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SUSTAINABILITY IN ENGINEERING. EVALUATION OF THE MECHANICAL BEHAVIOR OF POLYOXYMETHYLENE THROUGH REPEATED INJECTION CYCLES

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Abstract: The increasing global production of plastics raises sustainability challenges and underscores the necessity of transitioning to a circular economy. This study evaluates the mechanical behavior of polyoxymethylene (POM) after multiple mechanical recycling cycles to determine its potential for reuse in industrial applications. The research involved the initial injection of POM specimens, followed by successive grinding and reinjection over ten cycles. The analyzed mechanical properties included tensile strength, maximum tensile force, elongation at break, and Young's modulus. Results indicate a gradual decrease in tensile strength (4.1%) and elongation at break (29.7%), while Young's modulus remains stable. The study confirms the feasibility of mechanical recycling of POM for non-critical structural applications, with recommendations to limit recycling cycles or blend recycled material with virgin polymer to mitigate property degradation.

Key words: Polyoxymethylene, recycling, tensile properties, injection molding, sustainability.

1. INTRODUCTION

Plastic began to be produced on an industrial scale in 1950, and its production has grown to 390.7 million tons globally by 2021 [1].

Due to its excellent mechanical, chemical, and optical properties, as well as its durability, lightweight nature, and low cost, plastic has become ubiquitous in our daily lives [2, 3].

It is estimated that by 2060, annual plastic production will reach 1,800 million tons globally [2].

Therefore, it is clear that we must develop solutions for plastic reuse and transition to a circular economy as soon as possible. One of the most critical principles of the circular economy in the plastics industry is recycling. By using recycled polymers as raw materials, we simultaneously minimize the amount of virgin plastic synthesized and revalorize waste, integrating it into a new life cycle.

Currently, less than 10% of produced plastic is recycled, while the remainder ends up in landfills. There are several possibilities for reusing plastic components that have reached the

end of their lifecycle. The first and simplest solution is repairing and reusing them within the same product. The second option is mechanical recycling, which involves grinding, remelting, and using the resulting material to manufacture new components. A third solution is chemical recycling, which entails depolymerization into monomers that can subsequently be resynthesized into polymers, retaining their initial properties. Finally, another option for plastic reuse is incineration, aiming to recover energy in the form of heat [4].

Mechanical recycling represents the simplest and most efficient solution, as it combines low costs with the relative preservation of the material's properties [4]. In this article, we aim to evaluate how polyoxymethylene (POM) retains its mechanical properties after 10 recycling cycles.

Polyoxymethylene (POM) is a semicrystalline thermoplastic polymer that has been commercially available since the 1960s [5].

With properties such as excellent wear resistance, rigidity, mechanical strength, and chemical resistance, POM is widely applicable

in the automotive, electronics, and precision machinery industries. The dominant processing method for POM is injection molding [6].

In industrial applications, it is critical to determine how many recycling cycles polyoxymethylene (POM) retains its mechanical properties to prevent decrease in the quality of the injected part.

Studies have been conducted on the influence of mechanical recycling on the mechanical properties of POM [2], but what we bring in addition to this research is that we analyzed the influence of recycling POM up to 10 cycles, an essential aspect for the repetitive recycling of plastics, thus contributing to a more efficient circular economy.

The POM specimens were initially injection-molded, then ground and reinjected, resulting in 10 processing cycles. These specimens were subjected to mechanical testing to evaluate the influence of recycling on the material's properties. To exclusively analyze the impact of recycling, a key objective of this study was the consistent maintenance of processing parameters throughout the experiments.

All tests were carried out in the thermoplastic materials processing company S.A. Plastor.

2. EXPERIMENTAL

2.1 Materials

The type of POM used in this case study is Ultraform® N 2320 003 AT BK120 Polyoxymethylene (POM). Ultraform® is produced through the copolymerization of trioxane and another monomer.

2.2 Methods

The material was processed using an injection molding machine suitable for the dumbbell-shaped specimen mold shown in Figure 1.



Fig. 1. The moving part of the mold.

The selection of the machine was made following preliminary calculations (including the determination of clamping force, plasticization unit capacity, compression ratio, and others), based on the technical specifications of the mold and the material used. The results of these calculations led to the selection of an Arburg 370 S injection molding machine, which is shown in Figure 2. This machine has a clamping force of 50tF, a screw diameter of 25 mm, and an L/D ratio of 24.



Fig. 2. Arburg 370 S injection molding machine.

