

Mechanical properties variation and constitutive modelling of biomedical polymers after sterilization

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Purpose: In this work, the mechanical behavior of two block copolymers for biomedical applications is studied with particular regard to the effects induced by a steam sterilization treatment that biomedical devices usually undergo in healthcare facilities. This investigation is aimed at describing the elasto-plastic behavior of the stress-strain response, determining a functional dependence between material constitutive parameters, to obtain an optimal constitutive model. *Methods:* The mechanical properties of these polymers are analyzed through uniaxial tensile tests, before and after the sterilization process. The effect of sterilization on the mechanical behavior is evaluated. The Ramberg–Osgood model is used to describe the elasto-plastic behavior of the stress-strain response. *Results:* Data from uniaxial tensile tests are discussed in the light of previous data on the same polymeric materials, in order to highlight the correlation between physicochemical and mechanical properties variation. The material constitutive parameters are determined and the functional dependence between them is found, thus enabling an optimal constitutive model to be obtained. *Conclusions:* The effect of sterilization on the material constitutive parameters is studied, to evaluate the suitability of the model in describing the mechanical response of biomedical polymer before and after sterilization treatment. The same approach can be applied to other biomaterials, under various tensile tests, and for several processes that induce variation in mechanical properties.

Key words: sterilization, elasto-plastic behavior, constitutive model, biocompatible polymers, elastic properties, biomedical device

1. Introduction

The use of biomedical polymers for different applications has assumed a growing relevance, due to the promising combination of enhanced mechanical properties and biocompatibility. Significant challenges are faced in the development and characterization of polymers for biomedical applications, especially addressing their reliability and stability [10]. Indeed, the physicochemical and mechanical properties of biomedical polymers, which are exposed to physiological conditions, must remain constant in vivo [15]. The interaction of biomaterials with water and reactive environment can potentially lead to problems in implanted devices [17], eventually leading to dangerous

consequences as explant and replacement. Degradation of polymers may be induced by several factors [14], [19], including sterilization [16], [18], which is commonly carried out on medical devices. In particular, steam sterilization, which is achieved in an autoclave (100% relative humidity) at high temperature (above 115 °C) [12], is a very frequently used method. During the sterilization process, the combined effect of high temperature and humidity may affect polymer properties. The consequences of sterilization on the micro-phase structure and mechanical properties of biomedical polymers were investigated in an earlier work [18]. Some block copolymers that are currently adopted for the manufacturing of biomedical devices were selected for this purpose. These thermoplastic elastomers are frequently used in urethral and vascular

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catheters, intra-aortic balloon pumps, artificial heart components, drug delivery systems, microfluidic devices and micro-arrays [4], [5], [8].

The possibility to tailor the mechanical, micro-structural and chemical properties of block copolymers for specific applications has prompted an extensive research aimed at using these materials in innovative applications. In particular, different classes of copolymers have been analyzed in this work, including a thermoplastic polyurethane (TPU) and a poly(ether-block-amide) (PEBA). The use of these copolymers for the manufacturing of biomedical devices is mostly related to their mechanical stability and durability in use conditions. The consequences of sterilization on TPU and PEBA were investigated by means of different physicochemical characterization techniques, showing that steam induces a modification in the crystalline conformations of copolymers with a pre-existing hydrogen bonding network, as TPU and PEBA [18]. Therefore, mechanical properties of these polymers significantly change after sterilization, depending on the micro-domain structure variation.

In this work, the investigation of the mechanical behavior of biomedical polymers before and after sterilization is extended, leading to the formulation of a constitutive model addressing their mechanical response. Constitutive parameters are evaluated by the minimization of a function that specifies the discrepancy between model results and experimental data. The same approach is used for the constitutive characterization of TPU and PEBA, before and after sterilization, and the functional dependence between some of the resulting constitutive parameters is evaluated.

