Effects of Temperature and Stress Level on Creep and Tensile Property of Polypropylene Sutures

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ABSTRACT: An investigation was conducted on creep behaviors of polypropylene sutures under different temperatures and stress levels in a temperature-controlled water bath. The study showed that temperature and stress level significantly affected the creep behaviors of the sutures. High temperature and stress level resulted in large creep and permanent deformation to the sutures. The creep data could be well described by an empirical formula. For most of the test conditions, the creep tests caused limited permanent deformation in sutures. Dependency of the permanent deformation on temperature may be illustrated by an Arrhenius-type equation. The tensile properties of the sutures were not adversely affected by a short-term creep test, indicating good mechanical performance for the polypropylene sutures. For the creep experiment of less than 3 h, the creep rupture of the sutures was observed at a stress level of 220 MPa and temperatures ≥ 37°C. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 90: 3882–3888, 2003

Key words: polypropylene sutures; creep; tensile property; temperature and load effects; viscoelastic properties

INTRODUCTION

The viscoelastic behaviors over a wide temperature range, time duration, and loading conditions are among the most important properties for polymeric biomaterials. As such, polymer-based wound closure medical devices may behave viscoelastically during use. Evaluation of creep and stress relaxation of medical sutures becomes necessary because these properties may be related to their clinical performance. Additionally, our lab has been involved in the development of a fatigue test method for sutures. It was found that creep and stress relaxation contribute a great deal to the stiffness change of sutures during fatigue experiments. Understanding creep and stress relaxation of sutures will help in the development of a fatigue test method and the understanding of fatigue properties among others.

Poly(propylene) (PP) sutures are one class of important and widely used medical sutures. They find applications in general, cardiovascular, ophthalmologic, plastic, and orthopedic surgery, and in securing implants such as intraocular lenses and heart valves. Medical-grade PP fibers are also used to make surgical meshes for hernia repair and abdominal wall replacement. In the past, much work has been performed on PP sutures in the areas of clinical applications, tensile properties, knot security, structural analysis, and *in vitro* and *in vivo* studies.[1–16] However, relatively few investigations could be found on their viscoelastical properties. To the authors' knowledge, there are no studies on how the tensile property of PP sutures would change after they have been subjected to creep testing, although tensile strength is one of the most important properties for these sutures. To try to close the gap, we conducted a series of creep and stress relaxation experiments on PP sutures in a temperature-controlled water bath. The water bath would provide an *in vitro* condition to simulate body environment. Reported here are the creep results. Specifically, the effects of temperature and stress level on creep behaviors of PP sutures were evaluated. Effects of creep test conditions on tensile properties and permanent deformation of the sutures were fully examined.

EXPERIMENTAL

Materials

The experimental materials used in this study were polypropylene (PP) sutures manufactured by Ethicon (Somerville, NJ). They were size 2-0 blue monofilament sutures with a nominal diameter of 0.32 mm. For the purpose of this study, the sutures were cut into specimens of 430-mm length. Five samples were prepared for each test condition.

Creep test procedure

Creep is generally defined as deformation of a material under constant load at constant temperature. To

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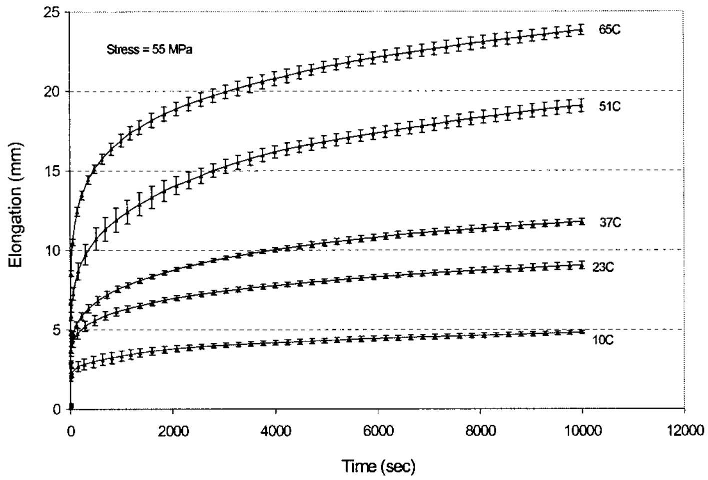

Figure 1 Creep behaviors of PP suture at 55 MPa and different temperatures.

