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MECHANICAL PROPERTIES OF SELECTED ENGINEERING POLYMERS UNDER TENSION AND COMPRESSION – EXPERIMENTS AND DESIGN APPLICATION FRAMEWORK [1]

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Abstract
Polymers can present larger yield strength under compression (being thus denoted uneven), as a result of sensitiveness to the hydrostatic stress state (tensile or compressive). Yield criteria currently used by engineers, however, are mostly based on metallic materials (e.g. Tresca and Mises original proposals), not taking unevenness into account. In this context, to obtain accurate failure predictions one must apply modified criteria including hydrostatic stress dependency, such as conic and parabolic Mises models, which in its turn demand compressive properties. The actual limitation is that these data are very scarce in the literature and unevenness levels are not known for most polymers. As a step in this direction, several polymers were evaluated under tension and compression. To consider different stiffness, strength and microstructures, the experimental matrix includes: PVC, PTFE, POM, PMMA and PC. Results provide elastic moduli, yield strength and unevenness levels. Based on the results, the conceptual framework regarding practical application and potential of modified yield criteria for design accuracy is addressed.
Key-words: Uneven polymers; Compression testing; Unevenness levels; Pressure-dependent yield criteria.

PROPRIEDADES MECÂNICAS À TRAÇÃO E COMPRESSÃO DE POLÍMEROS DE ENGENHARIA SELECIONADOS – EXPERIMENTOS E ARCABOUÇO DE APLICAÇÃO

Resumo
Polímeros podem apresentar maior resistência ao escoamento em compressão (sendo então definidos como desbalanceados) e os critérios de projeto atualmente utilizados pelos engenheiros (p. ex.: Tresca e von Mises originais) não são capazes de incorporar tal fenômeno. Neste contexto, previsões de falha acuradas só podem ser conseguidas pela combinação de critérios de escoamento dependentes da tensão hidrostática (tração ou compressão) alimentados por dados experimentais também de compressão. A grande limitação atual é que tais dados são muito escassos na literatura. Neste sentido, este trabalho estuda sob tração e compressão materiais de diferentes resistências, rigidez e microestrutura, incluindo: PVC, PTFE, POM, PMMA e PC. Os resultados fornecem as propriedades mecânicas e o nível de desbalanceamento em cada caso. De posse dos resultados, o arcabouço conceitual para a aplicação e o potencial de ganho de precisão de projeto são endereçados.
Palavras-chave: Polímeros desbalanceados; Ensaio de compressão; Nível de desbalanceamento; Critérios de escoamento modificados.

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1 INTRODUCTION

Mechanical properties of polymers have been significantly enhanced during the last decades, categorizing these materials as good engineering options even for responsibility applications. The interest for polymers comes from its attractive combination of mechanical and corrosion resistance with low density and easy manufacturing (molding, machining, etc.) with relatively low costs.[1] However, microstructures, stress-strain response and deformation micromechanisms are significantly altered if compared to metallic materials.[2-4] As a result, in several cases the mechanical behavior of polymers is misunderstood by engineers and designers,[1] whose theoretical background was developed during the last century based on metals. The occurrence of plastic deformation is a good example. In polymers, chains mobility is highly influenced by the applied hydrostatic stress level (also referred to as pressure). The more compressive is the hydrostatic stress, the higher can be the yield strength based on the lower mobility of macromolecules.[2,5] Consequently, several polymers present larger yield strength under compression, being denoted uneven. Additional phenomenological details can be found in the work of Lyon[6] and Pae & Bhateja[7] and will not be addressed here due to space limitations. The unevenness level in terms of yield strength is usually denoted "m" and defined as

$$m = \frac{\sigma_{ys-c}}{\sigma_{ys-t}} , \qquad (1)$$

where σ_{ys-t} and σ_{ys-c} represents the yield strength under tension and compression.

The most relevant compressive tests (albeit in very small number) were conducted during the 70's by Raghava[8] and Caddell[9] and recently in the 2000's by Mascarenhas et al.[10] and Jerabek et al.[11]. These results indicate that unevenness (m) usually presents levels between $m = 1.2$ and $m = 1.5$ [8-11]. Additional results recently published by Donato & Bianchi[12] revealed $1.00 \leq m \leq 1.40$ for selected polymers and an additional investigation conducted by the authors using the materials database of CES EDUPACK 2009 software[13] revealed that, for the available 198 unfilled thermoplastic polymers, the unevenness in most cases is expected $1.00 \leq m \leq 2.00$. These unevenness levels clearly call the attention for the potential of considering compressive yield strength of polymers for structural improvement. The work of Donato & Bianchi[12] presented a case study in which the incorporation of uneven mechanical properties of polymers (in this case a polypropylene, with $m \approx 1.24$) in design practices provided mass reductions up to 39.8 % keeping original stiffness and safety factors. It was possible because the component being studied operated under bending and presented regions loaded by a compressive hydrostatic stress state. On the other hand, in cases where the hydrostatic stress is predominantly tensile, or when polymers under investigation are even, current criteria can lead to unsafe solutions as will be discussed later.

