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# Mechanical resistance of safety elements in transportation

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**Abstract**

Polycarbonate is a thermoplastic polymer used in many sectors including security and transportation. Polycarbonate plastic parts can be used in automotive applications because of their low strain, durability, performance, and slow deterioration. This engineering polymer is easily moldable, processable, and thermoformable. This article tests the polycarbonate shield, grit from the polycarbonate shield, and injection molded polycarbonate specimens on a drop-weight impact test. This study is focused on the comparison of the mechanical properties (especially on the impact resistance) between injection molded polycarbonate, and polycarbonate safety shield. Statistical evaluation of the results shows that the injection molded polycarbonate does not reach the mechanical properties of the protect shield.



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

## 1. Introduction

Polycarbonate is an amorphous thermoplastic polymer used in many sectors such as construction, automotive, aerospace, healthcare, electronic, and engineering industries. This material is further used for office production, construction and sports equipment, packaging, security components, bullet-proof glass, displays, bullet-resistant windows in automobiles, and electrical telecommunication hardware (Kausar, 2018; Wu et al., 2018; Seo et al., 2021). Its excellent physical properties are suitable for previous applications, especially due to its toughness, strength, optical

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transparency, impact, and heat resistance (Čekon and Šikula, 2020; Liu and Lu, 2022; Sohrabi et al., 2022). However, some of the disadvantages of polycarbonates are high melt viscosity, notch sensitivity of mechanical properties (especially impact strength), relative softness, limited solvent resistance, weathering, hydrolysis, and scratches (Soekoco et al., 2022). Mentioned material can be used in the automotive industry, which is one of the areas, where this excellent material can be implemented.

Plastic parts made from polycarbonate can be used in automotive applications due to low stress, durability, performance, and slow deterioration. Due to its low weight and high impact strength, the major usage of polycarbonate in the automotive industry is in headlamp lenses. The molecular weight of polycarbonate affects its ability to withstand impacts. The physical properties of mentioned material can be influenced by weather, which can cause the breakdown of parts during their lifecycles. Another disadvantage is cracking caused by moisture, salt water, and plastisol (Beşliu et al., 2021; Ediz and Aktaş, 2022; Kodali et al., 2021; Tanaka et al.,2014). Moreover, it is also susceptible in contact with common industrial solvents, automotive fluids, and humidity at a higher temperature (Zengin et al., 2022). Visible parts such as door handles, car bumpers, and headlight lenses are also made from polycarbonate because they should have a good appearance as a decorative part, and excellent mechanical and thermal properties (Moradi et al. 2021).

There are a lot of possible ways how the polycarbonate components can be created. However, the most widespread production technologies are extrusion, injection molding, and vacuum thermoforming. The difference between thermoforming and injection molding is that in thermoforming the polycarbonate sheet is heated into a moldable and soft form and then it is stretched to the mold surface to retain the required geometry after being cooled. Due to thermoforming of the polycarbonate sheet, the 2D model becomes a 3D model (Takaffoli et al., 2020; Zulfiqar et al., 2021). Injection molding can repeatedly produce high-quality items in several huge batches. This technique has become widespread, for instance, in the automotive, aerospace, and electronics industries (Qin et al. 2021).

This study tests the mechanical properties (especially impact resistance) of a polycarbonate safety shield and injection molding technology-prepared polycarbonate specimens. The main goal of the study is to verify whether it is possible to produce an injection molded part as durable as the commercially used safety shield.

## 2. Materials and methods

This study is focused on the impact of mechanical properties of safety parts from polycarbonate. Especially the drop-weight impact test was used for determining the puncture resistance of safety parts namely polycarbonate shield AS-60-100/L (Fig.1) made by ESP which was used for this experiment. The mentioned shield is used as physical protection for police, and it can be also used in other safety applications. The thickness of the function part of the shield is 3 mm, and the dimensions are 57 x 100 cm.

