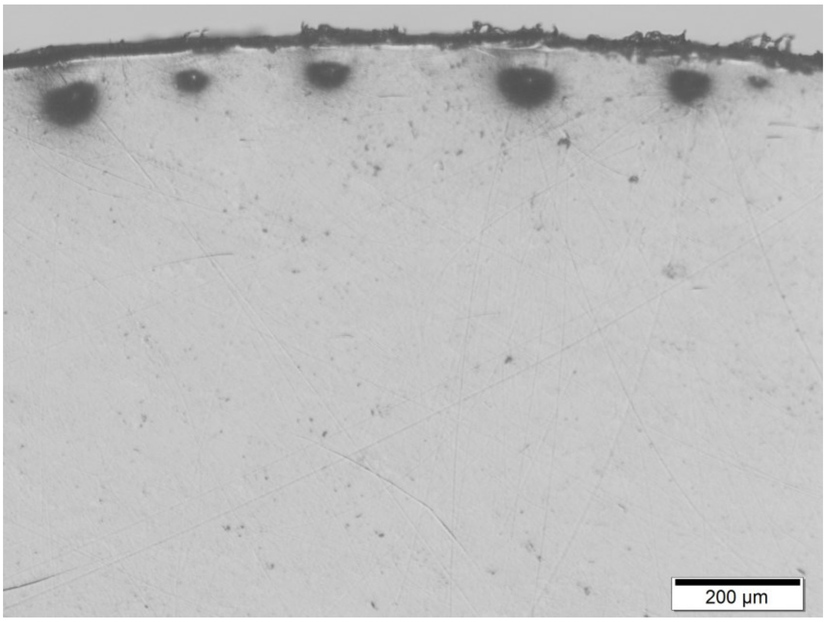

Figure 4D.