2.2.1 Material Preparation

A total of 12 kg of material was used, which was dried in a specialized dryer for at least 3 hours at a temperature of 100 °C.

For recycling, a grinder was prepared for granulating the recycled material, along with a dedicated dryer for the regrind, to prevent moisture absorption.

To measure the moisture content of the plastic materials, a mettler toledo device, known for its precision and reliability, was used in the experiment. The device operates based on the gravimetric method, utilizing the principle of weight loss through drying.

2.2.2 Equipment setup

The following steps were carried out:

Step 1: Cleaning the plasticization cylinder: Before the first injection cycle, the cylinder was cleaned using a purging material (Purjex) to eliminate any contamination from previous thermoplastics materials used before of the injection molding machine. After each subsequent cycle, the cylinder was cleaned with another batch of natural POM, highlighting the transition from one cycle to the next through color differences.

Step 2: Mold installation: The mold for the test specimens was mounted and properly aligned on the machine.

Step 3: Setting the adjustment parameters: The initial parameters were estimated using the material's technical datasheet and fine-tuned through preliminary tests.

Step:4 Optimization of Parameters:

1. Injection Speed

The injection speed was determined based on the viscosity curve to avoid defects caused by either too fast or too slow flow. The material's viscosity decreases as the injection speed increases due to the shear-thinning effect.

To determine the optimal injection speed, several consecutive injections were performed by varying the injection speed. For each injection speed, the required injection pressure to completely fill the mold cavity was measured, and the results were recorded (Table 1).

Using the results, the values of relative viscosity and injection pressure are plotted as a function of injection speed (Fig. 3 and Fig. 4).

Table 1

Results of determining the optimal injection speed.

Injection speed [mm/sec]	Injection time [sec]	Peak injection pressure [bar]	Relative viscosity [psi*sec]	L/D ratio
2	21.53	536	276961.9	24
5	8.62	671	138816.4	24
10	4.31	793	82027.9	24
15	2.88	869	60065.2	24
20	2.16	951	49299.8	24
25	1.74	1016	42428.1	24
30	1.45	1070	37236	24
40	1.09	1145	29953.2	24
50	0.88	1221	25787.5	24
60	0.74	1269	22537.4	24
70	0.64	1322	20305.9	24
80	0.56	1361	18291.8	24
90	0.51	1400	17136	24
100	0.46	1440	15897.6	24
120	0.39	1500	14040	24
140	0.34	1550	12648	24

Stability zone: In the graph, a portion can be observed where increasing the injection speed no longer produces a significant variation in pressure, and the relative viscosity no longer decreases as much. This indicates the optimal operating zone, where the material is injected efficiently without unnecessary strain. Therefore, the optimal injection speed is 40 mm/s.

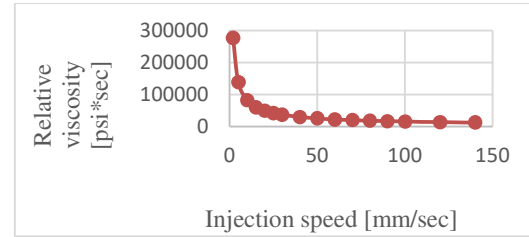


Fig. 3. Viscosity curve for determining the optimal injection speed

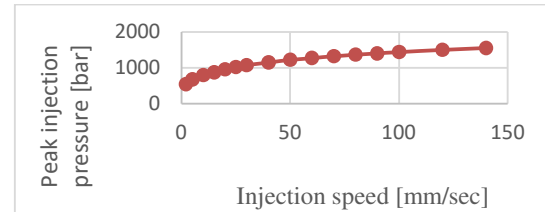


Fig. 4. Injection pressure curve for determining the optimal injection speed.

However, we cannot use the same speed throughout the entire injection phase. For the most efficient filling, certain rules must be followed. According to recommendations, the sprue was filled at a high speed: 50 mm/s, from a dosing stroke of 45 mm to 30 mm. Then, a low speed is needed to pass through the injection gates. At a speed of 10 mm/s, the gates were traversed from a stroke of 30 mm to 28 mm. Next, for filling the part, the optimal injection speed determined above through viscosity tests was used, which is 40 mm/s. Finally, for the end of the mold cavity filling, a low speed was used to optimize the switch to the holding phase.

2. Switchover point

Following several tests, the switchover point was set at 10 mm, in accordance with the theory, when the part is 98% filled (this can be seen in Fig. 5).



Fig. 5. The part at the 10 mm switchover point.

