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IMPROVING LONGEVITY OF SAFETY COMPONENTS IN TRANSPORTATION

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Abstract: Polycarbonate, a thermoplastic polymer, is widely used in sectors like security and transportation due to its low strain, durability, performance, and slow deterioration. It is easily moldable, processable, and thermoformable, making it ideal for automotive applications. This study evaluates the impact resistance of polycarbonate by testing polycarbonate shields, shield-derived grit, and injection-molded polycarbonate specimens using a drop-weight impact test. The findings reveal that injection-molded polycarbonate does not match the mechanical properties, particularly impact resistance, of the polycarbonate safety shields, highlighting the superior durability of the shields.

Keywords: Transportation, Mechanical resistance, Safety, Polycarbonate, Injection molding technology *life*.

Introduction

Polycarbonate is an amorphous thermoplastic polymer widely utilized across various industries, including construction, automotive, aerospace, healthcare, electronics, and engineering. This versatile material finds applications in office products, sports equipment, packaging, security components, bullet-proof glass, automotive bullet-resistant windows, displays, and electrical telecommunication hardware (Kausar, 2018; Wu et al., 2018; Seo et al., 2021). Its excellent physical properties, such as toughness, strength, optical transparency, impact resistance, and heat resistance, make it particularly suitable for these applications (Čekon and Šikula, 2020; Liu and Lu, 2022; Sohrabi et al., 2022).

However, polycarbonate also has several disadvantages, including high melt viscosity, notch sensitivity (especially impacting mechanical properties), relative softness, limited solvent resistance, susceptibility to weathering, hydrolysis, and scratches (Soekoco et al., 2022). Despite these drawbacks, polycarbonate remains a valuable material in the automotive industry due to its low stress, durability, performance, and slow deterioration. Notably, its low weight and high impact strength make it ideal for headlamp lenses. The material's molecular weight significantly influences its impact resistance, and environmental factors such as weather can degrade its physical properties over time. Additional challenges include cracking from moisture, salt water, and plastisol exposure (Beşliu et al., 2021; Ediz and Aktaş, 2022; Kodali et al., 2021; Tanaka et al., 2014). Furthermore, polycarbonate is vulnerable to common industrial solvents, automotive fluids, and high-temperature humidity (Zengin et al., 2022). Despite these issues, polycarbonate is used for visible automotive parts like door handles, bumpers, and headlight lenses due to its decorative appeal and excellent mechanical and thermal properties (Moradi et al., 2021).

Polycarbonate components can be produced using various methods, with the most common being extrusion, injection molding, and vacuum thermoforming. In thermoforming, a polycarbonate sheet is heated until pliable, then stretched over a mold to create a 3D shape upon cooling (Takaffoli et al., 2020; Zulfiqar et al., 2021). Injection molding, on the other hand, allows for the high-volume, consistent production of high-quality parts and is extensively used in the automotive, aerospace, and electronics industries (Qin et al., 2021).

This study investigates the mechanical properties, particularly impact resistance, of polycarbonate safety shields and injection-molded polycarbonate specimens. The primary aim is to determine whether injection-molded parts can match the durability of commercially used safety shields. Through comparative testing, the study seeks to validate the feasibility of producing robust injection-molded polycarbonate components that meet or exceed the performance standards of traditional safety shields.

2. Methodology

2.1. Experimental Procedures and Techniques.

This study explores three specific applications of machine learning (ML) techniques to predict key outcomes of Internal Lining Inspections (ILI) for pipelines. As illustrated in Figure 1, the process begins with the use of an ML classifier to identify potential pipeline defects. Following this, ML regressors are employed to predict the dimensions of these defects, including their length, width, and depth. Finally, another set of ML regressors is used to estimate the growth rates of defect length and depth. This prediction aids in evaluating the remaining life of the pipeline by analyzing the progression of defects over time. The growth rates are derived from defect depth data obtained from ILI results conducted in 2015 and 2020. This comprehensive approach allows for a detailed analysis of pipeline integrity and supports proactive maintenance strategies, ensuring the safe and efficient operation of energy transportation infrastructures.

Fig1. Polycarbonate shield AS-60-100/L.

