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THEORETICAL SIMULATION OF TEMPERATURE ELEVATIONS IN A JOINT WEAR SIMULATOR DURING ROTATIONS

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Introduction

Artificial joints are the most successful long-term treatment for arthritis. Artificial joints have improved the quality of life for millions of patients; however, one of their major limitations is that failure of the device requires a surgical revision. A wear simulator is a valuable tool for testing the long term wear behavior of artificial joints and developing optimal designs before they are implanted in clinical settings. One of the issues related to artificial joint wear is potential temperature elevations caused by friction between articulating components, which affects not only the lubricant in-between, but also induces heat conduction through the components of the simulator. It has been suggested that the temperature elevations, if sufficient, may roughen the component interface, therefore leading to increases in wear.[1-2]

The objective of this study was to simulate the temperature field in a joint simulator during rotations of artificial hip components: a ball on a cup. Simulation of a moving component on a fixed component was performed using COMSOL software package. The information from this study can be used to determine the maximum temperature elevation in the simulator and dominant factors that may contribute to the elevation.

Methods

A joint simulator currently used at the FDA for evaluating the long term wear behavior consists of three major components: a flat base representing the cup in a realistic joint, a cylinder representing the joint ball, and a lubricant layer between the base and the cylinder (Figure 1a). Note that the cylinder is held and controlled to rotate on the base at a frequency of 0.5 Hz, or two rotations per second. The load exerted on the cylinder is also controlled to represent the realistic load in clinical settings.

Based on the geometry of the apparatus, a theoretical model was developed using the COMSOL software package (Figures 1b, top view, Figure 1c side view). The base is represented by a cobalt-chrome disk with a diameter of 44.4 mm and thickness of 7.3 mm. The pin is made of ultra-high molecular weight polyurethane (UHMWPE) and has a shape of a cylinder that is 9.5 mm in diameter and 31 mm long. The lubricant layer is typically very thin and is approximately several μm. Here, this layer is not included in the model, however, the heat generation rate due to the friction is modeled as a boundary heat source only at the interface between the pin and the base. The pin rotates around the base center with a center-to-center distance of 15 mm.

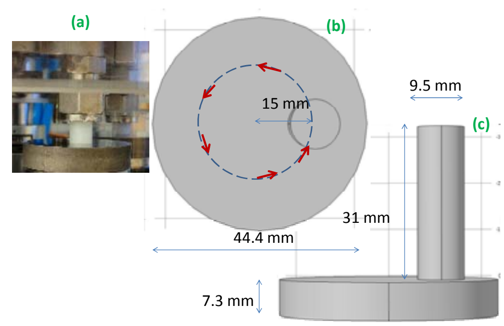

Figure 1. The experimental setup of the joint simulator and the computer Modeling of the pin and the base..

The heat generation rate due to friction is calculated by the following equation:

$Q_{generation}$ (J/s) = friction coefficient *x* load *x* velocity (1)

where the velocity is calculated from the frequency of the rotation and the center-to-center distance. The calculated $Q_{generation}$ is the boundary heat source used in the model. Since the pin rotates, the boundary heat source also moves with the pin. The initial condition of the simulation is 25°C in the domain in equilibrium with the surrounding. The bottom surface of the base and the top surface of the pin is prescribed as adiabatic boundary conditions, while the rest of the boundary surfaces are subject to a convection boundary condition (h = 10 W/m^2 °C, T_∞=25°C).

An experimental study of UHMWPE pins on cobalt-chrome disk was designed in a pin-on-disk configuration. The disks had a 1mm diameter center hole for thermocouple accommodation. The water bath temperature (external environment), temperature of lubricant and temperature at the surface of the disk center were continuously measured using k-type thermocouples. For the experimental study bovine serum was used as lubricant (20 mg/ml).

Results and Discussion

Table 1 gives the thermal properties of the base and the pin.[1-2] The total simulation time is 10 seconds or 5 rotations. We assume that the load is 354 N, the friction coefficient is 0.065,[1] and the velocity can be calculated as 0.047 m/s. The total heat generation rate at the interface is then calculated as 1.08 W.

Table 1. Thermal properties of the components

	k (W/m°C)	ρ (kg/m^3)	c_p (W/kg°C)
Base (cobalt-chrome)	14.86	8387	422.87
Pin (UHMWPE)	0.21	900	1000

The temperature contours in the three-dimensional simulation domain can be seen in Figure 2, where the four images give the different pin locations on the base component within one rotation. It clearly shows the success of modeling a moving component using the COMSOL software. This figure demonstrates a continuous temperature elevation at the interface between the base and the pin, and continuous heat conduction to the rest of the base region. In contrast, most of the pin region shows only mild temperature elevations.

