EXPERIMENTAL STUDY FOR THE DETERMINATION OF THE MECHANICAL PROPERTIES ON THERMAL AND MECHANICAL BEHAVIOR OF POLYMER

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Abstract

Polyacetal, a highly crystalline thermoplastic, is known for its exceptional strength, rigidity, and low moisture absorption. It also offers excellent sliding properties and wear resistance, making it suitable for fluid transport applications. For such uses, a comprehensive understanding of the material's mechanical behavior and long-term performance under mechanical stress is crucial. This study employs an experimental approach combining macroscopic tests—such as thermal analysis of POM, uniaxial tensile tests at varying strain rates and temperatures on notched axisymmetric specimens, along with volumetric change measurements—and microscopic observations (using SEM) to investigate the underlying causes of material damage.

Index Terms: Polyacetal, Tensile Testing, Thermogravimetric, Stress, MEB, Differential Thermal Analysis ADT.

1. INTRODUCTION

Research on the evolution of morphology in the field of polymer science and technology is of great importance, as it impacts the final characteristics of many polymer materials. Polymer blends are often separated in the presence of an external field such as a temperature gradient, shear flow, or chemical reaction [1-21].

Semi-crystalline polymers, such as polyacetal (POM), are widely used in various industrial applications due to their excellent mechanical, thermal, and chemical properties. However, setting up and conducting mechanical tests on these materials require a rigorous approach to capture the different aspects of their behavior under various loading conditions. For example, tensile tests conducted on POM must consider assumptions of homogeneous or isochoric deformation, as well as transverse isotropic deformation, to provide an accurate description of the material's mechanical properties [22].

POM is valued for its rigidity [44], wear resistance, and good tribological properties. Under low deformations, POM behaves as a linear elastic material under static loads and as a linear viscoelastic material under vibratory loads. For larger deformations, POM exhibits nonlinear viscoelastic behavior and can even behave as a plastic or visco-plastic material. These characteristics have been extensively studied in recent years, with particular attention to the deformation mechanisms at the molecular scale and their effects at the macroscopic scale. POM is a thermoplastic material with a high degree of crystallinity, characterised by high strength and rigidity. It has good sliding properties, good wear resistance and low moisture absorption. Its good dimensional stability and fatigue resistance, as well as its excellent chemical resistance, make POM a construction material that can be used in a wide range of applications, including the manufacture of small. [23, 24 and 25] complex parts. It also meets the most demanding requirements in terms of surface quality. Strength, rigidity and dimensional stability can be improved by incorporating fillers (organic, mineral, glass... etc.), although some properties may deteriorate. There are a multitude of thermal analysis techniques for polymers, whose information are complementary and enables the precise identification of the properties and transitions of materials, as well as their evolution.

The implementation of mechanical tests on flat POM specimens is a crucial part of this work. These tests are conducted at ambient temperature and are designed to evaluate the influence of the type of control (e.g., displacement control or force control) and the measurement principle (assuming homogeneous/isochoric deformation versus transverse isotropic deformation) on the material's response [26, 27]. A precise understanding of these aspects is essential to provide a comprehensive description of the mechanical properties of POM and to elucidate the mechanisms of deformation, damage, and fracture.

Mechanical testing of semi-crystalline polymers, such as POM, often encounters challenges due to the amorphous nature of some materials and the inherent variations in additive manufacturing techniques [28, 29, 30 and 31], such as Fused Deposition Modeling (FDM).

These challenges can lead to uneven distribution of failure cases among the tested specimens, necessitating a larger number of standardized specimens to obtain accurate results. Consequently, it is recommended to test an additional sample per batch beyond the number prescribed by specific standards. The results of these tests play a crucial role in understanding and characterizing the mechanical properties of POM under large deformations.

The main objective of this study is to provide a detailed description of the mechanical properties of POM under large deformations to better understand the mechanisms of deformation, damage [45], and fracture of this material. This in-depth understanding will contribute to the optimization of industrial applications of POM and the improvement of processing and shaping methods.

In the literature, many authors mention that PET initially whitens in the amorphous phase during its plastic deformation in tension [32, 33 and 34]. The variation in the material's birefringence is caused by the formation of microvoids within the material. These microvoids organize in such a way as to create cracks that propagate perpendicularly to the direction of the mechanical force [35-39].

In the past, initiation methods have sparked debates. A synthesis of the main mechanisms was conducted by Bucknall [40]. It is evident that the preferred initiation sites are the interchain shear zones, which, when restricted by the matrix entanglements, lead to the appearance of this volumetric damage [35, 36, 41, 42].