To prepare the test specimens, the polycarbonate shield was initially cut into plates measuring 63 x 63 mm using a band saw. The remaining portions of the shield were then chopped into smaller pieces, which were subsequently crushed into grit. This crushed material served as the feedstock for the injection molding process. The FRITSCH Pulverisette 19 laboratory high-speed knife mill was utilized for the crushing procedure, ensuring a uniform grit size suitable for molding. Figure 2 provides a visual overview of the entire process, detailing the steps from cutting the polycarbonate shield to preparing the test plates and producing the grit for injection molding. This comprehensive preparation process was essential for generating consistent and reliable specimens for subsequent mechanical testing and analysis.

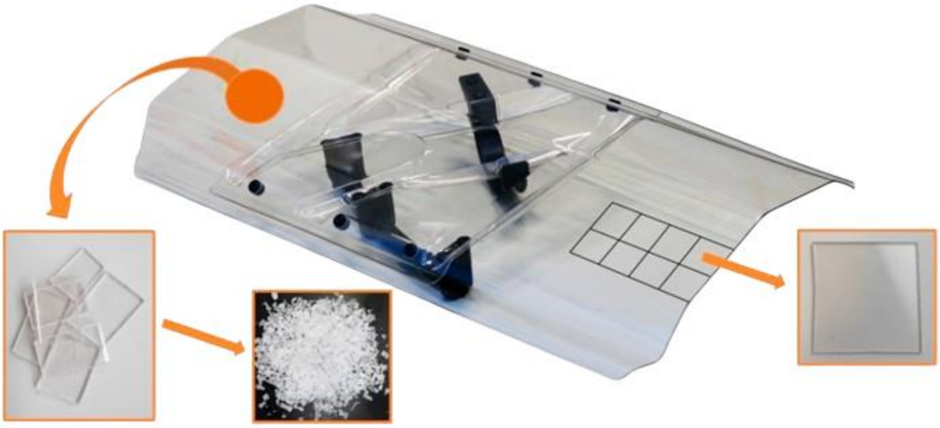

Fig. 2Polycarbonate Shield Test Plate and Grit Preparation: A Step-by-Step Guide

Initially, the polycarbonate shield underwent cutting using a band saw to produce test plates measuring 63 x 63 mm. Subsequently, the remaining sections of the shield were fragmented into smaller pieces, which were then crushed into grit. This grit material was employed in injection molding processes. The FRITSCH Pulverisette 19 laboratory high-speed knife mill facilitated the crushing operation. Figure 2 depicts the complete sequence of steps involved in the preparation of both test specimens and grit derived from the acquired polycarbonate shield. This process was crucial in ensuring standardized and consistent samples for subsequent testing and analysis. By utilizing advanced equipment and precise cutting techniques, the study aimed to maintain uniformity in the composition and properties of the test materials, thereby enhancing the reliability and accuracy of the experimental results.

Injection Parameters	Values
Injection Pressure [MPa]	80
Injection Velocity [$mm.s^{-1}$]	10
Holding Pressure [MPa]	60
Holding Time [s]	10
Cooling Time [s]	25
Mold Temperature [°C]	100
Meld Temperature [°C]	290

Table 1. Process parameters of injection molding.

To compare the mechanical properties of the shield material with an alternative polycarbonate material

Fig 3(a) Test Specimen Injection Molding from Grit (b) Utilizing Raw Granulate test plates were fabricated from both materials using injection molding technology. The process began with drying the polycarbonate grit and raw granulate for four hours at 120°C to eliminate moisture that could lead to defects. Optimal process conditions were established using dried polycarbonate grit with a melt flow index of 11.5 g/10 min. Test specimens measuring 63 x 63 x 3 mm were then produced from the polycarbonate grit, as depicted in Fig. 3 (a). The dried raw polycarbonate granulate, with a melt flow index of 41.7 g/10 min, underwent the same process conditions, and test specimens were manufactured accordingly, as illustrated in Fig. 3 (b).

Following the guidelines outlined in ISO 10350-1, the prepared specimens underwent preconditioning for seven days at a controlled environment of 23°C and 50% relative humidity. Subsequently, in accordance with ISO 6603-2 standards, the injection-molded specimens were subjected to testing using the ZWICK HIT 230F drop-weight testing apparatus. Each test specimen was securely positioned between two clamping rings, and an impactor featuring a hemispherical striker tip with a radius of 10 mm was employed. The impact energy was set at 230 J using the TestXpert II control program, and statistical analysis of the maximum impact force and consumed work was conducted after testing five specimens from each material group at this energy level. The fracture surface of each specimen was carefully examined following the completion of testing to assess any signs of damage or failure

3. Experimental Methodology

The primary objective of this study is to assess whether injection molded polycarbonate can exhibit comparable or superior mechanical properties compared to a polycarbonate protective shield. Specifically, the focus lies on puncture resistance, with the intention to compare the results with commonly used polycarbonate products manufactured through different methods such as calendaring or extrusion. Test specimens were categorized into three groups based on their production processes. The first group comprised specimens directly cut from the aforementioned shield, renowned for its impact, stab, and chop resistance. The second group involved crushing the safety shield to create precise test specimens via injection molding, a technique known for its speed and ability to produce intricate shapes.