In this context and from a solid mechanics point of view, classical design criteria currently employed by engineers (such as original Tresca and von Mises yield loci) deserve attention since can become inaccurate if directly applied for polymers. Such classical plasticity theories include several assumptions, such as[3,4]: i) the material is isotropic and homogeneous; ii) deformation proceeds under constant volume; iii) tensile and compressive yield strengths are equal; iiii) yielding phenomenon is uninfluenced by the hydrostatic component of the stress state (pressure)[4]. As

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discussed above, the last two assumptions mean that tensile and compressive stress-strain behaviors are identically treated in terms of structural integrity and should be critically reviewed to become applicable to polymers. Some pressure dependent yield criteria are available in the literature and consider the hydrostatic stress state and its effects on materials response in terms of yielding. The most popular criteria for polymers are the conically and parabolically modified von Mises theories[4,10], which will be presented in details in this work looking for the possibility of practical application. Both of them, however, demand mechanical properties evaluated under tension and compression.

As a step in this direction, this work evaluates several polymers under tension and compression. To consider different stiffness, strength and microstructures, the experimental matrix includes: PVC, PTFE, POM, PMMA and PC. Results provide elastic moduli, yield strength and unevenness levels. Based on the results, the conceptual framework regarding practical application and potential of modified yield criteria for design improvement is addressed. Taken together with previous results available in the literature, this work provides additional mechanical properties, insights and guidelines for design efforts employing polymers.

2. PRESSURE DEPENDENT YIELD CRITERIA AND NECESSARY DATA

Most pressure dependent yield criteria are based on the classic criterion proposed by Huber[13], Hencky[14] and Mises[15], nowadays known as von Mises, maximum octahedral shear stress or maximum strain energy criterion. It proposes that yielding occurs when the second invariant of the deviatoric stress tensor (J_2) reaches a critical value (k^2)[6], in the form

$$J_2 = k^2 \quad , \tag{2}$$

where

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \quad ; \quad k = \frac{1}{\sqrt{3}}\sigma_{ys-t} = 0{,}577 \cdot \sigma_{ys-t} \ . \tag{3}$$

The classical Mises equivalent stress is then presented by Eq. (4). The resulting yield locus for this criterion is presented by Fig. 1(a), being σ_1, σ_2 and σ_3 the three principal stresses. Since the hydrostatic stress (σ_h) can be written in terms of the first stress invariant (I_1) as presented by Eq. 5, it can be realized that there is no effect of σ_h on failure prediction (the locus is a cylindrical tube aligned to the hydrostatic axis).

$$\sigma_{vM} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{4}$$

$$\sigma_h = \frac{I_1}{3} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{5}$$

To include the pressure dependency on Mises original yield criterion, Hu and Pae[17] included in Eq. (1) a second term depending on I_1 according to Eq. (6), which has proven to be a consistent phenomenological approach[6]. Expanding this formulation as a polynomial in I_1, Ehrenstein and Erhard[18] and Miller [19] demonstrate that Eqs. (7,8) emerge for N = 1 and N = 2 respectively. Equation (7) represents the conically modified von Mises (or Drucker-Prager) criterion, while Eq. (8) represents the parabolically modified von Mises criterion. In the conical model,