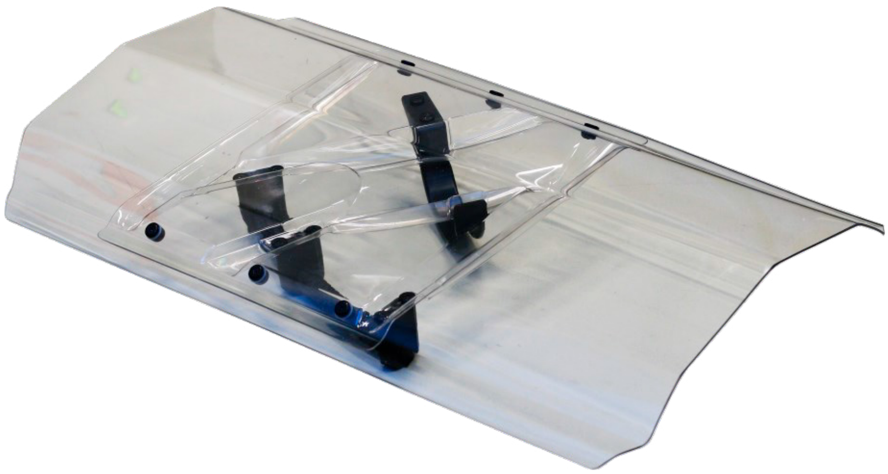

Fig. 1. Polycarbonate shield AS-60-100/L.

First, the polycarbonate shield was cut with a band saw into test plates with dimensions 63 x 63 mm, and the rest of the shield was cut into small pieces which were crushed into grit. The crushed material was used for injection molding technology, and the FRITSCH Pulverisette 19 laboratory high-speed knife mill was used for crushing. Fig. 2 shows the entire process of preparing test specimens and grits from the acquired polycarbonate shield.

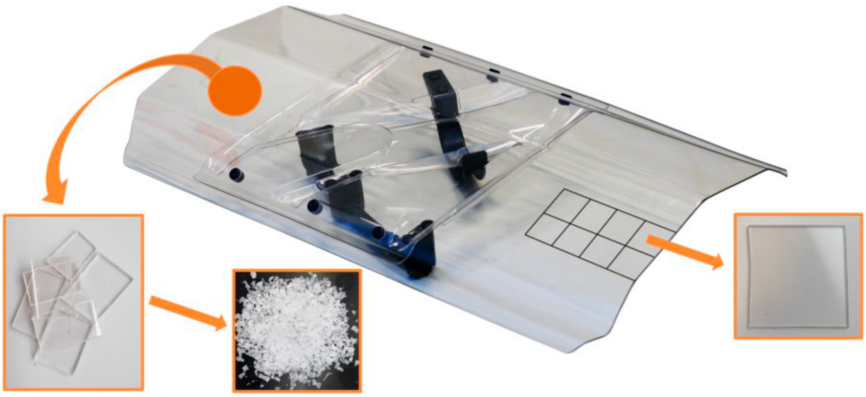

Fig. 2. The preparation process of test plates and grits from polycarbonate shield.

To compare the mechanical behavior between the shield material and the alternative polycarbonate material made by Sabic Lexan ML3729, test plates were prepared from both of these materials. Injection molding technology was used to produce test plates, which can be suitable for producing precise products in large series. First, the polycarbonate grit and the raw polycarbonate granulate were dried for 4 hours at 120 °C to remove all moisture from the material, which could cause defects in the manufactured parts. A dried polycarbonate grit with a melt flow index of 11.5 g/10 min (300 °C/1.2 kg) was used to set the optimal process conditions (Tab.1) for injection molding. The process of producing test specimens with dimensions 63 x 63 x 3 mm from polycarbonate grit is shown schematically in Fig. 3 (a). The dried alternative polycarbonate raw granulate with a melt flow index of 41.7 g/10 min (300 °C/1.2 kg) was processed under the same process conditions. Fig. 3 (b) shows the production of test specimens from raw polycarbonate granulate, which is commonly used in the production process.