perform a creep test, three key requirements are expected: (1) no shock during loading, (2) applying constant load, and (3) continuously monitoring deformation. It was found that programming of a creep test procedure could be easily realized using TestStar IIs MultiPurpose TestWare (MPT) software of MTS Corp. (MTS Systems, Eden Prairie, MN) The creep experiments were conducted on an MTS 858 Mini Bionix tester attached with a temperature-controlled water bath with deionized water. In comparison to a conventional oven, a water bath was considered to have better heat transfer and temperature control, and to be closer to body environment. The suture was connected to the MTS tester by suture grips and completely immersed into the bath. The gauge length (test section of sutures) was 76 mm. This was measured between two center points of suture grips. Five temperatures of 10, 23, 37, 51, and 65°C and three stress levels of 55, 110, and 220 MPa were selected. The lowest stress level was about 10% of suture tensile strength. Each creep experiment lasted 167 min (10,000 s). The load, time, and deformation (specimen elongation) were recorded, from which changes of deformation with time were monitored.

Permanent deformation calculation

It is important to know whether creep tests will cause any plastic deformation or permanent deformation in the sutures. This was examined by comparing the length of sutures before and after creep tests using the following formula:

$$\Delta L = \frac{L_c - L_0}{L_g} \times 100\%$$

where ΔL is the percentage permanent deformation; L_c is the suture length after creep testing (measured after at least a 7-day recovery at room temperature); L_0 is the original length; and L_g is the gauge length. These dimensions were measured by an engineering ruler. The data from this formula should be considered as maximum permanent deformation that a specimen may have in a creep test.

Tensile test

The purpose of the tensile test was to examine whether the tensile properties of the sutures would change after they had been creep-tested. To this end, the tensile tests were run on the creep-tested suture samples at room temperature using an Instron 4500 tensiometer with a 500*N* load cell after they had a recovery time of at least 7 days at room temperature after creep tests. A gauge length of 60 mm and an initial strain rate of 3.6%/s were used. The tensile properties were calculated based on the original cross-sectional area of a specimen before the creep test.

Data analysis

To determine statistical significance, the tensile data were analyzed by multiple comparison (Tukey–Kramer HSD) using JMP software (SAS Institute, Cary, NC). Values were significant at $p = 0.05$. Whenever possible, the experimental data were presented as means ± SD.

RESULTS AND DISCUSSION

Creep behaviors

The typical creep experimental results are presented in Figures 1 and 2. It is clear from these figures that the creep elongation increased with time. Generally, the creep deformation process can be divided into three

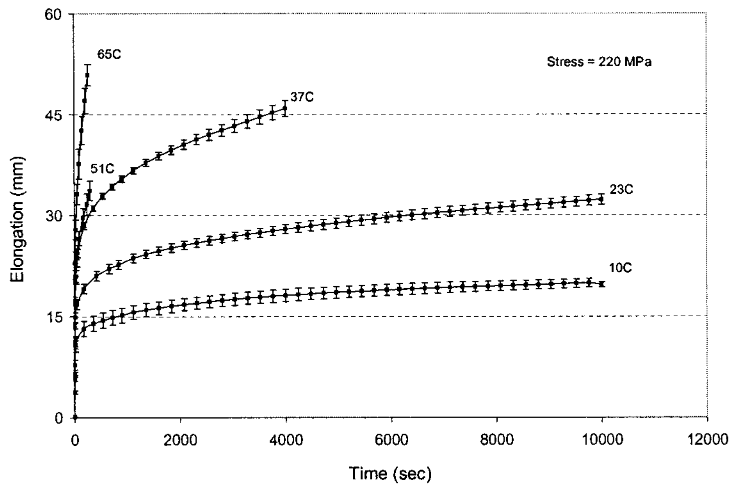

Figure 2 Creep behaviors of PP suture at 220 MPa nd different temperatures.

regions: (1) fast creep deformation region; (2) slow creep deformation region; and (3) the region between these two, or transition region. The fast creep deformation region consisted mainly of elastic deformation and ended quickly. The suture deformed viscoelastically in the slow creep deformation region and this region makes up most of the creep process. The creep deformation progressed gradually in this region. The permanent creep deformation predominated in this region. The transition region took only a few minutes to complete.