2. Materials and methods

2.1. Materials, sample preparation and sterilization

TPUs are segmented block copolymers comprising hard and soft segment blocks. The hard segment is generally based on short-chain diols and diisocyanates, while the soft-segment is composed of long-chain polyester or polyether [7]. In this study, a TPU based on diphenyl methane diisocyanate (MDI) and polytetramethylene oxide (PTMO), together with a short chain diol with the role of chain extender, is taken into account (Fig. 1a). PEBAs are based on polyamide (PA) and polyether (PE) blocks [13]. In this

work, a PEBA made of PA11 and PTMO (Fig. 1b) is considered.

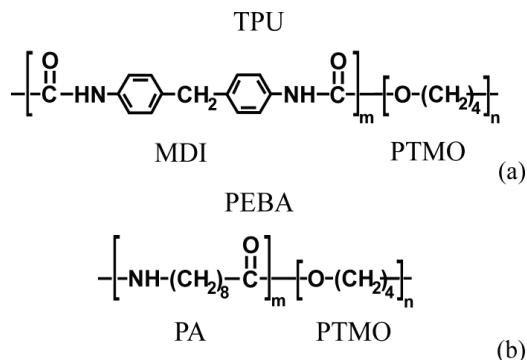


Fig. 1. Chemical structure of thermoplastic polyurethane (TPU), composed by diphenyl methane diisocyanate (MDI) and polytetramethylene oxide (PTMO), (a) and poly(ether-block-amide) (PEBA), made of polyamide (PA) and PTMO (b)

Dog-bone-shaped samples were produced via injection molding with an Engel e-Motion 440100 press, according to ISO 527-2 international regulation, with 1BA specimen size (75 mm long \times 5 mm wide \times 3 mm thick). A sterilization was carried out to simulate the steam sterilization in the same conditions defined by standard protocols in healthcare facilities and pharmaceutical industries [12]. Samples were put in an autoclave (E5 PBInternational) and heated to 121 °C under vacuum. Pressure was increased to 1.2 bar at 100% relative humidity. These conditions were retained for 30 minutes, then the autoclave was switched off and samples were left inside the chamber for approximately 15 minutes. Afterwards, the samples were re-equilibrated under atmospheric conditions.

2.2. Uniaxial tensile testing

Mechanical tests were carried out in uniaxial tensile mode, through an MTS Insight 5 Testing System equipment, equipped with a 5 kN tension load cell and MTS 647 hydraulic grips. The test procedure was planned in accordance with ISO 527-1 and ASTM D638 regulations. The tests were carried out at room temperature, at a strain rate of 10 mm min⁻¹.

2.3. Constitutive modelling

In this work, the Ramberg–Osgood model [1], [3], [9], [11] is adopted. In this framework, the nominal stress vs. nominal strain curve can be described by the following relationship:

$$\varepsilon = f(\omega, \sigma) = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{\sigma_0} \right)^n \quad (1)$$

where the parameters ω are α and n are a dimensionless, E is the Young's modulus and σ_0 is the stress coefficient that are expressed in MPa. As can be seen in Fig. 2, necking phenomena occurs during experimental testing. Thus, in the next section the Ramberg–Osgood model is applied only to the first part of the stress–strain curve, where an elastoplastic behavior is shown before the necking. The target of this investigation is the determination of the material parameters associated with the typical elastoplastic behavior. The set of parameters related to the constitutive model is:

$$\omega = (E, \sigma_0, \alpha, n) \quad (2)$$

belonging to the space Ω . The analysis of the regions of parameters that allow the model and the experiments to be matched provides a functional dependence between some of these material parameters. More precisely, for a given stress–strain curve of N points given through $\sigma^{\text{exp}}(j)$ and $\varepsilon^{\text{exp}}(j)$, there is defined the cost function:

$$G(\omega) = \sum_{j=1}^N \left| 2 - \frac{\varepsilon^{\text{exp}}(j)}{f(\omega, \sigma^{\text{exp}}(j))} - \frac{f(\omega, \sigma^{\text{exp}}(j))}{\varepsilon^{\text{exp}}(j)} \right|^2 \quad (3)$$