Table 1. Process parameters of injection molding.

| 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 |

According to standardization ISO 10350-1, prepared specimens were preconditioned for seven days at a temperature of 23 °C and relative humidity of 50%. Then, at a temperature of 23 °C, injection-molded specimens were put to the test on the ZWICK HIT 230F drop-weight testing apparatus by another standardization ISO 6603-2. Test specimens were placed into two clamping rings, and an impactor with a hemispherical striker tip (R = 10 mm) was utilized. The impact energy 230 J was set by the controlling program called TestXpert II and MS Excel 2019 was used to determine the statistical evaluation of the highest impact force and consumed work after five specimens from each group of materials at 230 J. After each test, the fracture surface was evaluated.


Fig. 3. The injection molding of test specimens from grit (a) and raw granulate (b).

## 3. Experimental part

The main goal of this study is to determine if it is possible to achieve the same or better mechanical properties, between the injection molded polycarbonate compared with the polycarbonate protect shield. This experiment was mainly focused on the puncture resistance, and it can be further compared to commonly used polycarbonate products that are prepared by a different technology (e.g. calendering, extrusion). The specimens prepared for the test were divided into three groups according to the technological process of production (Tab. 2).

Table 2. Description of the test specimens.

| 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 |

The first testing group contains specimens that were directly cut from the mentioned shield AS-60-100/L (ESP). The polycarbonate protect shield weighs 3.5 kg and, it is resistant to impact, stabbing, or chopping. This shield cannot be used as ballistic protection, because the 9 mm bullet would easily pass through it. However, it can be used as protection against smaller shotgun rounds or other little fragment. This material was chosen as a suitable material for this experiment, which can be used as safety parts in vehicles such as movable or immovable elements due to the mentioned properties.

For the second group of specimens, the safety shield AS-60-100/L (ESP) was crushed to prepare accurate test specimens on the injection molding machine. Plastic injection molding technology is one of the most widespread technologies for very precise products that are produced in large series. A significant advantage of injection molding is the production speed and possibility of producing complicated shapes. This technology is unique because with other plastic technologies (calendering, extrusion, and vacuum thermoforming) is impossible to create mentioned shapes. It is important to make standardized specimens from the same material used for the protect shield that will be compared with another specimen made from commonly used polycarbonate granulate, which is suitable for plastic injection molding technology.

The third group of specimens is made from standardized polycarbonate granulate as input for injection molding technology and it was produced with the same process conditions as test specimens from crushed polycarbonate protect shield (Tab. 1).

Based on the comparison of all prepared specimens it is possible to determine if polycarbonate granulate can be used in security applications by injection molding technology used in security products. This approach could lead to optimization of the shape, reduction of material requirements, an increase in production, and an overall reduction of the price of the final product. An instrumented puncture test performed on the ZWICK HIT 230F Drop-weight impact tester, was proposed for the evaluation of the prepared specimens because the material has to withstand the impact of various objects, kicks, stabbing weapons, etc.

The process of the deformation of individual specimens was tested for all the prepared specimens to evaluate the resistance to punching as reliably as possible. The most important part of the measurement was focused on the maximum force used for punching and the total consumed work for punching the specimens. Based on these results, it is possible to determine if the injection molding technology can match the material properties created by other technologies in safety applications.

## 4. Results and discussion

The prepared test specimens, which were divided into three mentioned groups, were exposed to a temperature of 23°C and a relative humidity of 50% for seven days. To verify the puncture resistance of individual specimens the drop-weight impact test was performed. The energy of 230J for the drop-weight test was set on the ZWICK HIT 230F instrumented device where the test specimens were broken through. Table 3 shows the statistically evaluated maximum impact force. Moreover, the maximum impact force of the safety shield (Shield) is similar to the test specimens made from its grit (Grit). The decrease between the maximum impact force of specimens (Shield), and specimens made from raw granulate (Granulate) is 1116.3N. The injection molding process parameters were set for the test specimens prepared from grit (Grit) which is a possible reason for the decrease in this force and the widening of the variation range of granulate (Granulate). These test specimens from granulate were prepared under the same process conditions, which may not be the most optimal conditions for production, but it makes the test properties comparable.

