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The integrity of welded interfaces in ultra high molecular weight polyethylene: Part 1—Model

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Abstract

The difficulty of eradicating memory of powder–particle interfaces in UHMWPE for bearing surfaces for hip and knee replacements is well-known, and 'fusion defects' have been implicated frequently in joint failures. During processing the polymer is formed into solid directly from the reactor powder, under pressure and at temperatures above the melting point, and two types of inter-particle defect occur: Type 1 (consolidation-deficient) and Type 2 (diffusion-deficient). To gain quantitative information on the extent of the problem, the formation of macroscopic butt welds in this material was studied, by (1) modelling the process and (2) measuring experimentally the resultant evolution of interface toughness. This paper reports on the model. A quantitative measure of interface structural integrity is defined, and related to the "maximum reptated molecular weight" introduced previously. The model assumes an idealised surface topography. It is used to calculate the evolution of interface integrity during welding, for given values of temperature, pressure, and parameters describing the surfaces, and a given molar mass distribution. Only four material properties are needed for the calculation; all of them available for polyethylene. The model shows that, for UHMWPE typically employed in knee transplants, the rate of eradication of Type 1 defects is highly sensitive to surface topography, process temperature and pressure. Also, even if Type 1 defects are prevented, Type 2 defects heal extremely slowly. They must be an intrinsic feature of UHMWPE for all reasonable forming conditions, and products and forming processes should be designed accordingly.

Keywords: Adhesion; Fracture toughness; Interface; Joint replacement; Polyethylene; Modelling

1. Introduction

Medical grade ultra-high molecular weight polyethylene (UHMWPE) remains the preferred material for one of the bearing surfaces in total joint replacement, because of its high wear resistance and biocompatibility (in bulk). However, wear debris formation and accumulated damage in UHMWPE implants in vivo limit their durability, especially under the high stresses encountered in knee replacements. One factor that has been associated with failure of UHMWPE tibial inserts for knee replacement is "fusion defects" observed in explanted failed components [1].

Complete fusion is difficult to achieve in this material [2]. Fusion defects have been reported in both explanted and non-implanted UHMWPE prosthesis components. Usually, they have the appearance of either particle boundaries reflecting the powder flakes of as-polymerised UHMWPE resin [1,3,4] or white specks (also called white inclusions) or voids [5,6]. Based upon his observations, Bragdon and co-workers identified three different types of UHMWPE defect [5]. The first type was occasional areas of unconsolidated powder appearing as white inclusions of one to two millimetres and could be seen with the naked eye. The second type was associated with separation at the grain boundaries without the white inclusions. These could only

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be seen by light microscopy. The third type was even smaller and could only be seen on freeze-fractured surfaces under electron microscopy. These were 10–20 μm in diameter and showed bead-fibril organisation reminiscent of the UHMWPE as-polymerised powder. They proposed that these microscopic defects could lead to wear in total knee replacements by initiating surface and subsurface cracks.

Wrona and co-workers reported the size and shape of fusion defects in explanted UHMWPE tibial components to be similar to that of a cauliflower floret. Their sizes vary typically from 50 to 200 μm in diameter: matching the size range of the as-polymerised particles from which the components had been manufactured [1]. UHMWPE tibial components manufactured from material with fusion defects were found to be less resistant to the fatigue-fracture process than components without fusion defects.

Fusion defects cannot be considered an occasional manufacturing fault: they are common in UHMWPE prosthesis components. Landy and Walker found that all of 90 randomly chosen explanted components contained fusion defects [3]. In another study, fusion defects were identified in 44% of 122 UHMWPE explanted tibial components [7]. Moreover, numerous authors have reported fusion defects as being present in non-implanted UHMWPE components [8,9].

These fusion defects suggest the presence of weakly bonded locations in UHMWPE, leading to a predisposition for surface damage [3]. They could act as stress raisers and increase the possibility of crack initiation. Once the failure process starts at these sites, it may take a very short time to reach catastrophic failure of the component [10]. There is much evidence that fusion defects cause delamination and wear of UHMWPE components and that the delamination rate increases with the number of fusion defects [3,11,12]. The reason may be that delamination of the polymer surface is initiated by the development of a subsurface crack 0.5–1.5 mm below the surface, in an area where high stresses occurred at fusion defects [3,12–15]. Moreover, Oonishi and co-workers have shown that the volumetric wear rate tends to increase with an increasing number of fusion defects [16]. Thus, it is clear: fusion defects are a common feature of UHMWPE bearing surfaces in knee replacements, and they play a major role in their failure.

Finding a technically and economically viable solution to this problem is a challenging task for polymer engineering, and it remains unresolved. One obvious source of fusion defects may be prevented, by simply avoiding the use of UHMWPE powder coated by calcium stearate, that forms an additional barrier to inter-particle cohesion [17]. But there remains the intrinsic problem of UHMWPE: the great lengths of the majority of its molecules reduce its mobility in the melt, impeding consolidation and cohesion of the polymer during forming of the powder.

The present work is part of a wider study aimed at developing an engineering solution. In earlier work from our laboratory [18,19] we shed further light on the nature of "fusion defects". Thus we showed that the term itself is ambiguous, since two separate stages are involved in welding powder particles together to form a solid. Firstly, there is compaction and consolidation of particles by flow. Secondly, there is development of interparticle cohesion by molecular diffusion across the interfaces. Thus, if the first stage is incomplete interparticle voids remain, that we termed Type 1 fusion defects. These will give rise to stress concentrations when the component is loaded, and hence will be available as starter cracks for fatigue failure. However, even if the first stage is complete and there is full consolidation, the second stage may not be. In this case, there will be fully conforming, but diffusion-deficient, inter-particle interfaces, that we termed Type 2 fusion defects. These may not be visible under the microscope when as-moulded, but they were revealed as markings on the (side) surfaces of fractured specimens [18,19]. They are unlikely to be significant stress concentrators at small strains,[3] but because of their expected low strength and toughness they will represent vulnerable planes in a moulding: potential sites for fatigue crack initiation or propagation. Thus, in terms of "fusion defects" seen in prosthesis components, those in non-implanted components are definitely Type 1 defects. Those seen in explanted components, however, may have originated as Type 1 defects or alternatively as Type 2 defects that opened into voids under loads experienced during use. There is no doubt that defects of both these types often exist in UHMWPE. But further progress in finding the optimal engineering solution requires better understanding and quantification of (a) their dependence on processing conditions, and (b) their effects on the mechanical performance of the solid polymer.

The present paper is the first of a series addressing the underlying process: the welding of UHMWPE to itself. This is simplified by considering only the formation of butt welds between flat edges of well-consolidated moulded plates of UHMWPE. The simple geometry, combined with a few further simplifying assumptions, makes possible an analytical treatment of the build-up of integrity of the welded interface, the removal of Type 1 defects and reduction in severity of Type 2 defects. In addition, the geometry allows experimental measurements to be made of the toughness of the interfaces, by adapting the essential work of fracture (EWF) method used previously for ductile polymers including UHMWPE. Here the model is presented. A companion paper reports experimental measurements of interface toughness and relates them to results from the model [20].

[3]The elastic constants of polyethylene at, say, 37 °C are dominated by short-range molecular interactions that will be established across the interface essentially instantaneously once wetting occurs, hence no persisting elastic discontinuity and associated stress concentration are expected.