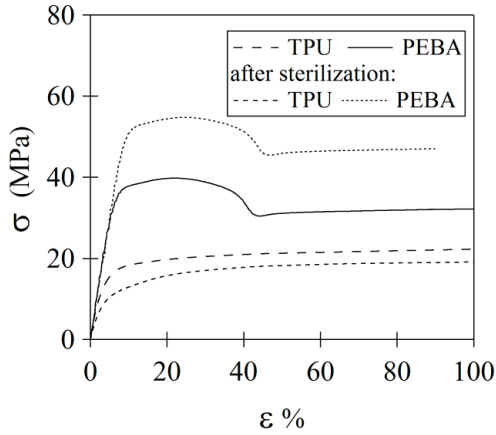


Fig. 2. Stress–strain behavior of TPU and PEBA at room temperature, before and after sterilization

As shown in the next section, the minimization of the function $G(\omega)$ (here the MATLAB minimization algorithm *lsqnonlin* is applied) for any of the four curves in Fig. 2 provides four vectors of material parameters. Considering the different experimental curves, a region of these parameters, indicated in the following as $\bar{\omega}$, is deduced. It will be shown that in the neighborhood of $\bar{\omega}$ there are parameters ω that allow the same minimization of the cost function, namely we can look for $\omega \in \Omega$ such that

$$G(\omega) \leq G(\bar{\omega}) \quad (4)$$

and taking into account $\pm 2\%$ error terms for σ .

The distribution of material parameters $\omega \in \Omega$ minimizing (3) and satisfying the inequality (4) will be shown in the next section.

3. Results

The results of tensile tests of TPU and PEBA before and after sterilization are reported in Fig. 2.

The minimization of the cost function (3) in the case of the stress–strain curve of PEBA before and after sterilization gives the constants in Table 1, showing their change with the sterilization process. In view of the above parameters, the match between model and the PEBA experimental stress–strain curves is displayed in Fig. 3.

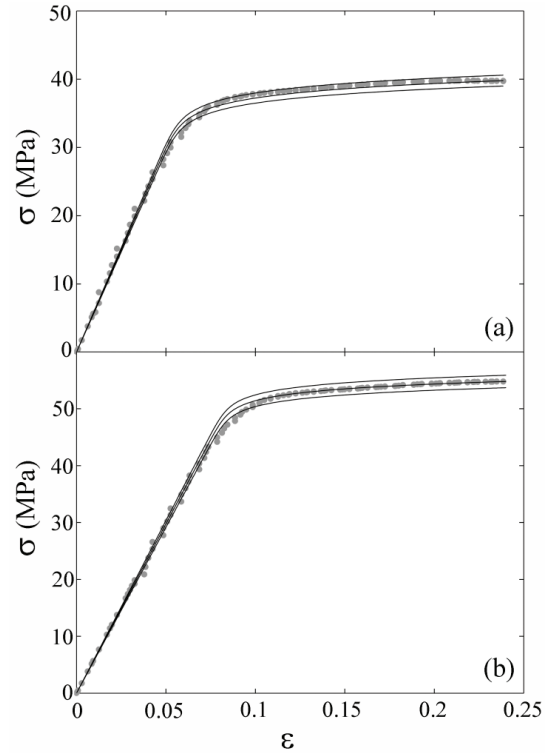


Fig. 3. Experimental and modeled stress–strain curves of PEBA before (a) and after (b) sterilization

The inequality (4) is considered for the stress–strain curves of PEBA before and after sterilization given in Fig. 3 and for parameters $\bar{\omega}$ shown in Table 1. This allows the two dimensional regions of material parameters to be displayed in different sub-spaces of the constitutive parameters, as shown in Fig. 4. In Fig. 4b, the distributions of two sets of parameters, which are

related to the error range of $\pm 2\%$, can be seen. The regions in the sub-space of σ_0 and α are shown in Fig. 5.