Table 3. Statistically evaluated maximum impact force from drop-weight impact test.

| 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 |

The statistically evaluated total consumed work for punching from the drop-weight impact test is listed in Table 4. It also shows the gradual reduction in total consumed work, where the highest total consumed work value of 161.9 J has the safety shield (Shield). The total work decreased by 24.9 J by crushing and preparing the test specimens with injection molding technology. This decrease could be caused by reprocessing and shortening of the polymer chains, which could have occurred during the plasticization of the materials and injection through the nozzle into the mold cavity (Pérez et al., 2010).

The grit from the safety shield is not suitable material for injection molding, and the process conditions should be changed to match the mentioned injection molding technology process. This approach could also lead to a decrease of 42.2 J in the total work for the test specimens made of raw granulate, in comparison with the shield.

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

| 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 |

Figure 4 shows a percentage comparison of the studied parameters, where the maximum impact force due to different processing of the same material (Shield x Grid) has not decreased. A significant reduction of more than 15% in total consumed work was measured. The specimens from raw granulate were a noticeable decrease in maximum impact force by 10% and total consumed work by more than 26% compared to the values measured at the safety shield.

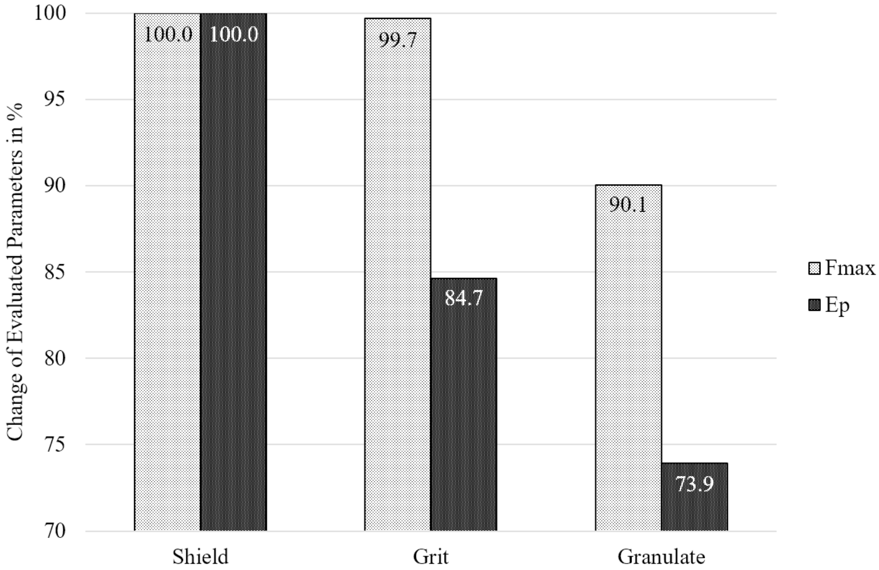


Fig. 4. Percentual change of evaluated Maximum impact force (Fmax) and total consumed work for punching (Ep)

Figure 5 shows the test record for the individual tested Shield, Grit, and Granulate groups. The curves have the same trajectory up to a force value of 6000 N. After this threshold, the curves start to diverge slightly until the maximum force value and the test specimens break. Figure 6 shows the deformed specimens after the puncture test. There is almost no visual difference between deformed specimens. All specimens were deformed with subsequent penetration of the material around the perimeter of the penetrator.

