Chemical and Process Engineering: New Frontiers, 2025, 46(2), e92
DOI: 10.24425/cpe.2025.153677

Sandwich composites containing thermoplastic core structures manufactured by 3D printing for defense industry applications

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Article info:
Received: 11 April 2025
Revised: 30 May 2025
Accepted: 02 June 2025

Abstract
This paper investigates the effect of material type, shape and cell size of cores on impact energy absorption properties. For this purpose, thermoplastic cores were prepared by 3D printing and compared with commercially available composites containing aluminum and aramid cores. The impact energy absorption properties were evaluated using "falling arrowhead" impact puncture tests. Obtained results showed that composites containing thermoplastic cores had significantly higher impact energy absorption compared to reference composites. Structures with a small cell area, especially those with a rectangular shape and parallel cell arrangement, performed the best. In contrast, composites with aramid and aluminum cores, despite their lower weight, had worse impact properties. It was also shown that increased energy absorption by thermoplastic structures was associated with higher composite weight, which may be an important factor in applications requiring optimization of mass and impact-ballistic resistance.

Keywords
polymer composites, core structures, 3D printing, ballistic properties

1. INTRODUCTION

The continuous development of military equipment and the specific character of the modern battlefield force the arms industry to develop more and more modern types of armor, which will be characterized by high strength, lightness and resistance to extreme operating conditions. Polymer composites are an engineering material that meets these requirements. They have become a key solution in the design of modern military constructions due to their unique properties, such as low weight, corrosion resistance and high mechanical strength (Czech et al., 2021; Tran et al., 2018).

Sandwich-structured composites are one of the used types, characterized by a high strength-to-weight ratio, good energy absorption and impact resistance. Their mechanical properties depend on the materials used in their preparation (Balakumaran et al., 2021; Dogan, 2021; Rao et al., 2022). They consist of a thermoplastic or duroplastic matrix and a reinforcement embedded in it, which consists of three main layers: two outer skin facings and an inner core structure. The facings consist of several layers of fibrous materials, such as fabrics or mats made from e.g. aramid fiber. Forming the outer layers of the composite, they are responsible for its flexural, compressive and other mechanical strength (Ashraf et al., 2021; Borsellino et al., 2004). The core structure between the facings acts as a core, providing low composite weight simultaneously enhancing its stiffness as well as bending and tensile strength (Alphonse et al., 2021; Patekar and Kale, 2022). Most commonly, the core is in the form of a "honeycomb" structure (Fig. 1).

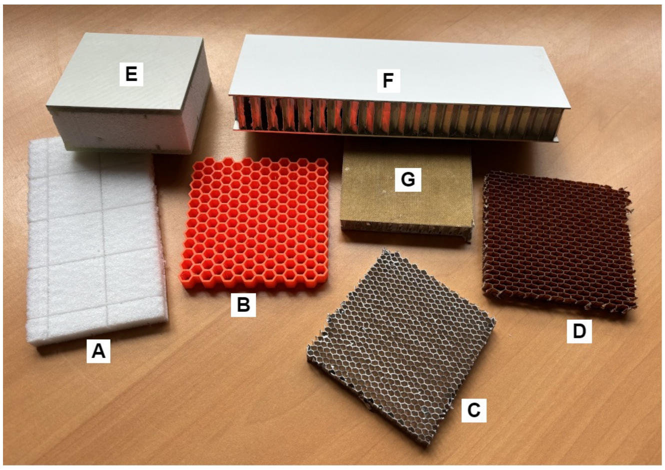

Figure 1. Examples of structural reinforcements (A–D) and composites reinforced with such structures (E-G): A – porous PUR cube structure, B – thermoplastic (ABS), C – aluminium, D – aramid "honeycomb" structure, E – composite reinforced with PUR cube structure, F and G – composites reinforced with aluminium "honeycomb" structure.

This material is most often composed of hexagonal cells, which, connected together, form an entire sheet. The cells can take the shapes of triangles, squares or rectangles, or even octagons. "Honeycomb" sheets, of different thicknesses, are commonly made of aluminum or aramid paper (Chandrasekaran and Arunachalam, 2021). However, cores made of these materials have low compression and shear strength which, under concentrated impact, leads to deflection and destruction of the structure (Gao et al., 2020). Structures made of thermoplastics are also encountered, which are an innovative alternative to traditional materials used in composites, providing both sufficient stability and flexibility to the structure. Their advantages include low density, high strength-to-weight ratio, recyclability, ease of molding and modification, through which mechanical properties and flexibility of the material can be enhanced (Liu et al., 2020; Sahu et al., 2021; Schneider et al., 2015). At the stage of designing ballistic composites, a particularly promising direction is to produce "honeycomb" structures using additive manufacturing techniques. Using 3D printing, it is possible to relatively cheaply and quickly produce structures made of various polymers and their modifications, with different geometries, cell sizes, wall thicknesses or printing densities (Gohar et al., 2023; Mondal et al., 2023). In a short time, it is possible to obtain a large number of samples. This allows an extensive analysis of the influence of various factors (material, construction) and parameters (printing) on the mechanical properties of the obtained structures and to choose the optimal solution.

