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# Constitutive Modeling and Experimental Validation of Thermoplastic Polyurethane for Additively Manufactured Industrial Manipulators

Gustavo F. C e Silva[1], Leonardo Avane[1], Hugo S. Idagawa[1], Renato L. Pilan[1]

[1]*Faculdade de Tecnologia SENAI "Roberto Mange"*
*Rua Pastor Cicero Canuto de Lima, 71, São Bernardo, 13036-210, São Paulo, Brazil*
gustavovinhedo12@gmail.com, leonardoavane@gmail.com, hugo.sakai@sp.senai.br, renato.pilan@sp.senai.br

**Abstract.** Thermoplastic polyurethanes (TPUs) are elastomeric materials with nonlinear, rate-dependent mechanical behavior, making them attractive candidates for use in soft robotic components. This study aims to characterize and experimentally validate a three-dimensional constitutive model for TPU, targeting its application in the design of industrial manipulators manufactured through additive processes. The modeling framework incorporates phenomena such as hysteresis, relaxation, creep, and the Mullins effect through visco-hyperelastic formulations. Uniaxial tensile tests will be conducted using specimens fabricated in accordance with ASTM D638, enabling the extraction of key material parameters such as Young's modulus, yield stress, and strain rate sensitivity. The collected data will be used to calibrate constitutive models such as Mooney-Rivlin and Bergstrom-Boyce, which will then be implemented in finite element simulations. The validated model will support the design of flexible TPU-based manipulators subjected to complex loading conditions in automated environments. This study presents experimental results on the mechanical behavior of TPU, while the computational modeling aspects will be incorporated in the second stage of this work, which may be presented during the congress or at a later stage.

**Keywords:** TPU, Constitutive Modeling, Additive Manufacturing, Soft Robotics, Finite Element Analysis.

## 1 Introduction

The use of viscoelastic thermoplastics has grown significantly across various engineering and industrial sectors due to their versatility, durability, and tunable mechanical behavior. Among these materials, thermoplastic polyurethane (TPU) stands out as an excellent option for applications requiring high deformability, mechanical strength, and thermal stability. TPU exhibits remarkable properties such as elasticity, resistance to chemical abrasion, a wide operating temperature range (from −40 °C to +80 °C), good adhesion and bonding capabilities, efficient processability, and recyclability. These features make it suitable for a wide range of applications, including automotive, footwear, biomedical, packaging, and more recently, soft robotics.

Structurally, TPU consists of alternating soft and hard segment domains, which are responsible for its highly nonlinear mechanical response Cho et al. [1], Qi and Boyce [2], Gabriëlse et al. [3]. The soft segments contribute to the elastic behavior, while the hard segments increase rigidity and generate energy dissipation through hysteresis. The interaction between these phases gives rise to complex effects such as stress softening (Mullins effect), strain rate dependence, hysteresis, relaxation, and creep. These phenomena make the mechanical behavior of TPU difficult to predict, as multiple mechanisms act simultaneously during deformation. This complexity requires the use of robust and multiscale constitutive models for accurate material description.

Several studies have aimed to develop suitable constitutive formulations for such materials. In particular, the Parallel Rheological Framework (PRF), composed of hyperelastic and hyperelastic-viscoplastic branches in parallel, has proven effective in modeling TPUs under different loading regimes. A notable example is the work by Reyes et al. [4], who conducted an extensive characterization of a high-hardness TPU using type 3 specimens according to ISO 37:2017. Their study explored tensile, compressive, creep, and relaxation tests to validate a

rheological model with multiple time scales.

Inspired by this approach, this paper presents the experimental characterization of a commercial TPU, focusing on its behavior under uniaxial tensile loading. Type 1 specimens were prepared according to ASTM D638, and tests were conducted using parameters adapted to the capabilities of the available testing equipment. From the collected data, key material parameters such as Young's modulus, maximum stress, and strain at failure were extracted, with the goal of verifying consistency with the literature and providing a foundation for future constitutive modeling efforts aimed at flexible components and industrial soft manipulators.