The stress levels had a great impact on the amount of creep deformation of the sutures. This can be understood by examining the data in Figures 1 to 3. The higher the stress, the greater the creep deformation. When the stress was doubled, the creep elongation was almost doubled. The experimental results show, for example, that the elongation at the end of creep tests was about 9 mm at 23°C for a stress level of 55 MPa; when the stress was increased to 110 MPa, the elongation was about 18 mm; and when the stress was further increased to 220 MPa, the corresponding elongation was about 32 mm. Thus there was about a fourfold increase in elongation when the stress was increased from 55 to 220 MPa. Such results may suggest that the increase in creep deformation was proportional to the increase in load or an approximate linear relationship between them when the temperature was constant. However, Figures 1 to 3 show that the rate of creep propagation did not seem to be greatly affected by stress levels.

The dependency of creep behavior on temperature can be understood from Figures 1 and 2. Similar to the stress level, the temperature had significant effects on the creep properties of the sutures. The higher the temperature, the greater the creep elongation. This is

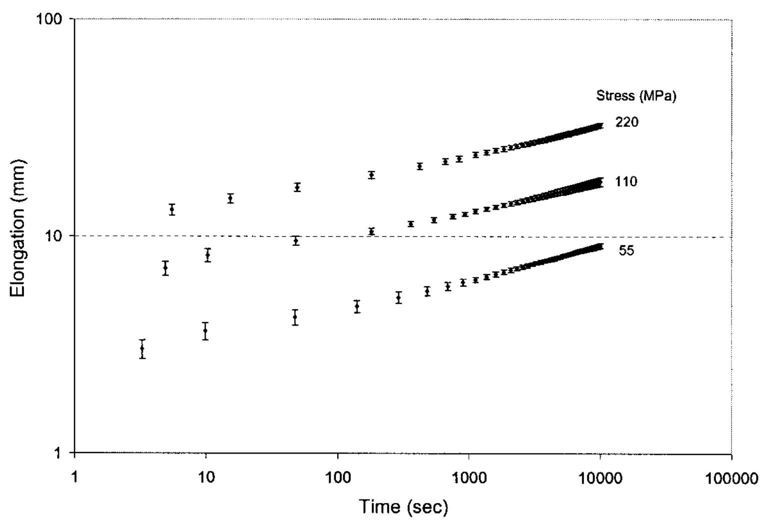

Figure 3 Creep experimental results at 23°C.

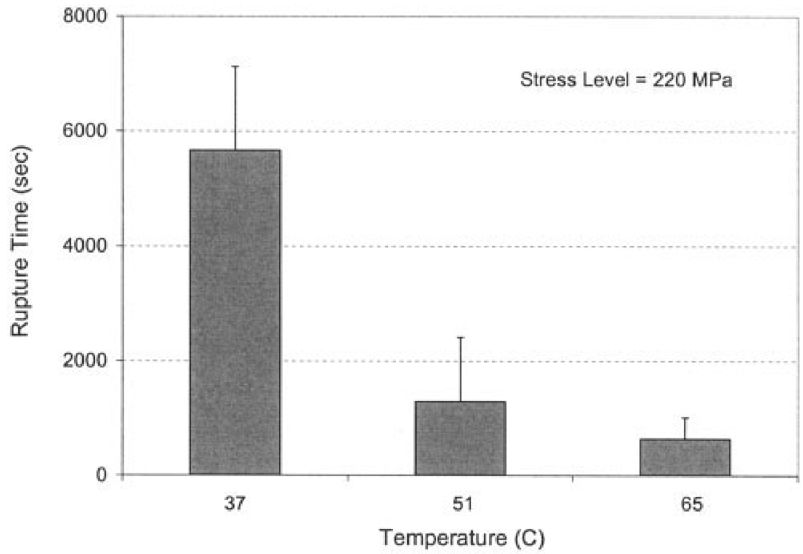

Figure 4 Effect of temperature on creep rupture time at a stress level of 220 MPa.

because high temperature renders the sutures more compliant. When the temperature was increased from 10 to 65°C, the elongation was increased more than 300% for all three stress levels.