3. Holding time

We injected test specimens with holding times ranging from 1 second to 15 seconds and weighed each specimen. When the weight of the

specimen no longer increased significantly, it meant that the gates had solidified, and we could proceed to the next phase. In our case, a holding time of 10 seconds was selected.

2.2.3 The injection and grinding process

After drying the virgin material, determining its moisture content, and selecting and optimizing the injection parameters, the first injection cycle was initiated. The injected specimens were dumbbell-shaped, in accordance with the ISO 527 standard [8], used for mechanical testing. The weight of each specimen was monitored to ensure consistency throughout the experiment. The resulting parts were collected and ground using an industrial grinder.

Then, after grinding all the parts, a new injection cycle was initiated using the obtained regrind.

Throughout the experiment, the injection and testing parameters were monitored and documented in a centralized table to facilitate subsequent analysis of the results.

2.3 Tensile tests

The tensile test evaluates the mechanical properties of plastic materials. This test complies with the ISO 7500 [8] and ISO 5893 [9] standards, which ensure the accuracy and repeatability of the measurements. Five specimens from each injection cycle were subjected to tensile testing. Tensile strength, maximum tensile force, elongation at break, Young's modulus, and the standard deviation of the elastic modulus were analyzed. The tests were conducted under standard conditions at 23 °C and 50% relative humidity with the apparatus shown in Figure 6.



Fig. 6. Tensile testing machine.

The tests conducted are relevant for highlighting the changes in the mechanical properties of POM after each recycling cycle. Thus, by comparing the results, we will be able to identify the point at which recycling has a negative impact on the quality of the part.

3. RESULTS AND DISCUSSION

Following this, the mechanical properties of the injected parts made from recycled POM are presented and analyzed, with the aim of evaluating the impact of multiple recycling cycles on the material. Essential mechanical parameters such as maximum tensile force, tensile strength, elongation at break, and Young's modulus were measured to identify any changes in mechanical behavior over the 10 recycling cycles.

Table 2

Mechanical Properties of POM.

Nr. Test	Peak Tensile Force [N]	Tensile Strength [N/mm ²]	Strain at Break [%]	Tensile Modulus [MPa]
1	2168,1	61,94	10,99	2914,5
2	2153,9	61,54	10,41	2891,9
3	2146,7	61,33	10,57	2868,7
4	2143,3	61,23	8,87	2856,5
5	2144,1	61,26	8,79	2847,7
6	2144,3	61,26	8,91	2843,8
7	2141,2	61,18	9,78	2855,3
8	2132,3	60,92	8,42	2856,1
9	2128,2	60,81	7,88	2820,8
10	2077,7	59,36	7,73	2904,9

The maximum tensile force represents the maximum value of the force applied to the specimen before fracture. This serves as the primary indicator of the material's strength.

Tensile strength represents the maximum stress a material can withstand before fracture.

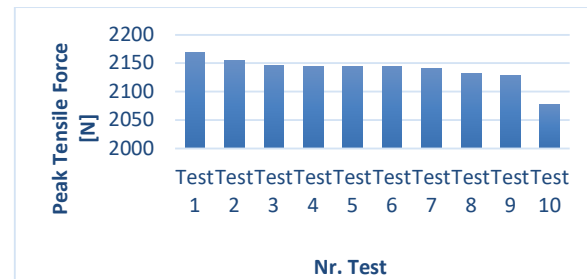


Fig. 7. Variation in maximum tensile force after recycling.

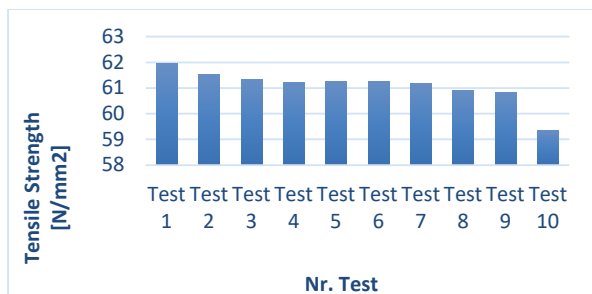


Fig. 8. Variation in Tensile Strength after recycling.

As the number of polymer recycling cycles increases, a gradual decrease in maximum tensile force (Fig. 7) and tensile strength (Fig. 8) is observed. Compared to the virgin material (Test 1), after ten cycles, the maximum tensile force decreased by approximately 4.2%, and the tensile strength by 4.1%. This reduction is explained by the thermal and mechanical degradation of the polymer during repeated grinding and reinjection processes. The observed progressive embrittlement tendency represents a phenomenon specific to mechanical recycling.