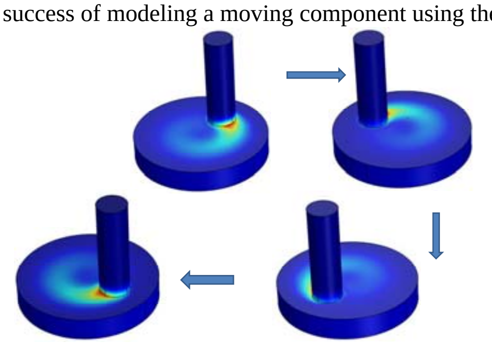

Figure 2. The 3-D images during the simulation of rotation of the pin on the base.

Figure 3 presents the temperature contours in the side view. The first image shows the initial uniform temperature field of 25°C. The second image gives the temperature field after the 1st rotation (Figure 3b), and the temperature elevation at the interface is approximately 1.1°C after the 1st rotation, later, it continues to rise. Once the 5th rotation is completed, the maximum temperature at the center of the base is around 26.7°C, 1.7°C higher than its baseline (Figure 3f). The simulation results agree with the experimental results observed, where the surface temperatures at the center of the disk was always 1.27°C higher compared to external environment. The non-continuous heat generation rate at the interface of any specific base region due to the rotation of the pin has resulted in on-and-off patterns of the temperature behavior. However, due to the frequency of the rotation, one can still see significant residual heat conducted in the base component.

Temperature elevations in the base component are evident as the pin rotates (figure 4). Due to the friction-induced heat generation, a tail-like region of elevated temperature can be seen following the pin's track. Comparing Figure 4b (after the 1st rotation) to Figure 4f (after the 5th rotation), one can see significant heat accumulation in the base component. In addition, the maximum temperature observed in the top view does not occur exactly at the center of the pin's bottom surface (Figure 4f). The maximum temperature increased from 26.3°C, after the 1st rotation, to 27.1°C after the 5th rotation. For the base region not in direct contact with the pin, its temperature rises steadily to 25.5-26°C after the 5th rotation. The steady increase in the base region of the disk not in direct contact with pin is verified experimentally by observing a higher lubricant temperature of 0.7°C relative to the external environment.

In summary, we were able to conduct a preliminary study to show the feasibility of using the COMSOL software package to simulate heat transfer in a domain with moving components and a moving boundary source term. The finite element model for temperature changes agrees in general trends with experimental data. Five rotations of the polyurethane pin on the cobalt-chrome generate more than 2.1°C temperature elevation from its initial baseline temperature. Temperature elevations occur primarily in the highly conductive base component. In future, additional modeling will be conducted to simulate the temperature field following more pin rotations.

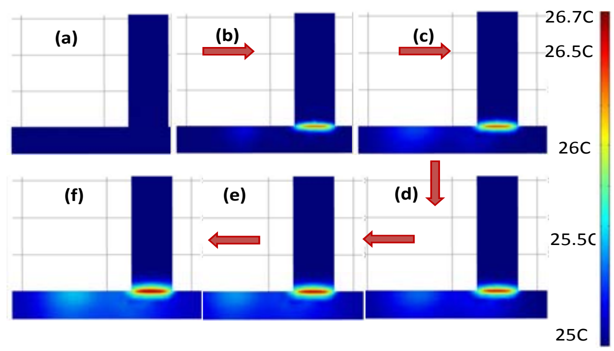

Figure 3. The simulated temperature fields in the pin and the base at the end of each rotation.

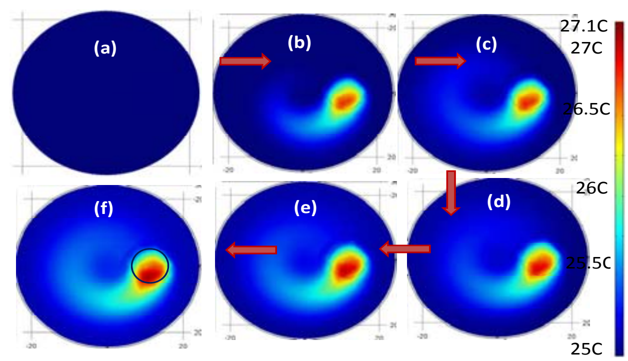

Figure 4. The simulated temperature field of the top surface of the base at the end of each rotation.

Acknowledgement

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