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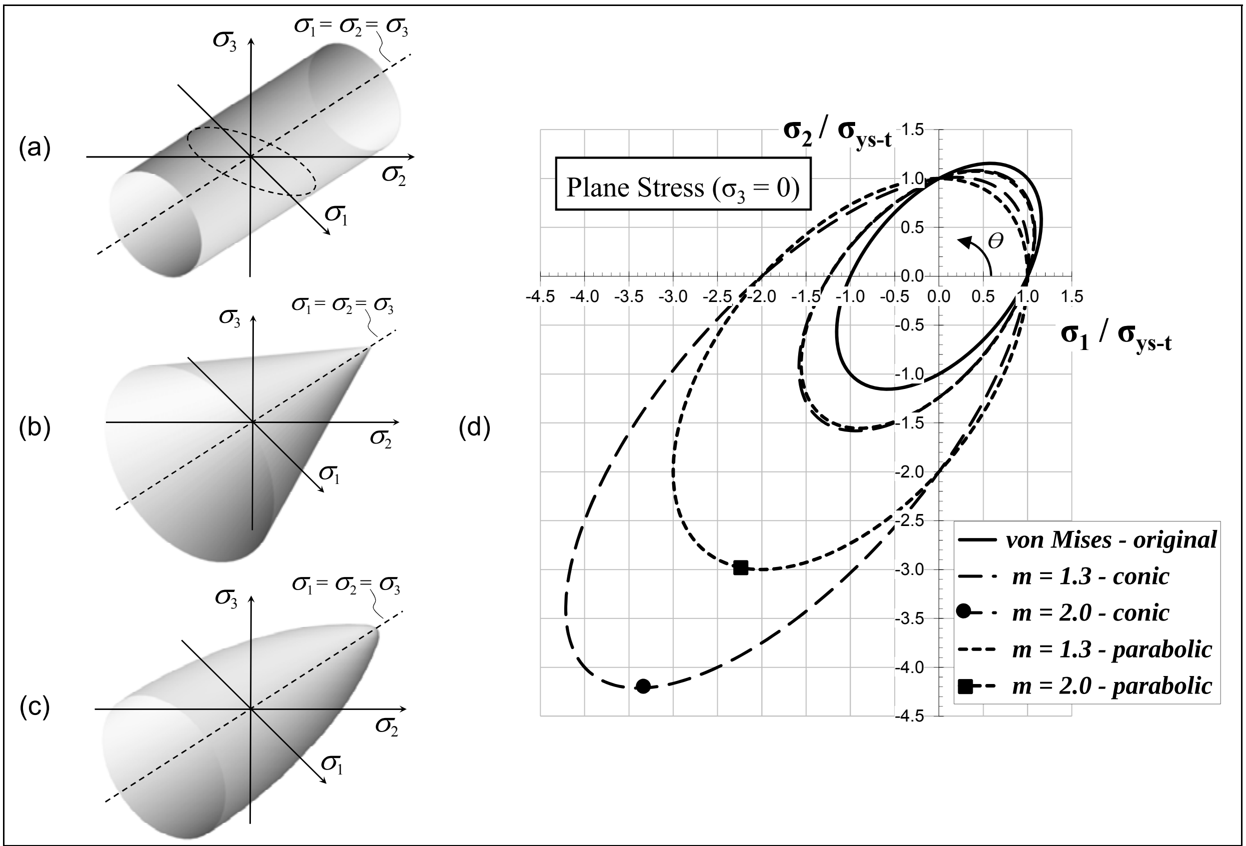
Eq. (7) reveals that the effect of I_1 is linear, providing the yield surface shown by Fig. 1(b). In the parabolic model, in its turn, Eq. (8) reveals that the effect of I_1 is quadratic, providing the yield surface shown by Fig. 1(c). In both cases, the higher the compressive hydrostatic stress, the higher is the predicted yield strength, and yielding occurs when the modified equivalent stress is greater than the tensile yield strength, as stated by Eq. (9). Figure 1(d) presents a comparison between the original and the modified yield criteria for plane stress conditions and two levels of unevenness (m). It can be realized that the conical model is more sensitive to high m values, which is expected due to the linear dependence on σ_h. However, for $m \sim 1.30$, both criteria lead to essentially similar results. Based on literature reports, the parabolic model is considered as more realistic when compared to experimental results[(5-9)]. One relevant fact is that modified criteria predict increased yield strength under compression, but reduction on yield strength under tension (see the 1st quadrant of Fig. 1(d)). Based on these models, it can lead to unsafe evaluations.

$$J_2 = k^2 + \sum_{i=0}^{N} \alpha_i \cdot I_1^i \tag{6}$$

$$\sigma_{vM-C} = \frac{1}{2m} \cdot \left[(m-1)\cdot(I_1) + (m+1)\sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]} \right] \tag{7}$$

$$\sigma_{vM-P} = \frac{m-1}{2m}\cdot(I_1) + \sqrt{\left[\frac{m-1}{2m}\cdot(I_1)\right]^2 + \frac{1}{2m}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]} \tag{8}$$



Source: Author, adapted from Roesler, 2007[(4)].

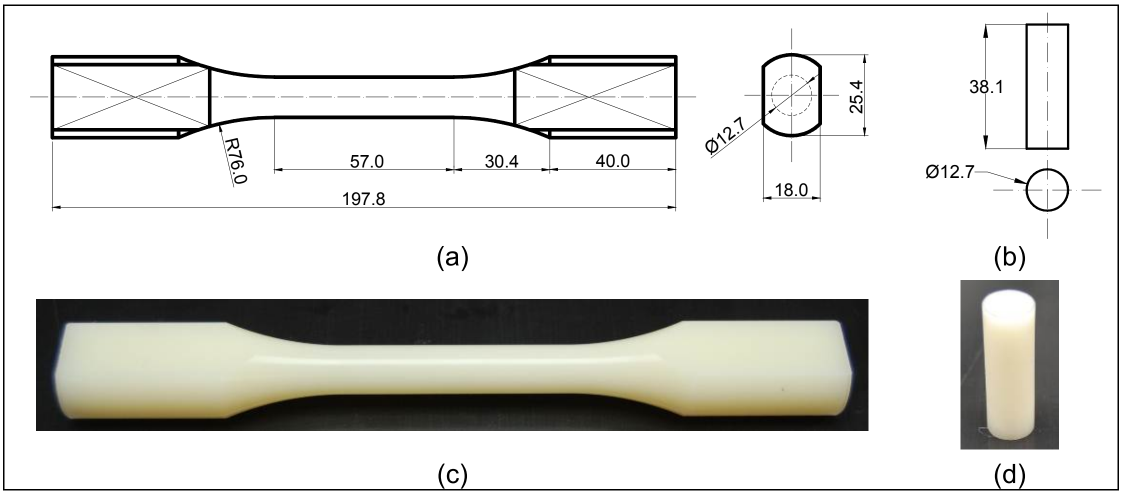
Figure 1. Illustrative yield surfaces plotted relative to the three principal axes considering (a) classical von Mises, (b) conically modified and (c) parabolically modified von Mises criteria.

$$\sigma_{vM-C} \leq \sigma_{LE-T} \quad ; \quad \sigma_{vM-P} \leq \sigma_{LE-T} \tag{9}$$

In this context, the application of the aforementioned modified criteria and the attainment of accurate and safe predictions for yielding of polymers demand precise tensile and compressive yield strength. In addition, elastic moduli must be evaluated to support analytical or finite element computations to provide adequate stress distributions. All these properties are evaluated and discussed next.