Tensile modulus quantifies the material's ability to resist elastic deformation.

Its value remains relatively constant, ranging between 2914.5 MPa (Test 1) and 2904.9 MPa (Test 10). This stability suggests that the material's overall rigidity is not significantly affected during the recycling process, which may indicate good retention of POM's crystalline phase even after multiple processing cycles (Fig.9).

The variation in strain at break characterizes the change in ductility of the recycled material compared to the virgin material.

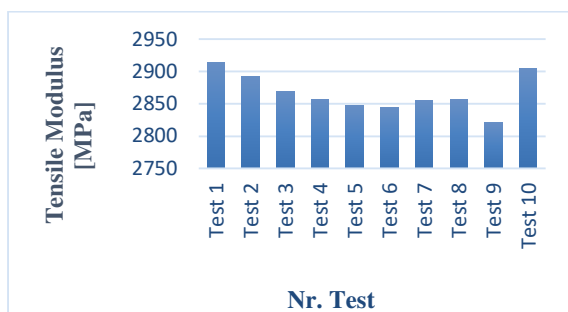


Fig. 9. Variation in Tensile modulus after recycling.

A significant decrease in strain at break **29.7%** between Test 1 and Test 10 is observed, indicating an increase in the brittleness of the

polymeric structure as the number of recycling cycles progresses (Fig. 10).

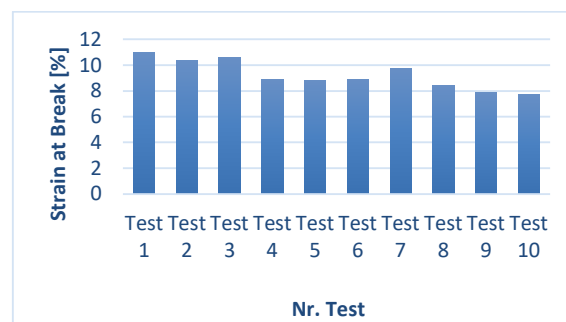


Fig. 10. Variation in strain at break after recycling

The reduction in elongation at break can be attributed to the shortening of molecular chains and the increase in internal defects, which impair the polymer's ability to undergo plastic deformation prior to failure.

4. CONCLUSION

The study results demonstrate that mechanical recycling of polyoxymethylene (POM) selectively affects the material's mechanical properties. Maximum tensile force and strain at break exhibit significant decreases (approximately 4% and 30%, respectively) after 10 recycling cycles, reflecting a reduction in strength and ductility. However, Young's modulus remains stable, indicating that the material's rigidity is preserved. This finding underscores the potential of recycled POM for structural applications where rigidity is critical (e.g., fastening components, housings) but highlights limitations in its use in dynamic stress environments or applications requiring plastic deformation (e.g., shock-resistant parts). The study confirms the viability of mechanical recycling of POM (polyoxymethylene) for waste reduction, with acceptable performance in non-critical applications for up to 5–7 recycling cycles. For applications requiring high mechanical strength or ductility (e.g., critical automotive components), it is recommended to limit the number of recycling cycles or incorporate blends of recycled and virgin material to compensate for property degradation.

For future research, it would be useful to investigate the effects of different proportions of

recycled material on mechanical and thermal properties, to extend the study to other plastics such as polypropylene and polyamide, and to analyze thermal and rheological properties to assess how recycling influences processing temperatures and material flow"

Our conclusions are implementing this study in the plastic industry would prove to be efficient by saving time and by leaving no room for errors.

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Sustenabilitate în inginerie. Evaluarea comportamentului mecanic al polioximetilenei prin cicluri repetate de injectare

Creșterea producției globale de produse din plastic ridică probleme legate de sustenabilitate și necesitatea tranziției către o economie circulară. Acest studiu evaluează comportamentul mecanic al polioximetilenei (POM) după multiple cicluri de reciclare mecanică, pentru a determina posibilitatea reutilizării sale în aplicații industriale. Cercetarea a implicat injectarea inițială a probelor din POM, urmată de măcinare și reinjectare succesivă timp de zece cicluri. Proprietățile mecanice analizate includ rezistența la tracțiune, forța maximă la tracțiune, alungirea la rupere și modulul lui Young. Rezultatele indică o scădere treptată a rezistenței la tracțiune (4,1%) și a alungirii la rupere (29,7%), în timp ce modulul lui Young rămâne stabil. Studiul confirmă fezabilitatea reciclării mecanice a POM pentru aplicații structurale non-critice cu recomandarea limitării ciclurilor sau amestecului cu material virgin.

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