Table 1. Parameters $\bar{\omega}$ for PEBA before (a) and after (b) sterilization

	E [MPa]	σ_0 [MPa]	α	n
(a)	595	59.24	2.8	0.026
(b)	680	45.23	3.2	0.043

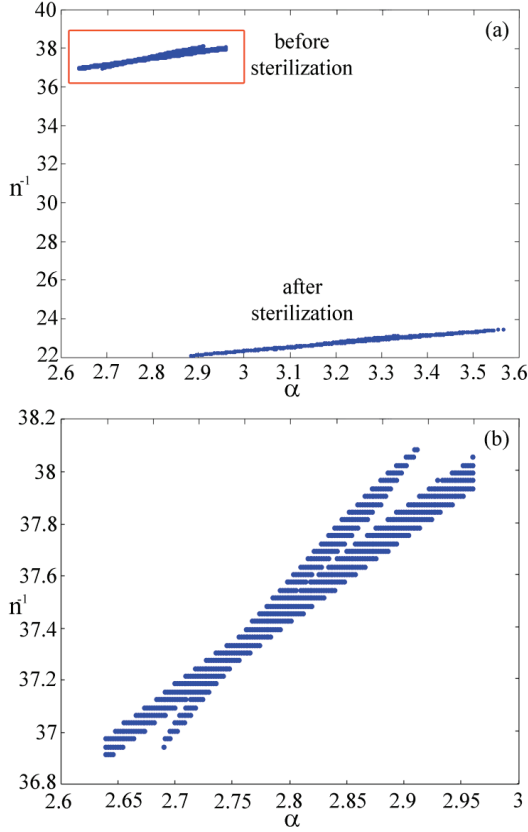


Fig. 4. Distribution of parameters (α, n^{-1}) for PEBA before and after sterilization (a). Detail of the distribution of parameters before sterilization (b)

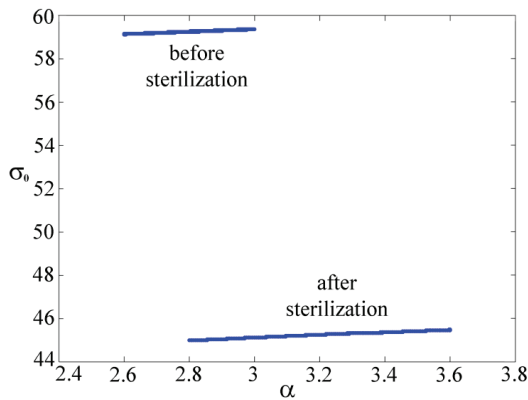


Fig. 5. Distribution of parameters (α, σ_0) for PEBA before and after sterilization

In what follows, the results for TPU before and after sterilization are shown, by providing the material parameters, the match between model and experimental curve and by the graph exhibiting the material parameters. The minimization of the cost function (3) in the case of the nominal stress vs. nominal strain curve of TPU before and after sterilization, gives the results reported in Table 2.

Table 2. Parameters $\bar{\omega}$ for TPU before (a) and after (b) sterilization

	E [MPa]	σ_0 [MPa]	α	n
(a)	400	26.29	5.4	0.080
(b)	250	28.80	3.2	0.19

The match between model and TPU experimental stress-strain curves is given in Fig. 6.

The inequality (4) is considered for the stress-strain curve of TPU before and after sterilization given in Fig. 6, and for parameters $\bar{\omega}$ shown in Table 2. This allows the regions of parameters (α, n^{-1}) to be displayed in Fig. 7. The distribution of the pair of parameters (σ, α) for TPU is shown in Fig. 8.

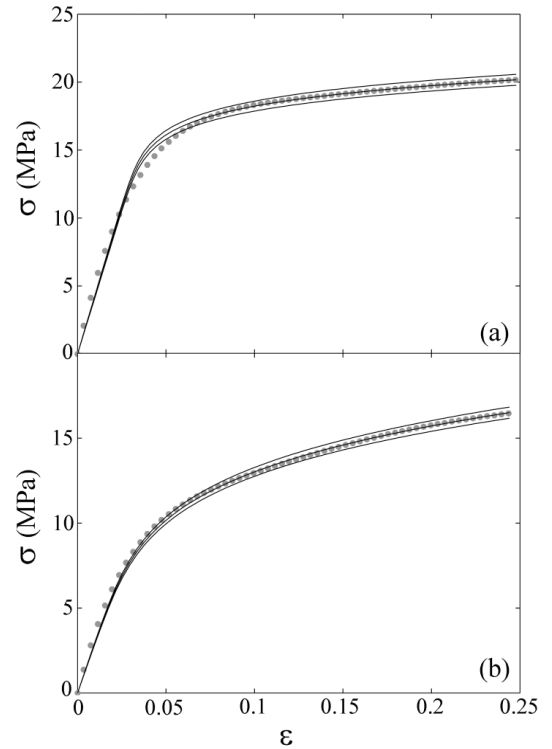


Fig. 6. Experimental and modeled stress-strain curves of TPU before (a) and after (b) sterilization