3. TESTED MATERIALS AND EXPERIMENTAL PROCEDURES

Five thermoplastic polymers were tested under tension and compression. To consider different stiffness, strength and microstructures (crystalline or amorphous), the experimental matrix includes: PVC, PTFE, POM, PMMA and PC. All materials were purchased from polymers distributors and came as round 3 meter long bars with 25.4 mm (1 inch) diameter. All specimens for each material were obtained from the same bar in order to avoid any shuffle or different batches. Figure 2 presents the dimensions and real examples of the tested specimens. It can be realized that both specimens present circular cross-section and $\phi 12.7\,mm$ to sample the same volume of material being strained. All of them were machined parallel and with its centers aligned to the longitudinal axis of the bars, in order to sample the same material characteristics. Machining was conducted in CNC machines with small passes to avoid residual stresses or damage to the raw material.



Source: Author.
Figure 2. Dimensions and real example of tested specimens for (a,c) tension and (b,d) compression.

The specimens were kept and tested at 21 ºC and 60 % relative humidity, using the same strain rate for tensile and compressive testing (0.051 min^{-1}) as recommended by ASTM D638[20] for tension and ASTM D695[21] for compression. Ten valid specimens were tested for each material (being 5 tensile and 5 compressive). The compressive specimens were lubricated using commercial Molykote A-2 grease to minimize friction effects and guarantee accurate elastic modulus and yield strength evaluation. Tensile tests were conducted using a 250 kN servohydraulic MTS testing machine (model 810) and compressive tests using a 30 kN electromechanical INSTRON testing machine (model 5567). The two different machines were employed due to the most adequate apparatus available for each loading regime. All results were acquired as ASCII files and post-processed using a

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specially developed MATLAB code, evaluating for each specimen: i) elastic modulus (E); ii) offset yield strength considering 0.2, 0.5, 1.0 and 2.0% plastic strain offsets ($\sigma_{ys\text{-}off\text{-}0.2}$, $\sigma_{ys\text{-}off\text{-}0.5}$, $\sigma_{ys\text{-}off\text{-}1.0}$ e $\sigma_{ys\text{-}off\text{-}2.0}$); iii) maximum yield strength ($\sigma_{ys\text{-}max}$) based on the first point were $d\sigma/d\varepsilon = 0$.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Figures 3 and 4 present all tested specimens after final deformation or failure, combined to respective stress-strain response under tension and compression for each material. Only one selected curve is presented for each case to enhance comprehension, since in all cases very good agreement was found between the five tested specimens. First, it can be realized that some tensile specimens presented large plastic deformation and necking prior to failure (PVC, PMMA and PC), while other revealed a flat fracture surface (PTFE and POM). Under compression, some specimens failed by buckling, but it happened for high strains, away from the evaluated levels, which did not compromise evaluated moduli and yield strengths. Comparing the respective representative tensile and compressive stress-strain curves, Fig. 3 shows that yield strength unevenness clearly exists for PVC and PMMA. A closer look to Fig. 3 reveals that stiffness (elastic modulus) is also altered, especially for PVC. These quantities will be detailed and quantified next, both for engineering and true data. Following the same approach, Figure 4 reveals that PTFE, POM and PC present almost even yield strength considering engineering data, while the stiffness is once again slightly altered by the hydrostatic stress regime.