While the experimental characterization of TPU is the focus of this study, the computational modeling aspects, including finite element analysis and visco-hyperelastic simulations, will be addressed in the second stage of this work. These computational results are expected to be presented in a future iteration of this paper, possibly during the congress or subsequent publication.

# 2 Experimental methodology

## 2.1 Material and specimen preparation

The material used in this study was a commercial thermoplastic polyurethane (TPU) filament with a nominal Shore A hardness of 82, supplied in extruded spools and processed by additive manufacturing using the Fused Deposition Modeling (FDM) technique. The printing process was performed on an Ender-3 PRO, under the following basic parameters: extrusion temperature of 220 °C, print speed of 30 mm/s, infill of 100%, and layer height of 0.16 mm.

The specimens were prepared according to ASTM D638, type 1 geometry, which defines standardized dumbbell-shaped samples for tensile testing of elastomers and flexible thermoplastics. This ensures repeatability and comparability across different experiments. Figure 1 illustrates the specimen used in this study.

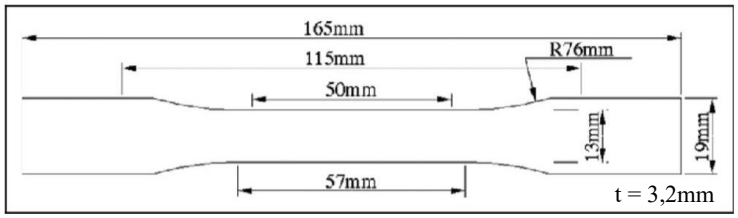



Figure 1. Tensile test specimen (ASTM D638, type 1)

## 2.2 Test Setup

Tensile tests were performed using a Kratos universal testing machine MOD. K 80.4 CAP. 20.000 kgf, equipped with proprietary software for data acquisition and preliminary processing. The tests followed general guidelines from the ASTM D638 standard, with adjustments according to the capabilities of the laboratory equipment.

Two distinct testing protocols were conducted:

- **Test A:** consisted of six loading-unloading cycles with a maximum load of 20 kgf, aiming to assess the cyclic behavior and hysteresis of the material. A 1000 kgf load cell was used, with a crosshead speed of 200 mm/min and a preload of 0.35 kgf.
- **Test B:** consisted of a sequence of tensile tests with increasing maximum loads, ranging from 20 to 40 kgf, with individual data collected for comparative analysis. In this case, the crosshead speed was 270 mm/min, using a 2000 kgf load cell, and no preload was applied.

During the tests, signals of force (kgf), displacement (mm), and time (s) were recorded. The data was exported to spreadsheets and later processed to calculate stress, strain, and key mechanical parameters of the TPU.

# 3 Results and discussion

Figure 2 presents the results obtained from Test A, in which six loading-unloading cycles were applied with a maximum load of 20 kgf. The Mullins effect is clearly observed, characterized by irreversible softening of the material after the first loading cycle, along with hysteresis and stress relaxation. This phenomenon is typical of viscoelastic materials and highlights the energy dissipation associated with the internal microstructure of TPU.

Figure 3 shows the curve obtained from Test B, conducted under different maximum load levels. Based on the data collected—force, displacement, and initial gauge length—it was possible to calculate the material's Young's modulus. The values extracted are summarized in Table 1.