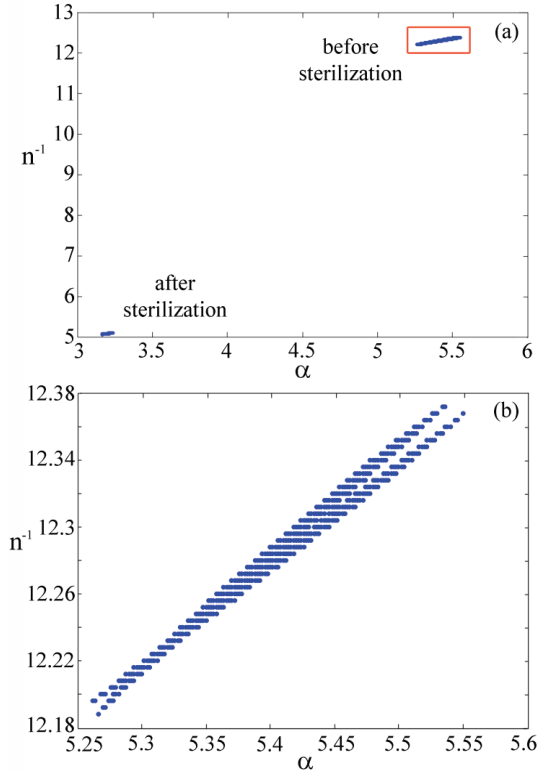


Fig. 7. Distribution of parameters (α , n^{-1}) for TPU before and after sterilization (a).

Detail of the distribution of parameters before sterilization (b)

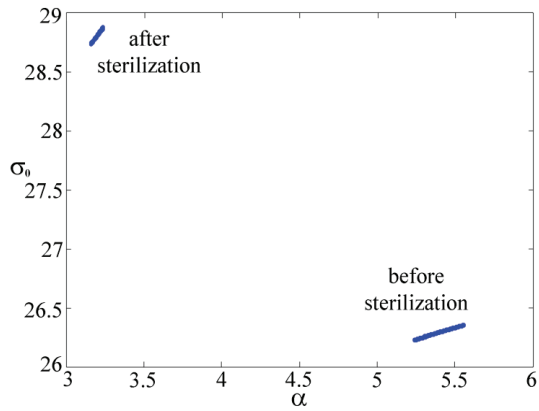


Fig. 8. Distribution of parameters (α , σ_0) for TPU before and after sterilization

4. Discussion

As shown in Fig. 2, both copolymers show an initial linear elastic stress–strain behavior, followed by a non-linear inelastic region at increasing strain. In particular, the estimation of an elastic limit is important to assume acceptable stress values, according to the safety factor adopted in the design of biomedical devices.

TPU stiffness is significantly decreased after sterilization, while the elongation at break is slightly increased. This effect is clearly explained based on previous results [18] that demonstrated a reduction of strong hydrogen bonds between TPU segments, allowing molecular chains to flow more easily during tensile tests and thus decreasing the bulk copolymer stiffness. Concurrently, a lower crystallinity degree entails a higher elongation before the breakage of intra-molecular bonds. This behavior is in accordance with other studies [2], [6], which showed that water acts as a plasticizer and reduces TPU elastic modulus. Otherwise, PEBA stiffness is significantly increased after sterilization and the elongation at break diminishes. This behavior can also be explained in the light of microstructural variations in PEBA. Indeed, crystallinity degree was found to increase after the interaction with water at high temperature. Macromolecular motion is restrained after the extension of the intermolecular bonding network and higher forces are necessary to strain the polymer.