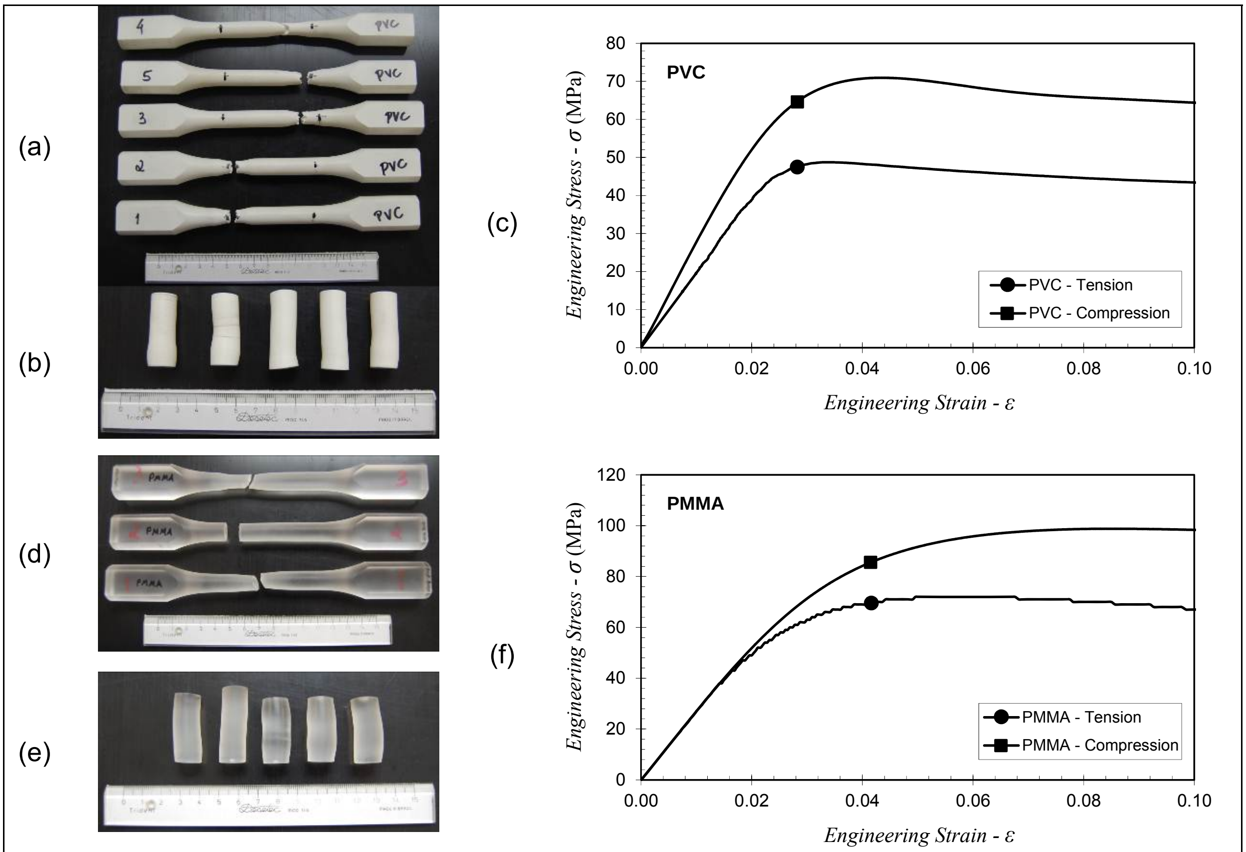

Figure 3. Tensile and compressive specimens after testing and stress-strain response under tension and compression respectively for (a,b,c) PVC and (d,e,f) PMMA. Stress-strain curves are based on engineering data and these materials clearly reveal larger yield strength under compression.

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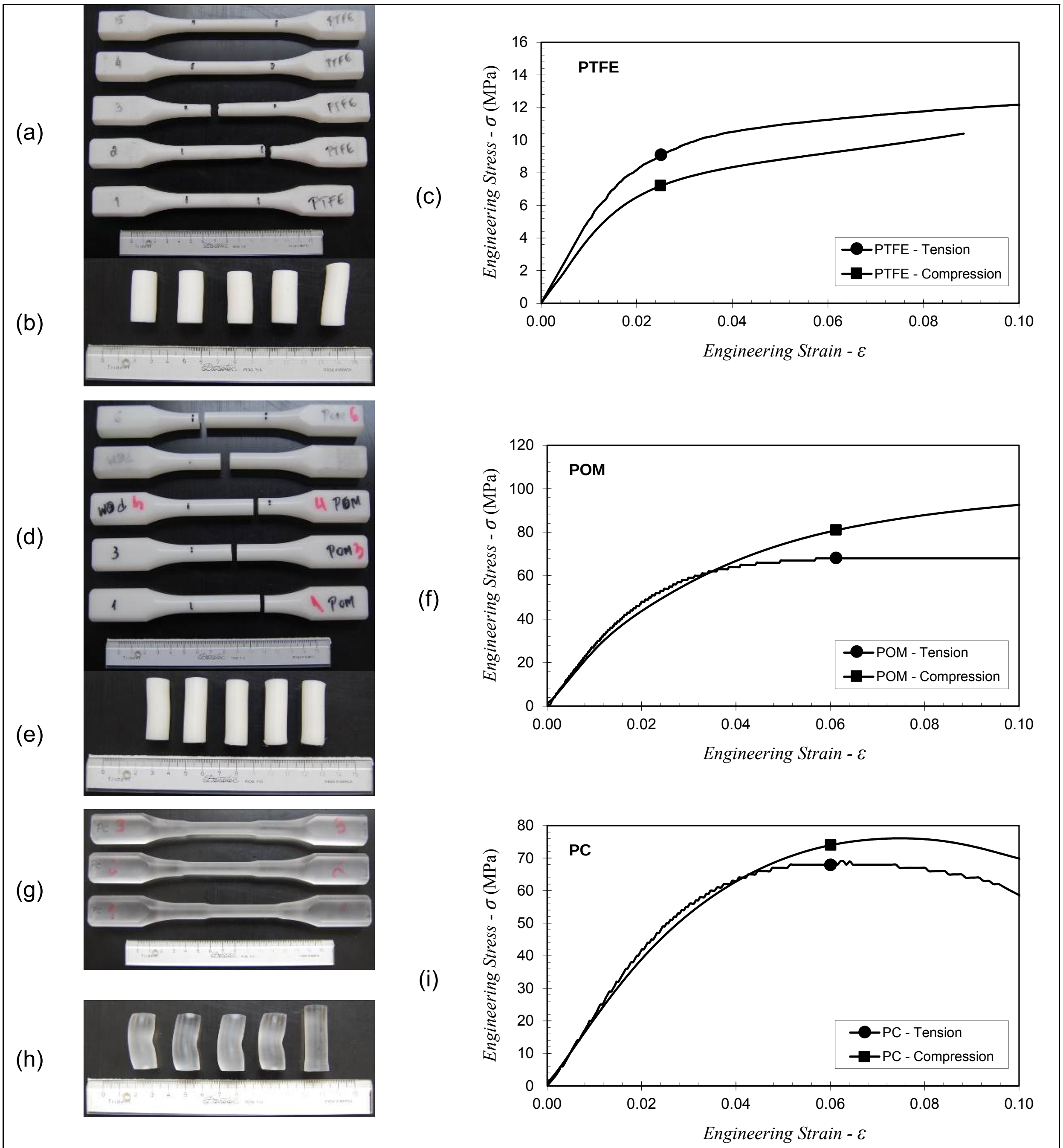