The third group consisted of specimens produced from standardized polycarbonate granulate using the same injection molding process conditions as the crushed shield specimens. By comparing these specimens, the study aims to determine if injection molding technology can be viable for security applications,

Group	Abbreviation	Description
1	Shield	63 x 63 x 3 mm plates cut from polycarbonate protect shield AS-60-100/L
2	Grit	Injection-molded plates from crushed polycarbonate protect shield AS-60-100/L
3	Granulate	Injection-molded plates from raw polycarbonate granulate - Sabic Lexan ML3729

Table 2. Description of the test specimens

potentially leading to shape optimization, material reduction, increased production efficiency, and lower final product costs. An instrumented puncture test conducted on a ZWICK HIT 230F Drop-weight impact tester was employed to evaluate specimen resistance to deformation, focusing on maximum punching force and total work consumed. These findings will inform whether injection molding can achieve material properties comparable to other manufacturing methods in safety applications.

4. Findings and Analysis

The experiment involved subjecting the prepared test specimens, categorized into three groups, to ambient conditions of 23°C temperature and 50% relative humidity for a period of seven days. Subsequently, a drop-weight impact test was conducted to assess the puncture resistance of each specimen. The ZWICK HIT 230F instrumented device was utilized with an energy setting of 230J to break through the test specimens. Table 3 presents the statistically evaluated maximum impact force, revealing similarities between the safety shield (Shield) and the specimens made from its grit (Grit), while a decrease of 1116.3N was observed in specimens made from raw granulate (Granulate). This decrease in force and the widened variation range in granulate specimens may be attributed to differing injection molding process parameters. Despite being prepared under similar conditions, the test specimens from granulate showed reduced total consumed work for punching compared to the safety shield.

Statistical Characteristics [N]	Shield	Grit	Granulate
Number of measurements	5	5	5
Arithmetic mean	11228.6	11194.6	10112.3
Type error A	107.1	108.8	154.1
Standard deviation	239.6	243.4	344.5
Minimum value	11026.4	10791.9	9564.4
Median	11157.0	11264.8	10151.0
Maximum value	11601.6	11435.6	10486.0
Variation range	575.2	643.7	921.6

Table3.Statistically evaluated maximum impact force from drop-weight impact test

The reduction in total work could be attributed to polymer chain reprocessing and shortening during material plasticization and injection molding. The grit from the safety shield proved unsuitable for injection molding, necessitating adjustments in process conditions. Such modifications could potentially decrease the total work for granulate specimens by 42.2 J compared to the shield. Figure 4 illustrates a percentage comparison of the studied parameters, indicating a significant reduction in total consumed work for granulate specimens compared to the shield. Additionally, a noticeable decrease in maximum impact force and total consumed work was observed in specimens from raw granulate compared to the shield.

Statistical Characteristics [J]	Shield	Grit	Granulate
Number of measurements	5	5	5
Arithmetic mean	161.9	137.0	119.7
Type error A	1.3	3.9	2.9
Standard deviation	3.0	8.7	6.4
Minimum value	158.5	124.1	112.4
Median	160.5	136.5	119.4
Maximum value	165.6	148.1	128.8

Variation range	7.1	24.1	16.4

Table 4. Statistically evaluated total consumed work for punching from drop-weight impact test.

Figure 4 illustrates a percentage comparison of the examined parameters, indicating that despite variations in processing methods for the same material (Shield x Grid), the maximum impact force has remained unchanged. However, there was a noteworthy reduction of over 15% in total consumed work. Furthermore, specimens crafted from raw granulate exhibited a notable decrease in maximum impact force by 10% and total consumed work by more than 26% compared to the values recorded during safety shield processing.