Although this study was not intended to investigate the creep rupture of the PP sutures, the creep ruptures were observed at the highest stress level of 220 MPa. Figure 2 illustrates such results at 220 MPa and 37, 51, and 65°C. The data in this figure show the shortest time when the creep rupture occurred at each test condition for three samples. Figures 4 and 5 illustrate the averaged time and elongation at which creep rupture occurred for the three test conditions. The higher the temperature, the shorter the average creep rupture time, but the greater the creep rupture elongation. The creep rupture may possibly be caused by (1) the rapid increase in the creep elongation, which exceeded the ultimate elongation of the sutures; and (2) the reduction in cross section that led to stress increase, which exceeded the breaking strength of the sutures. These, ultimately, were attributed to the combined effects of load and temperature. However, one should understand that such high load and temperature levels will not appear in the intended application of the size 2-0 PP sutures.

Modeling of creep

It is desirable to illustrate the creep behavior of a material using some analytical formula. If one can derive a formula based on the short-term creep experimental data, then it is possible that the long-term creep behavior of a material could be predicted. This is important because in most actual cases we will not be able to run a month- or year-long creep experiment,

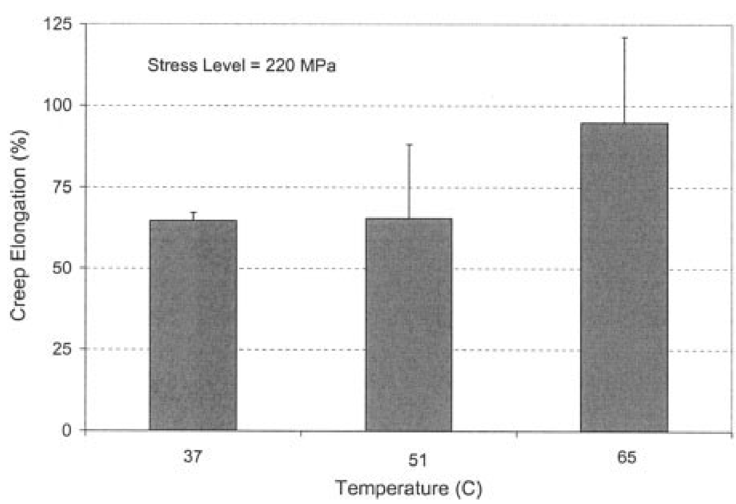

Figure 5 Effect of temperature on creep rupture elongation at a stress level of 220 MPa.

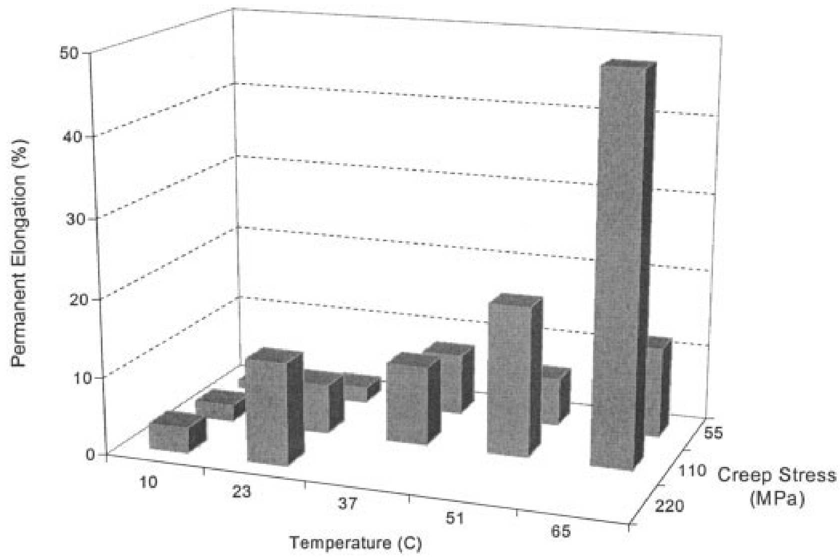

Figure 6 Effects of testing conditions on permanent deformation.

although we wish to know the long-term creep behaviors, given that permanent implants will be in the body for years. To explore this, the representative creep data at 23°C are replotted in Figure 3 in a double-logarithmic graph. One could see that there are nearly linear relationships between elongation and time, suggesting that the creep data could be described by the following equation:

$$\ln L = a + b \ln t$$

where L is the creep elongation, t is the creep time, and a and b are constants. The deviation of experimental data from the above equation increases with increases in load and temperature, indicating that the sutures tended to behave more nonlinearly viscoelastically at high load and temperature. The above equation is a very practical formula given that in no case will creep time equal zero. It is easy to determine the constants a and b using curve fit. In fact, the equation illustrates the creep data well with $R^2 > 0.90$ for all the experimental conditions. Furthermore, the dependency of creep behaviors on temperature and load can be evaluated by examining the effects of temperature and load on the constants a and b. The same analysis could be applied to the data at stress levels of 55 and 110 MPa and temperatures higher than 23°C.