2. EXPERIMENTAL SECTION

Understanding the mechanisms of deformation and damage requires exploring the mechanical response of the material under different conditions. As with other classes of materials, the mechanical response of POM depends on the type of test, the loading conditions, and the geometry of the specimens used. Mechanical tests aim to characterize the material behavior laws. A behavior law establishes a relationship between stresses and strains.

Based on the analysis of the stress state during necking in a uniaxial tensile bar proposed by Bridgman, and further developed by Hill [43], a flat specimen is considered. In the proposed hypothesis, the deformation analysis in the minimum section of the specimen is assumed to be uniform. This assumption appears to be fairly well verified on a slightly notched specimen. However, the notch effect introduces additional stresses that are no longer all directed along the uniaxial loading axis.

There is no exact solution that provides the fields of constraints and deformations in a notched specimen. In order to properly define the stress distribution in a state of plane stress, and in the vicinity of the notch; a schematic representation of the geometry of the test specimen is provided in figure (1-a), with a detailed stress distribution diagram in figure (1-b).



Figure 1: Schematic for constraints analysis

(1)

In order to analyze the tests on the evolution of the behavior of our polymer under a state of plane stress, we have considered the behavior of our material to be assumed perfectly elastic-plastic.

This assumption is not valid for most polymer materials, due to their large deformations. However, obtaining equilibrium equations for large deformations is very complex.

In a Cartesian coordinate system, the mechanical equilibrium is then expressed as:

$$\sigma_{ij} = 0$$

When using flat test tubes with thin thicknesses, we assume that the stress distribution is planar; meaning that the stress representing the normal direction to the surface is considered zero, and that the radial displacement in the minimum section is therefore proportional to the width.

It is also inferred that the radial and circumferential deformations are equal and constant. Thus, the stress and strain tensors take the following form:

$$\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{yx} & \sigma_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad and \quad \varepsilon = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$
(2)

This yields the following equilibrium equations:

Therefore, any point at the end of the notch depends only on two directions (x and y):

$$\begin{cases} \sigma_{xx} \cos \alpha = \sigma_{xy} \sin \alpha \\ \sigma_{yx} \cos \alpha = \sigma_{yy} \sin \alpha \end{cases}$$
(3)

In this case, the equations will be written as follows:

$$\begin{cases} \sigma_{xx} = \sigma_{yy} \tan^2 \alpha \\ \sigma_{yx} = \sigma_{yy} \tan \alpha \end{cases}$$
(4)

At the notch center Y = 0, where a = 0, we obtain:

$$\begin{cases} \sigma_{xx} \big|_{x=0} = 0 \\ \sigma_{yx} \big|_{y=0} = 0 \end{cases}$$
(5)

3. RESULTS AND DISCUSSION

The mechanical tests aim to characterize the material's behavior laws. A constitutive law establishes a relationship between stress and strain. The tests are conducted at controlled strain rates and different temperatures.



Figure 2: Curve stress strain under different temperatures

Figure 2 clearly illustrates the effect of temperature on the mechanical properties of the HOSTAFORM C 27021 material. At low temperatures, the material is rigid and exhibits high strength but with low deformation before rupture. As the temperature increases, the material becomes more ductile but loses strength. This can influence the choice of this material for applications requiring specific performance in various thermal environments.



Figure 3: Curve of dynamic shear modulus under different temperatures

This graph represents the evolution of the secant shear modulus of the material HOSTAFORM C 27021 as a function of strain at different temperatures.

This graph illustrates the significant effect of temperature on the shear modulus of polyacetal. At low temperature (-40°C), the material exhibits significant initial rigidity, but its resistance to deformation decreases sharply under stress. As the temperature increases, the material becomes more ductile, which is evident from the reduction in the initial modulus and a more stable response to deformation. These results indicate that the mechanical behavior of the material can be optimized for specific environments, with trade-offs between rigidity and ductility depending on the application temperature.



Figure 4: Curve of dynamic shear modulus under temperature

The figure illustrates the dependence of the dynamic shear modulus on the temperature change for the material "HOSTAFORM C 27021". The data show a progressive decrease in the shear modulus with increasing temperature.

At low temperatures (below 0 °C), the shear modulus is high, reaching about 4000 MPa. This indicates that the material is rigid and has high mechanical properties in this temperature range. As the temperature increases, a noticeable decrease in the modulus is observed, with a significant thermal transition around 100 °C.

At high temperatures (near 150 °C), the modulus decreases sharply, reaching values of about 400 MPa, reflecting a significant softening of the material. Physical interpretation: This trend could be related to changes in the internal structures of the material, such as the glass transition or an increase in molecular mobility. The drastic decrease in the modulus at high temperatures may indicate an entry into the viscoelastic phase or a softening of the polymer.