Figure 4. Tensile and compressive specimens after testing and stress-strain response under tension and compression respectively for (a,b,c) PTFE, (d,e,f) POM and (g,h,i) PC. Stress-strain curves are based on engineering data and these materials reveal even properties.

Table 1 presents all post-processed results for elastic modulus and yield strength for different definitions. Unevenness levels were then calculated for both engineering (m_e) and true stress-strain (m_t) data following classical formulae for true stress $\tilde{\sigma} = \sigma(1+\varepsilon)$ and true strain $\tilde{\varepsilon} = \ln(1+\varepsilon)$.[1,20,21] Considering the standard deviations, POM and PC can be considered even, while other materials (PTFE, PVC and PMMA) present relevant yield strength unevenness. Figure 5(a) presents the average values of (m_e) and (m_t) considering all offset definitions of σ_{ys} (maximum definition was not considered since it did not take place in some compression tests). In spite of not being a physical measurement, these average values represent the unevenness behavior through elastic loading until plastic instability and are

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considered representative of the material behavior under tension and compression. It can be realized that there exist a relevant difference between using engineering and true stress-strain data. Results based on true data reveals less unevenness as expected and are considered more realistic due to the large strain response of polymers even for low stress levels. For comparison purposes, Fig. 5(b) presents the same kind of results recently obtained by Donato and Bianchi[12] for PA-66, PA-6, PP and HDPE. Similar trends and unevenness levels were obtained.

Table 1: Results for evaluated mechanical properties. Unevenness levels were calculated for both engineering (m_e) and true (m_t) stress-strain data. It can be noticed the reduction for true data