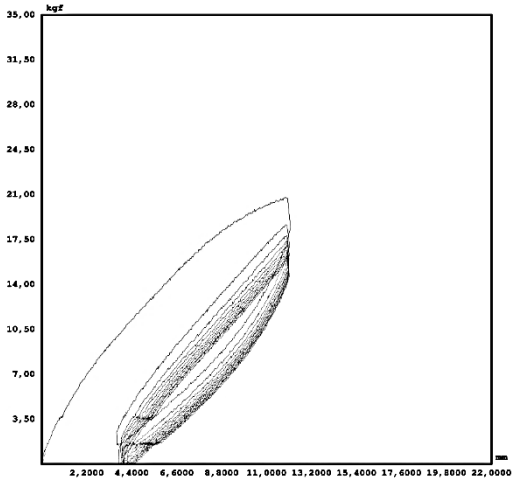



Figure 2. Test A

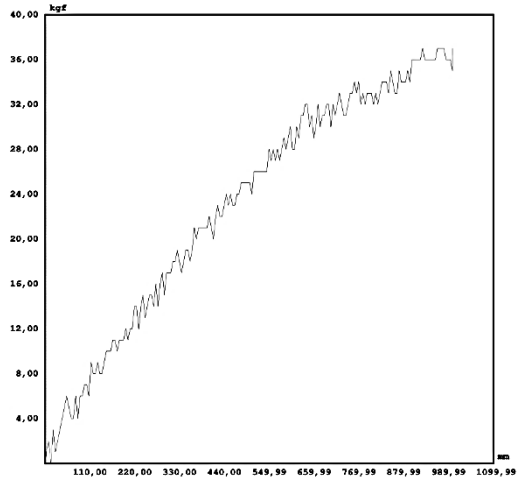



Figure 3. Test B

Table 1 presents the applied force, initial length, axial displacement, and the corresponding Young's modulus, calculated using the following equation:

$$E = \frac{\sigma}{\varepsilon}, \text{ where } \sigma = \frac{F}{A}, \ \varepsilon = \frac{\Delta L}{L_0} \tag{1}$$

Table 1. Data extracted from test B

| Load (kgf) | Initial Length (mm) | Displacement (mm) | Young's Modulus (MPa) |
|---|---|---|---|
| 15 | 40 | 3 | 37.7 |
| 20 | 41.4 | 4.1 | 38.1 |
| 25 | 43 | 6.4 | 36.4 |
| 30 | 45.1 | 9.7 | 26.31 |
| 35 | 51.2 | 11.8 | 28.6 |
| | | | Average: 33.42 |

The results indicate a variation in elastic modulus as a function of load level, which may be attributed to pre-strain effects, initial plastic deformation, or minor inconsistencies in specimen alignment. Nevertheless, the values remain within the expected range for high-hardness TPU, exhibiting the characteristic non-linear behavior of elastomeric materials.

In addition, when comparing the experimental Young's modulus obtained in this study with the reference values provided by Ultrafuse® TPU 85A from BASF, the average Young's modulus found was 33.42 MPa, while the BASF model specifies 27 MPa [5]. This increase in Young's modulus may be attributed to differences in the manufacturing process, such as printing parameters and temperature, as well as the specific characteristics of each material batch. The comparison between the obtained data and the reference is summarized in Table 2.

Table 2. Comparison between the experimentally obtained Young's modulus and the value provided by BASF

| Source | Young's Modulus (MPa) |
|---|---|
| BASF (Ultrafuse® TPU 85A) | 27 |
| This Study | 33.42 |

Moreover, when comparing these curves to those reported by Reyes et al. (2023) [4], good qualitative agreement is observed—particularly in terms of initial stiffness, hysteresis, and maximum strain—reinforcing the validity of the tests conducted, even with adjustments to accommodate the available experimental setup.

# 4 Conclusions

This study presented an experimental characterization of thermoplastic polyurethane (TPU) under uniaxial tensile loading, aiming to understand its mechanical behavior and validate parameters for future constitutive modeling. Two types of tests were performed: a cyclic test (Test A), which revealed the Mullins effect and energy dissipation, and a monotonic test (Test B), used to extract Young's modulus at different load levels.

The results obtained show consistency with literature data, particularly regarding the material's nonlinear behavior, hysteresis, and high deformability. The extracted values for Young's modulus and maximum stress fall within the expected range for TPU with similar hardness, reinforcing the reliability of the experimental approach even with adaptations in specimen preparation and equipment availability.

As future work, the implementation of constitutive models based on parallel rheological structures—such as the Parallel Rheological Framework (PRF)—is proposed. The experimental data obtained in this study will serve as a foundation for model calibration and simulation of the material in applied contexts, such as flexible manipulators and impact-absorbing components.

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**Authorship statement.** The authors hereby confirm that they are the sole liable people responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

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