Permanent creep deformation

The permanent deformation of PP sutures after creep tests is summarized in Figure 6. It is clear that the

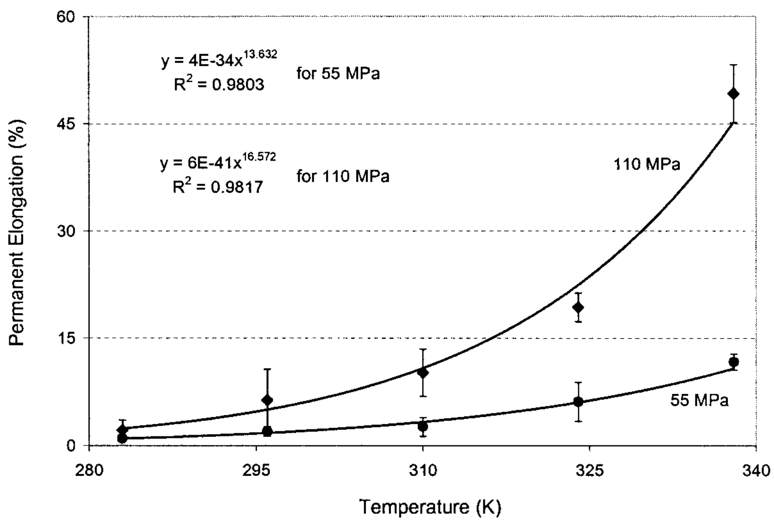

Figure 7 Change of permanent creep deformation with load and temperature.

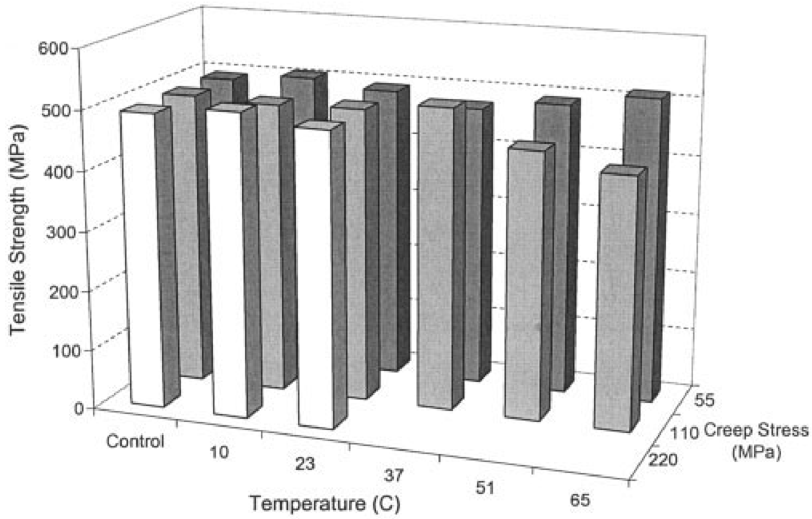

Figure 8 Tensile strength of PP suture after creep tests.

amount of permanent deformation increased with the increases in load and temperature. The smallest permanent deformation was found to be about 1% at 10°C and 55 MPa. However, at 65°C and 110 MPa, more than 40% permanent deformation was observed. Figure 7 illustrates the change of permanent deformation with temperature for the stress levels of 55 and 110 MPa, which is well described by a power law. Furthermore, it was found that the temperature dependency of permanent deformation could be described by an Arrhenius-type equation as follows:

$$\Delta L = Ae^{-(E_a/RT)}$$

where ΔL is permanent deformation, A is a constant, R is the gas constant, E_a is the active energy, and T is the temperature. By curve-fitting the data ($R^2 > 0.90$), E_a was found to be 8.35 and 10.17 kcal/K mol at 55 and 110 MPa, respectively.