Engineering stress-strain data						
Material	E	$\sigma_{ys\text{-}off\text{-}0.2}$	$\sigma_{ys\text{-}off\text{-}0.5}$	$\sigma_{ys\text{-}off\text{-}1.0}$	$\sigma_{ys\text{-}off\text{-}2.0}$	$\sigma_{ys\text{-}max}$
PVC $_{Compr.}$ (MPa)	2717 ± 20	57.1 ± 0.6	65.1 ± 0.3	69.6 ± 0.5	---	70.9 ± 0.9
PVC $_{Tension}$ (MPa)	1960 ± 36	45.8 ± 0.3	48.3 ± 0.5	48.7 ± 0.6	---	48.7 ± 0.6
$m_{e\text{-}PVC}$	1.39 ± 0.03	1.25 ± 0.02	1.35 ± 0.01	1.43 ± 0.02	---	1.45 ± 0.03
PMMA $_{Compr.}$ (MPa)	2659 ± 17	64.7 ± 0.5	76.5 ± 0.5	85.6 ± 0.5	93.5 ± 0.5	98.1 ± 0.8
PMMA $_{Tension}$ (MPa)	2784 ± 153	51.1 ± 1.4	60.3 ± 0.3	67.5 ± 0.7	72.0 ± 1.6	73.0 ± 1.4
$m_{e\text{-}PMMA}$	0.96 ± 0.05	1.27 ± 0.04	1.27 ± 0.01	1.27 ± 0.02	1.30 ± 0.03	1.34 ± 0.03
PTFE $_{Compr.}$ (MPa)	396 ± 33	6.6 ± 0.5	7.6 ± 0.4	8.4 ± 0.4	9.2 ± 0.5	---
PTFE $_{Tension}$ (MPa)	615 ± 58	6.7 ± 0.5	7.9 ± 0.5	9.2 ± 0.3	10.4 ± 0.3	---
$m_{e\text{-}PTFE}$	0.64 ± 0.08	0.99 ± 0.11	0.95 ± 0.08	0.91 ± 0.05	0.88 ± 0.05	---
POM $_{Compr.}$ (MPa)	2447 ± 139	38.9 ± 1.0	48.5 ± 0.8	59.4 ± 0.7	72.6 ± 0.7	---
POM $_{Tension}$ (MPa)	2833 ± 79	41.4 ± 1.7	50.5 ± 1.2	58.3 ± 1.0	64.1 ± 1.3	---
$m_{e\text{-}POM}$	0.86 ± 0.05	0.94 ± 0.04	0.96 ± 0.03	1.02 ± 0.02	1.13 ± 0.03	---
PC $_{Compr.}$ (MPa)	2159 ± 151	44.4 ± 1.0	54.3 ± 1.2	63.2 ± 1.3	72.0 ± 1.4	76.3 ± 0.4
PC $_{Tension}$ (MPa)	2214 ± 46	46.7 ± 2.1	55.3 ± 0.6	62.5 ± 0.8	67.7 ± 0.6	68.7 ± 0.6
$m_{e\text{-}PC}$	0.98 ± 0.07	0.95 ± 0.05	0.98 ± 0.02	1.01 ± 0.02	1.06 ± 0.02	1.11 ± 0.01
True stress-strain data						
Material	E (MPa)	$\sigma_{ys\text{-}0.2}$	$\sigma_{ys\text{-}0.5}$	$\sigma_{ys\text{-}1.0}$	$\sigma_{ys\text{-}2.0}$	$\sigma_{ys\text{-}máx}$
PVC $_{Compr.}$ (MPa)	---	55.8 ± 0.5	62.6 ± 0.2	66.8 ± 0.3	---	67.8 ± 0.7
PVC $_{Tension}$ (MPa)	---	46.7 ± 0.3	49.6 ± 0.6	50.3 ± 0.7	---	50.3 ± 0.7
$m_{t\text{-}PVC}$	---	1.19 ± 0.01	1.26 ± 0.02	1.33 ± 0.02	---	1.35 ± 0.02
PMMA $_{Compr.}$ (MPa)	---	61.1 ± 0.3	72.2 ± 0.4	80.5 ± 0.4	87.2 ± 0.4	90.1 ± 0.6
PMMA $_{Tension}$ (MPa)	---	52.3 ± 1.1	62.8 ± 0.3	70.2 ± 1.1	75.3 ± 1.5	78.0 ± 1.8
$m_{t\text{-}PMMA}$	---	1.17 ± 0.03	1.15 ± 0.01	1.15 ± 0.02	1.16 ± 0.02	1.16 ± 0.03
PTFE $_{Compr.}$ (MPa)	---	6.4 ± 0.4	7.3 ± 0.4	8.1 ± 0.4	8.7 ± 0.4	---
PTFE $_{Tension}$ (MPa)	---	6.7 ± 0.7	7.9 ± 0.7	9.3 ± 0.4	10.7 ± 0.3	---
$m_{t\text{-}PTFE}$	---	0.97 ± 0.11	0.93 ± 0.09	0.86 ± 0.06	0.81 ± 0.05	---
POM $_{Compr.}$ (MPa)	---	37.9 ± 0.9	46.5 ± 0.7	56.0 ± 0.6	67.3 ± 0.6	---
POM $_{Tension}$ (MPa)	---	42.7 ± 1.7	52.1 ± 1.6	60.4 ± 1.2	66.7 ± 1.8	---
$m_{t\text{-}POM}$	---	0.89 ± 0.04	0.89 ± 0.03	0.93 ± 0.02	1.01 ± 0.03	---
PC $_{Compr.}$ (MPa)	---	42.1 ± 0.9	51.1 ± 1.1	59.1 ± 1.1	66.9 ± 1.3	70.5 ± 0.3
PC $_{Tension}$ (MPa)	---	48.6 ± 1.7	58.1 ± 1.1	66.0 ± 0.6	71.8 ± 1.3	73.3 ± 0.8
$m_{t\text{-}PC}$	---	0.87 ± 0.04	0.88 ± 0.02	0.90 ± 0.02	0.93 ± 0.02	0.96 ± 0.01

Source: Author

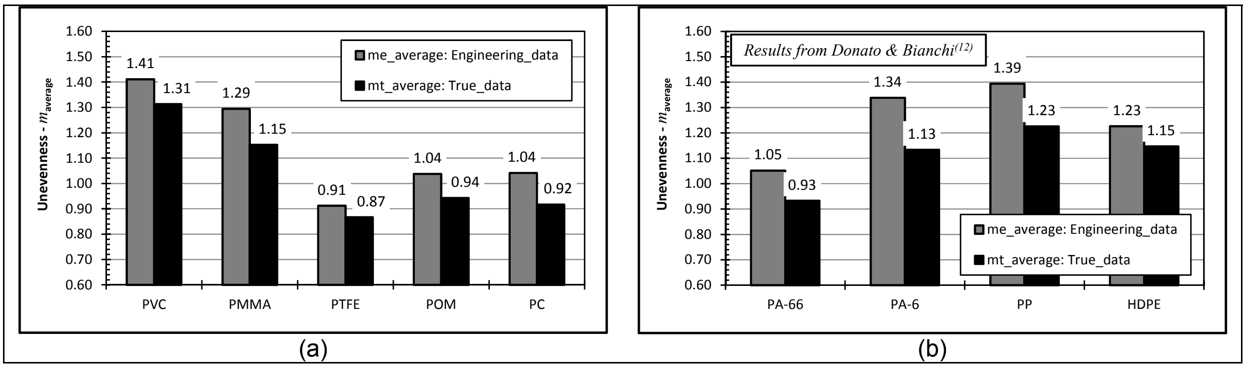

Figure 5. (a) Average values of (m_e) and (m_t) considering all the definitions of $\sigma_{ys\text{-}offset}$ from Table 1. (b) Analogous results for other materials recently presented by Donato and Bianchi.[12]

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5 FRAMEWORK REGARDING PRACTICAL APPLICATION AND POTENTIAL

The experimental results presented by Figure 5 are of great interest for accurate failure predictions and structural improvement of polymeric components. To quantify this potential and call the attention for the limitations, this section contains a brief exploratory study about stress distributions and yield loci deviation.