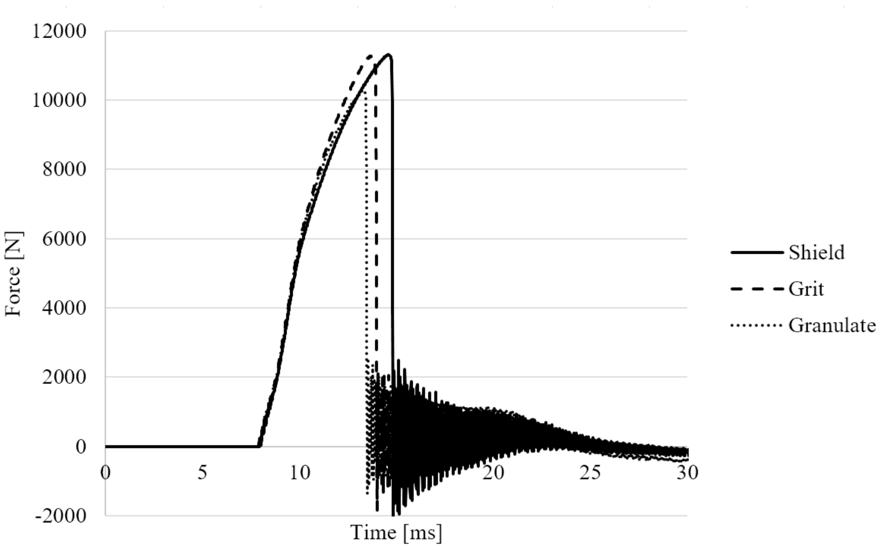


Fig. 5. The test record for the individual tested groups: Shield, Grit, and Granulate.

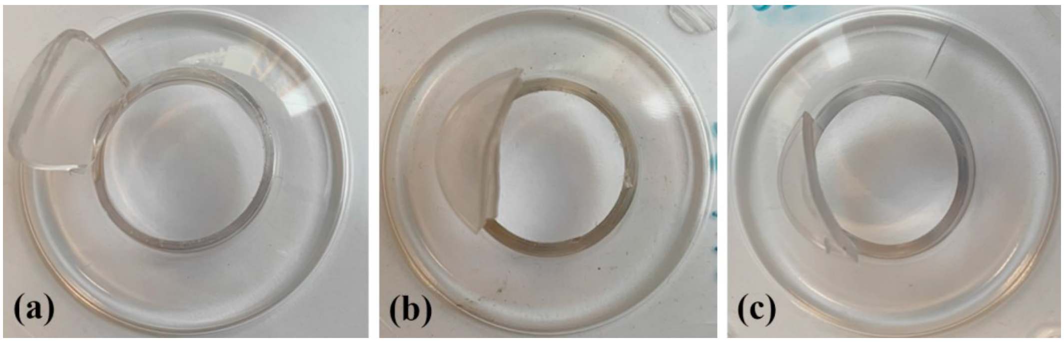


Fig. 6. The damages of the specimens after the drop weight test: polycarbonate shield (a), polycarbonate grit (b), and polycarbonate raw granulate (c).

## 5. Summary

Injection molding technology is suitable for the precise production of plastic parts, which can have different dimensions from miniature to enormous dimensions. This technology is better for more complicated parts, especially for the larger production series, and it is important to test the final products produced by different technologies to verify whether they have the same properties to achieve the final properties as prescribed. This approach can be used especially in the safety elements in means of transport, where it is necessary to observe the highest standards regarding their properties.

This study was focused on the mechanical properties especially puncture resistance of a polycarbonate safety shield used by security forces. It is necessary, that this shield must withstand numerous impacts without damaging itself, and it is not intended for ballistic purposes. This shield was crushed, and specimens were prepared from it by injection molding technology as an alternative material that is suitable for mentioned technology. The shield material is not primarily intended for injection molding technology, and it was found that the injected test specimens did not reach the puncture resistance of the safety shield. The reason for the mentioned problem is that the optimal process conditions were not chosen to produce test specimens from raw granulate. Another option is to use a different type of polycarbonate suitable for injection molding technology or to modify it to get better-required properties.

Further studies can be focused on other materials that could achieve the demanding requirements of safety features. In the future, there will be an expansion of testing areas, such as resistance to sharp objects or scratches.

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