Focusing on the constitutive modeling described in the previous section, the material parameters are determined and the functional dependence between them is discussed. The minimization of the cost function (3) in the case of the stress–strain curve of PEBA before and after sterilization, gives the material constants that change with the sterilization process.

In Fig. 3, experimental data are displayed together with model results, considering the resulting material parameters. Moreover, the related two curves involving the errors of +2% and –2% on σ are shown. A correspondence between the model and the experimental results is exhibited up to $\pm 2\%$ error terms, except for the region describing the transition between the elastic behavior and the plastic behavior where model results are not contained in this error interval.

As shown in Fig. 4, the distribution of parameters after the sterilization is more localized. Moreover, the parameters exhibit a functional dependence that is clearly a linear dependence. In the case after the sterilization, a larger range of parameters is found, but, on the other hand, the functional dependence is more clearly exhibited, due to a better match between the experimental data on PEBA after sterilization and the model. The distribution of (α , n^{-1}) for PEBA after sterilization is similar, even if it is much more localized around a line.

Also in the case of the regions in the sub-space of σ_0 and α , a linear distribution of material parameters is shown. In view of Figs. 4 and 5, α can be considered as a leading parameter and σ_0 and n^{-1}

determined as a linear function of α . However, it can be easily seen that also α can be seen as linear function of σ_0 (inverting their linear relationship). The parameter E is not involved in this study since its value is much more localized and thus it can be interpreted as an independent parameter with respect to the other ones as well as to the variations of the parameters affected by the error terms in the experimental data.

While in the case of PEBA the value of α increases after the sterilization, the opposite behavior is observed in the case of TPU polymer. This is explained by looking at the stress–strain curves where PEBA shows higher stress values for the same strain level after the sterilization treatment, whereas stress values are smaller for TPU after sterilization. The match between model and TPU experimental stress–strain curves is improved after the sterilization, as shown in Fig. 6b.

As in the case of PEBA, a highly localized distribution of parameters can be seen for TPU, that can be described by a linear relationship. Moreover, the range of parameters involved by these distributions are smaller than in the PEBA case. Recalling the previous case analyzed related to Fig. 4, this effect could be related to a better match between the experimental data and the model for TPU.

The distribution of the pair of parameters (σ , α) for TPU in Fig. 8 and the comparison between Fig. 8 and Fig. 5 show that the linear dependence between σ_0 and α is still satisfied. However, it can be noticed that in Fig. 8 the range of the parameters involved is smaller after the sterilization than in the case of PEBA. In conclusion, both for PEBA and TPU, the relationship between different pairs of parameters of the Ramberg–Osgood model shows a linear functional dependence. Moreover, the distribution of the parameters becomes more localized after the sterilization for TPU whereas PEBA has the opposite behavior, also corresponding to the fact that the Ramberg–Osgood model applied here becomes more reliable in the PEBA case, in particular, after the sterilization process.

The study of material parameters and their distribution can be useful in order to evaluate the suitability of a constitutive model in describing the mechanical response of a polymer, in particular after sterilization treatment. By a wider set of experimental data involving different steps of sterilization or different treatment conditions (in terms of time, temperature, relative humidity and number of sterilization cycles) and uniaxial tensile testing, it would be possible to study in more detail the changes in the distribution of the material parameters.

5. Conclusions

In this work, the mechanical behavior of different block copolymers for biomedical applications is studied. The mechanical properties of these polymers have been investigated through uniaxial tensile tests before and after a steam sterilization process, commonly carried out on biomedical devices. An elastoplastic behavior of the stress–strain response is shown and described by the Ramberg–Osgood model. Furthermore, the related material parameters are determined and, in addition, the functional dependence between some of them is investigated to obtain an optimal model. The effect of sterilization on the mechanical properties is studied by this analysis and correlated with previous results on the same polymeric materials.

The approach developed in this work can be applied to different materials and related constitutive models, under various tensile tests, and for other processes that may induce a change in the mechanical properties of polymers. Additional investigation could be oriented towards viscoelastic behavior of such materials, which is also important in several applications.

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