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Running-in behavior of internally plasma-treated silicone tubing

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ABSTRACT

When employed in biomedical applications, the bore of silicone tubing must be modified to become highly lubricious, for example, by means of plasma treatment. In this context, the determination of the degree of lubricity is normally accomplished with the aid of a frictional tribopartner. In practice, this determination is made uncertain and overly lengthy due to running-in behavior. The focus of this investigation is to characterize the running-in behavior, diagnose the factors that contribute to its existence, and develop means by which to eliminate the running-in process. The tribological system that was studied may be categorized as polymer/metal frictional interaction. It was discovered by systematic experimentation that transfer of material, rather than traditional wear, is at the root of the encountered running-in phenomena. These investigations included frictional-based and chemical-detection methodologies. Once the fundamental cause of the running-in behavior had been discovered and confirmed, a method for eliminating running-in was proposed and experimentally validated.

1. Introduction

Running-in behavior is intrinsic to tribological processes [1]. During the running-in period, compatibility between moving parts is established by mechanical wear, chemical action, structural changes, and other mechanisms. There is an extensive literature documenting the operating conditions that control the running-in process, its duration, and its impacts for a very wide range of tribological systems. A much more limited literature is devoted to means of controlling running-in behavior or even eliminating it altogether.

There is a broad array of materials for which running-in behavior has been widely observed and documented. Among these, tribological interactions between polymeric media and metals are of particular interest here [2–11]. This focus is motivated by the use of polymeric media in biomedical applications.

For biomedical applications where a metallic device with its concomitant lead wires are implanted within the human body, biomedical-grade silicone in tubing form is the near-universal choice for insulating the leads. The silicone tubing used for this study is a polymer that is primarily composed of polydimethylsilioxanes or PDMS with fumed silica as a bulk filler. The tubing has tear resistant properties and is suitable for human implants. For optimal use of the tubing, both its internal and external surfaces must be highly lubricious. In particular, the bore of the tubing houses electrical leads which are extremely difficult to put in place in the presence of the natural tackiness of the internal surface of the tubing. To significantly diminish the tackiness and obtain lubricious surfaces, plasma treatment has been used successfully.

Subsequent to the plasma treatment, evaluation of the achieved degree of lubricity is performed by means of the U-bend test which will be described shortly. The tribopartner (force-sensing element) used in the execution of this test is a nickel alloy coil used as received. The coil is compositionally an MP35N alloy (35 wt% Co, 35 wt% Ni, 20 wt% Cr, and 10 wt% Mo) which is a nonmagnetic material with an ultrahigh tensile strength. The material is ductile and tough with exceptional corrosion resistance. The measured forces from the U-bend experiments performed here exhibit test-order sequence effects, with the initial measurements in the sequence tending to be higher and more variable, whereas later force measurements tend to be more stable. This outcome is clearly indicative of running-in behavior.

The goals of this investigation are twofold. The first is to determine the mechanism which underlies the observed running-in behavior, and the second is to develop a protocol to eliminate the behavior.

2. Apparatus and procedure

The polymeric medium in question is a biomedical-grade silicone tubing, whose inner and outer diameters are, respectively, 0.09 and 0.12 cm. The as-received tubing is arranged to form a single 762 m length on a processing spool to plasma process. Subsequently, the bore and the external surfaces of the tubing are plasma treated in a

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batch-mode manner to reduce the tackiness-based friction inherent to the medium. The treatment consists of subjecting the tubing surfaces to plasma processing that deposits a thin layer of material that makes the surface more lubricious [12]. Prior to the use of the tubing, it is necessary to evaluate the outcome of the treatment to determine whether the lubricity requirements have been fulfilled. The lubricious status of the tubing bore is, by far, the most critical characteristic, and future attention will be focused on it here.

The lubricity evaluation is performed by use of the U-bend test, a basic version of which is presented in Fig. 1. The test was developed in the writers' laboratory and is not an industrial standard. A U-shaped groove can be created by means of a rotating ball end mill that cuts into a metal plate along a trajectory that is numerically controlled. The surface finish of the groove is not relevant to the outcome of the test. For the present tests, the radius of curvature of the bend was set at 1.3 cm after preliminary experiments performed to give the most accurate result for the force measurement. Prior to the execution of the test, a carefully executed protocol is employed to obtain discrete samples of processed tubing each having a length of 36.2 cm. Next, a nickel alloy coil tribopartner without markings, shown in Fig. 2, is carefully threaded through the silicone tubing. The clearance between the outside diameter of the coil and the inside diameter of the treated tubing is about 0.01 cm. Subsequent to the introduction of the tribopartner, the tubing is locked in place at its longer end as indicted in Fig. 1. The locking action holds the tubing in place but does inhibit the movement of the coil. The contact area of the coil with the tubing is approximately 2.32 cm^2

At the shorter end of the test assembly, a small length of the coil is exposed. This length is gripped by a clamp that is connected to a load cell. The test is performed by exerting a fixed pull on the coil for a programmed distance at a set speed 38 cm/min During the pull, the force is registered, but the post-processing algorithm is programmed to ignore the force needed to overcome static friction. The separation between the friction and bending forces is not relevant to the goal of the work, which is to display how to avoid running-in behavior. The final test result is the average pull force.