In this work, POM and PC could be considered even ($m \approx 1.0$), while PVC and PMMA presented $m > 1.0$. Maximum unevenness levels considering yield strength reached $m = 1.31$ considering true data for PVC. Conversely, PTFE presented lower yield strength under compression ($m < 1.0$), as can be seen in Figure 5(a). Two interesting conclusions emerge: i) the existence of larger yield strength under compression cannot be generalized as pointed out by some authors – here, for example, the opposite was found for PTFE with small deviation; ii) modified yield criteria are of great relevance since can take advantage of uneven materials ($m>1$) for structural improvement or correct yield loci looking for safety when $m<1$. Figure 6(a) illustrates the deviation of original Mises yield locus for PVC and PTFE using the parabolically modified Mises model. Figure 6(b) quantifies, for varying σ_1/σ_2 ratios (quantified by θ) the deviation from Mises model. It can be realized that the use of parabolic model for $m>1$ allows great structural improvement for several stress states (90 < θ < 360), reaching up to 49.6% yield increase for PVC. Conversely, for tensile-tensile loadings (0 < θ < 90), the model predicts that yielding in PVC takes place earlier than predicted by original Mises. For PTFE the opposite applies. These occurrences have great technological relevance if properly employed and deserve further phenomenological (rheological) investigation and experimental validation.

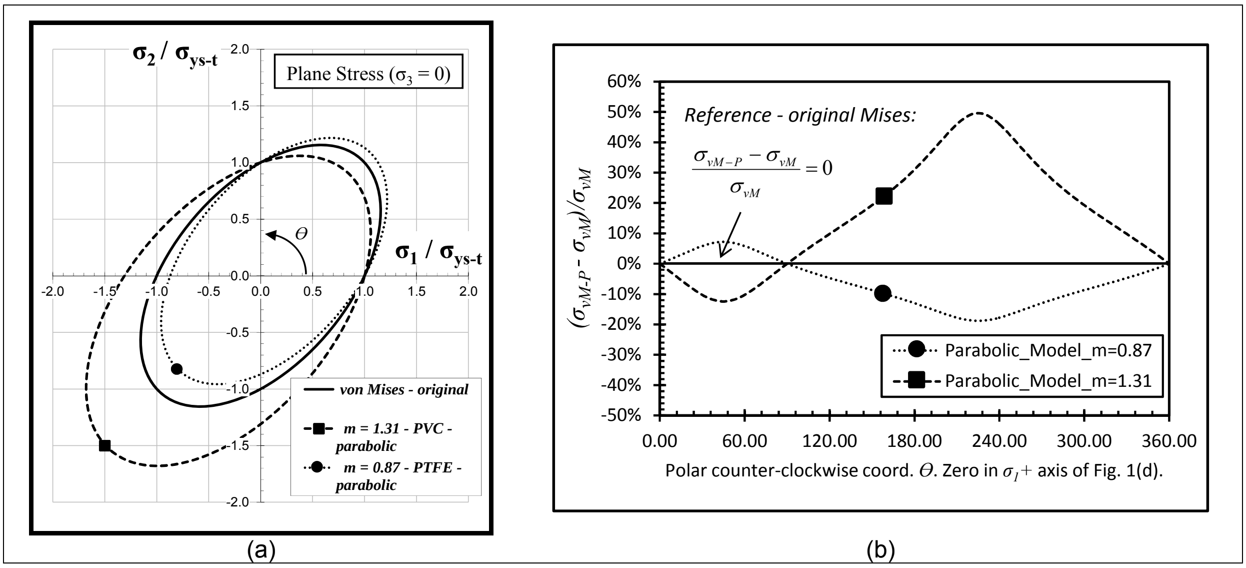

Figure 6. (a) Yield loci based on the parabolic model and adapted for PVC and PTFE and (b) deviations from yield predictions based on original von Mises model.

6 CONCLUDING REMARKS

From this work it is possible to conclude that:

- Elastic modulus was altered under tension and compression for most tested materials, except PMMA and PC.
- Considering deviation, POM and PC could be considered even ($m \approx 1.0$), while PVC and PMMA presented $m > 1.0$. Maximum unevenness levels

considering yield strength reached $m = 1.31$ for true data and $m = 1.41$ for engineering data considering PVC.

- PTFE presented lower yield strength under compression ($m < 1.0$), which proves that the existence of larger yield strength under compression cannot be generalized for thermoplastic polymers as pointed out by some authors.
- Modified yield criteria are of great relevance since, combined to adequate stress states (which derives from geometrical features and loads), can provide structural improvement (here, up to 49.6% yield prediction for PVC).
- This calls the attention to the potential of critically investigating mechanical behavior of polymers in order to achieve structural improvement and, at the same time, safe and efficient solutions.

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