The results show that polyacetal retains significant stiffness at low temperatures but loses its mechanical performance above about 100 °C. This behavior must be taken into account in applications requiring mechanical strength under variable thermal conditions.

The mechanical properties of the polyacetal for the different speeds are given in table (1).

dε/dt (S-1)	E (MPa)	σy(MPa)	v
0,0001	2143	63	
0,0005	2254	66	0.38
0,001	2325	70	
0.1	2415	72	

 Table 1: Mechanical properties of polyacetal

This figure (4) presents data on the variation of yuoung modulus, impact strength and POM energy on different samples. The graph (4-a) shows two sets of data: one for Young's modulus (a measure of stiffness of a material) in percentage terms (E%), and another for energy in joules (J). A black dotted line with data points indicates the trend in energy values, with error bars suggesting variability or uncertainty in the measurements. Similarly, Young's modulus also has error bars, although no connecting lines are drawn between these points. From the data, it appears that the Young's modulus peaks at sample 2 and then decreases, while the measured energy shows a less clear trend but appears to decrease slightly after sample 2.

This figure could suggest a correlation between Young's modulus and the energy characteristic of a new material or coating design, possibly indicating optimal properties for sample 2. The innovation may lie in how these two properties interact or are optimized in the new material design. This could imply that the stiffness of the material (Young's modulus) has a direct effect on its energy absorption or release characteristics (POM energy), which is important for applications where mechanical stiffness and energy management energy are crucial.





The figure (4-b) shows a comparative analysis of impact strength and energy on five different samples, presumably of one material, given the abbreviation POM that is commonly used for this thermoplastic.

On the chart there are two sets of data, A bar represents the impact resistance in kilojoules per square meter (Re (kJ/m²)), corresponding to the main y-axis on the left.

and the other mean energy in joules (Energy (J)), which relates to the secondary y-axis on the right.

The variability or precision of measurements. Likewise, a dotted line connects the data points above the orange bars, again with error bars.

From the graph, we can observe that the impact strength shows a pronounced peak at sample 2 and then decreases. The energy also peaks at sample 2 but experiences a less dramatic drop. There is a clear correlation between the trends in both properties, with sample 2 representing a peak in both impact resistance and energy.

This figure can be used to illustrate the mechanical properties of a new POM coating design. The focus would likely be on how the material's impact resistance correlates with its energy characteristics, which could be crucial for applications requiring materials that not only effectively absorb shock, but also effectively retain or dissipate impact. 'energy. Innovation may lie in the formulation or processing of POM to improve these properties, with Sample 2 possibly representing an optimized balance between impact resistance and energy management. Such a balance could be critical to the material's function and purpose in practical applications, such as automotive parts, consumer electronics, or mechanical gears, where durability and impact resistance are essential.

4. CONCLUSION

As anticipated from the outset, substituting Polyoxymethylene (POM) will not be an easy task. Given its specific and unique properties, finding an equivalent material poses significant challenges. POM is known for its high strength, rigidity, low friction, excellent wear resistance, and stability under varying environmental conditions. These attributes make it an ideal material for a wide range of applications, particularly in the automotive, consumer electronics, and industrial sectors.

In this study, we set out with the primary objective of providing a comprehensive description of the mechanical, physical, and thermal properties of POM, as well as identifying some polymers that could potentially serve as its substitutes. This goal has been successfully achieved through extensive research and analysis. We have meticulously documented the properties of POM, including its tensile strength, impact resistance, thermal stability, and tribological characteristics. Additionally, we have evaluated several alternative polymers, assessing their suitability based on similar criteria.

Despite the identification of potential substitutes, it is evident that no single material can match all the advantageous properties of POM. Each alternative comes with its own set of trade-offs, whether it be in terms of mechanical performance, thermal resistance, or processing characteristics. Therefore, the selection of a substitute will likely depend on the specific requirements of the application, with compromises being made on certain properties.

To further model and predict the behavior of materials that could replace POM, it will be necessary to develop a sophisticated plasticity model that incorporates damage mechanisms. This model should take into account phenomena such as void growth and coalescence, which are critical to understanding the material's performance under very large deformations. These mechanisms are essential for predicting failure in polymers, particularly under conditions of high stress and strain.

The development of this plasticity model will enable more accurate predictions of material performance, guiding the design and selection of suitable substitutes for POM in various applications. This approach will not only enhance our understanding of the material's capabilities but also facilitate the development of new polymers with tailored properties to meet the stringent demands of modern engineering applications.

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