Tensile properties

The effects of creep tests on tensile properties of the PP sutures are presented in Figures 8 to 10. These are the averaged data points. It seems that the tensile properties of the sutures were affected only at high stress level and temperature. Statistical analysis showed that compared to the control the tensile strength values were not affected significantly by the creep tests. The sutures creep-tested at 110 MPa and 65°C had significantly lower strength than those creep-tested at 55 MPa and 65°C, 220 MPa and 10°C, 55 MPa and 10°C,

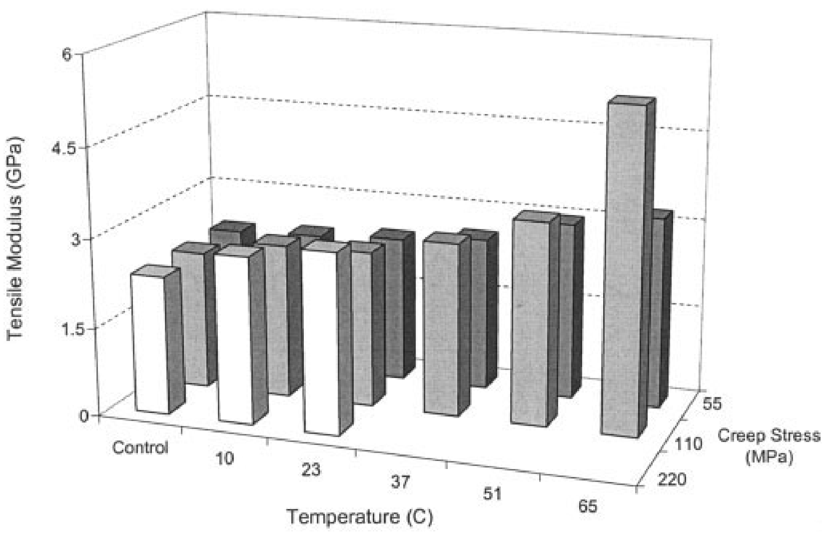

Figure 9 Tensile modulus of PP suture after creep tests.

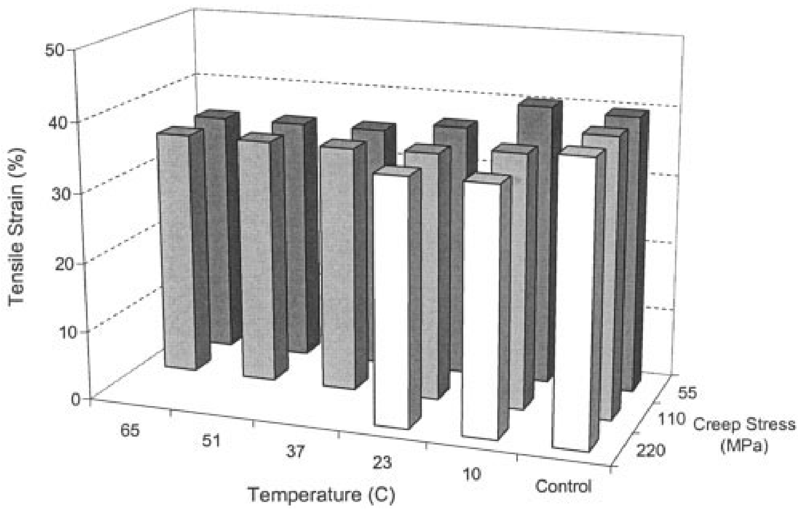

Figure 10 Tensile elongation of PP suture after creep tests.

and 110 MPa and 37°C. Such results suggest that the PP sutures maintain their tensile strength after the creep tests in this study. Compared to the control, the sutures creep-tested at 110 MPa and 65°C, 110 MPa and 51°C, 55 MPa and 65°C, 220 MPa and 23°C, 55 MPa and 51°C, 110 MPa and 27°C, and 220 MPa and 10°C showed significantly higher modulus, indicating that the creep tests were further drawing and orienting the sutures. Finally, all the testing conditions except 55 MPa and 10°C significantly reduced the breaking elongation of the sutures. The above results may suggest that tensile modulus and elongation could be more sensitive to further drawing and orientation compared to tensile strength for the PP sutures.

CONCLUSIONS

The effects of load and temperature on creep behaviors of size 2-0 PP sutures were investigated in a temperature-controlled water bath. The results showed that the creep properties of the sutures depended significantly on the experimental conditions. The creep data could be well described by an empirical formula. The creep tests of the sutures caused significant permanent deformation at high stress and temperature. Effects of temperature on the permanent deformation can be illustrated by an Arrhenius-type equation. Creep did not affect the tensile strength of the sutures. For a short-term creep, the creep rupture was observed at high load level and temperature.

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