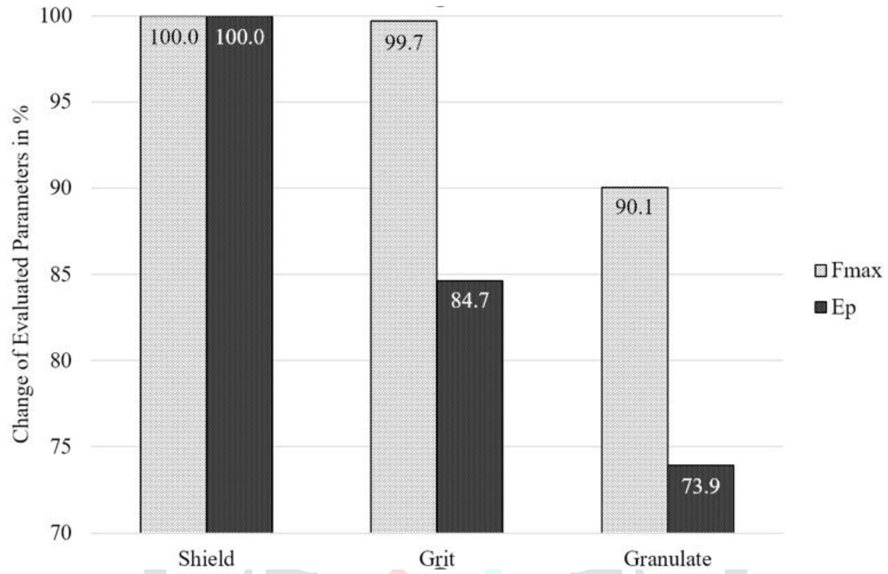

Fig 4 Percentage Change in Maximum Impact Force (Fmax) and Total Consumed Work for Punching (Ep)

Figure 5 depicts the test record for the Shield, Grit, and Granulate groups, showcasing similar trajectories up to a force value of 6000 N, beyond which slight divergence occurs until the maximum force value is reached and the specimens fracture. Figure 6 displays the deformed specimens after the puncture test, demonstrating minimal visual differences between them, with all specimens showing deformation and material penetration around the penetrator perimeter.

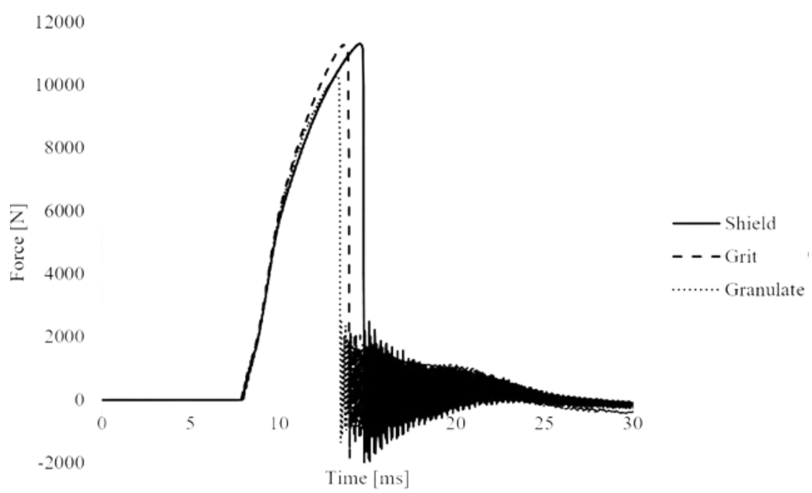

Fig 5.Test Results for the Examined Groups: Shield, Grit, and Granulate

Fig 6 Damage Assessment of Specimens Following the Drop Weight Test: (a)Polycarbonate Shield ,(b) Polycarbonate Grit , and (c) Polycarbonate Raw Granulate.

5. Conclusion

Injection molding technology is highly suitable for producing precise plastic parts, ranging from small to large dimensions, particularly for complex parts and large production runs. It's crucial to assess the properties of final products produced by different technologies to ensure they meet specified standards, especially for safety elements in transportation applications.

This study specifically investigated the mechanical properties, particularly puncture resistance, of a polycarbonate safety shield used in security applications. The shield must endure multiple impacts without damage, although it's not designed for ballistic purposes. Test specimens were prepared by injection molding technology from crushed shield material. However, the injected specimens did not achieve the puncture resistance of the safety shield, likely due to suboptimal process conditions.

Future research could explore alternative materials that meet stringent safety requirements. Additionally, expanding testing to include resistance to sharp objects or scratches could provide valuable insights for enhancing safety features in transportation applications.

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