Test specimens cut from the plasma-processed tubing were randomly organized into six batches, with 14 specimens in each batch. Each batch was assigned its own tribopartner coil. This same coil was used sucessively as the tribopartner in the U-bend test for each of the 14 test specimens in each batch. The 14 individual force data points for each batch were non-dimensionalized by means of the *Z*-score method, where the *Z* value for a particular specimen *i* is defined as follows:

$$Z_i = \frac{X_i - \overline{X}}{s}, \quad 1 \le i \le 14 \tag{1}$$

where X_i, $\overline{X}$, and s denote an individual force data point, the batch-mean force, and the batch standard deviation respectively. In physical terms, Z_i is the number of standard deviations that an individual data point is from the mean. Therefore, the *Z* values reflect variability within one batch. The *Z*-data for each batch are particularly relevant with respect to the trend as a function the test sequence. The data reflect variability within one batch but not a capability to determine if one batch is 'better' than another.

The experiments were performed in an air-conditioned space but no other overt controls were in place to diminish the important factor of humidity on the friction results.

3. Running-in results

Fig. 3 conveys the data for all six of the batches, with the results for each batch displayed on a separate graph. Inspection of Fig. 3 reveals a common trend for all batches. The initial data point of each sequence exhibits the highest force among all of the 14 data for that batch. The succeeding data in the measurement sequence display a clear downward trend and, aside from normal scatter, it appears that a constant value is ultimately attained. The rate of downward progression of the data varies from batch to batch. For example, for batch 1, it appears that the constancy of force is not attained until the coil has interacted with 10 tube specimens, whereas force constancy for batch 2 is achieved after five interactions. Notwithstanding these differences in detail, Fig. 3 displays traditional running-in behavior.

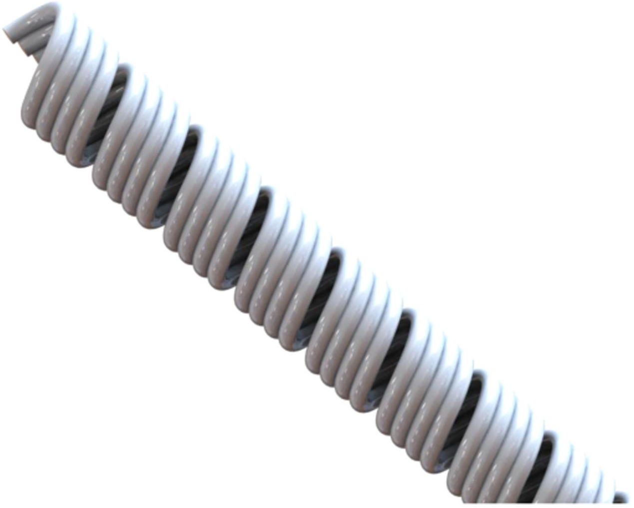

Fig. 2. Nickel alloy tribopartner for the implementation of the U-bend test.

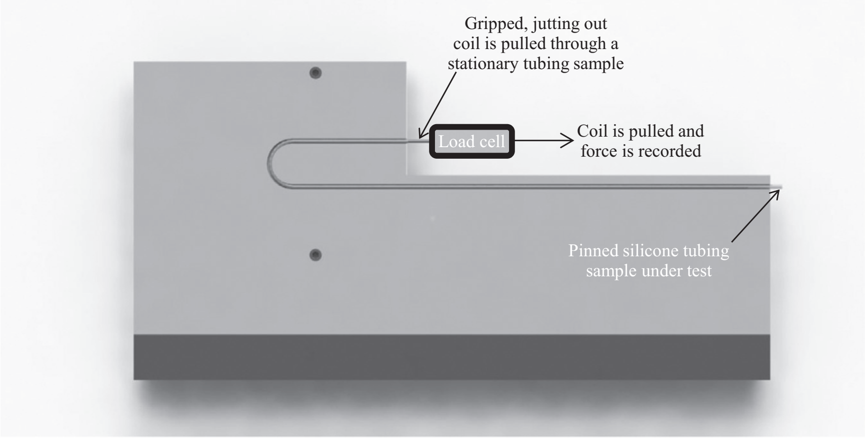

Fig. 1. Plan view of the U-bend test apparatus.