One of the ways to test the impact properties of materials, including ballistics, under laboratory conditions is the "falling arrowhead" impact puncture test (Henderson et al., 2020; Zhao et al., 2020). The test is carried out on a device called a drop tower, in which a arrowhead loaded with a specified weight is dropped onto a specimen, placed in a special socket, from a predetermined height to induce an impact (Moure et al., 2018; Siddiqui et al., 2023). Standardized arrowheads of precisely defined shape and size are used. With this method, based on the obtained parameters such as maximum (E_m), puncture (E_p) or absorption (E_a) energy, it is possible to assess a material's resistance to dynamic loading and identify characteristics related to its strength and susceptibility to fracture under sudden impacts (Czech and Oleksy, 2024; Czech et al., 2022; Lv et al., 2023; Nossol et al., 2013).

2. EXPERIMENTAL PART

The study focused on obtaining and then investigating the ballistic properties of composites containing core structures made of various composite materials. Samples of sandwich composites used in the study were obtained using the vacuum bag technique, which consisted of honeycomb structures made of aluminum, aramid and thermoplastics (acrylonitrile-butadiene-styrene copolymer (ABS) and polycarbonate (PC)). Four layers of aramid fabric per side were used as facings. The main reference sample was the sandwich composites supplied by Huta Stalowa Wola S.A. (Fig. 2), from which 80 × 80 mm samples were obtained and labeled "AL_REF".

The vacuum bagging method consisted of the following steps. On a flat mold surface coated with a release agent, successive layers of aramid fabric and the 3D-printed core structure were manually impregnated with resin using a roller. After the lay-up was completed, a perforated release film and breather

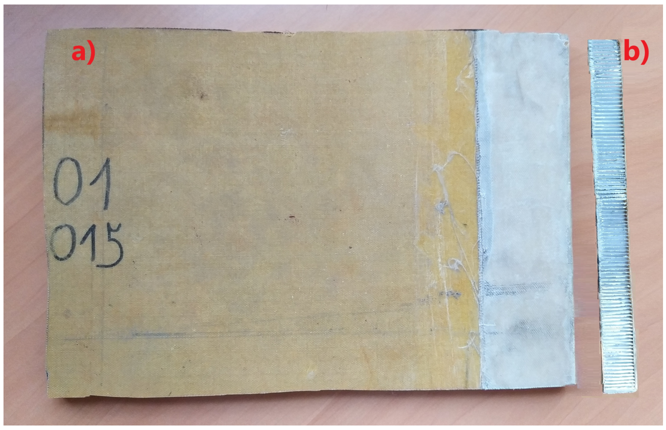

Figure 2. The view of the structural composite (consisting of aluminium core and aramid facings) provided by HSW S.A., a) front view, b) cross-sectional view of the composite.

fabrics were placed on top to absorb excess resin. The entire assembly was then sealed in a vacuum bag and connected to a vacuum pump. The system was held under a vacuum level of -0.95 bar during the curing process, which was carried out at room temperature for 24 hours.

2.1. Materials

Epidian 624 (EP624) epoxy resin (Sarzyna Chemical Sp. z o.o.) was used as the matrix crosslinked with Z-1 triethylenetetramine (Z1) hardener (Sarzyna Chemical Sp. z o.o.) at 13% by weight. Aramid fabric with a weight of 220 g/m^2 and a plain weave (Rymatex Sp. z o.o.) provided reinforcement for the outer layers of the composites (facings). "Honeycomb" core structures made of: aramid (Rymatex Sp. z o.o.), aluminum (Huta Stalowa Wola S.A.), polycarbonate PolyLite PC (PC) (Polymaker), acrylonitrile-butadiene-styrene coplimer ABS Extrafill (ABS) (Fillamentum Manufacturing Czech s. r. o.) and acrylonitrile-butadiene-styrene copolymer filled with chopped aramid fibers (ABS+kev) (Spectrum Group Sp. z o.o.) were used as cores.

2.2. Obtaining core structures by 3D printing

Thermoplastic "honeycomb" structures were obtained using additive manufacturing techniques, i.e. fused filament fabrication (FFF) using a UP BOX+ 3D printer (Fig. 3). The printing parameters for the individual thermoplastics were presented in Table 1.

The models of the printed cores were designed in Autodesk Inventor Professional 2023. Examples of the designed models of the cores are presented in Fig. 4. The pattern on which the model creation was based (Fig. 4a) was aramid cores, with rectangular-shaped cells and an area of 15 mm^2, arranged alternately with respect to each other.

Table 1. Processing parameters used for printing thermoplastic cores.

Thermoplastic type	Nozzle temperature [°C]	Plate temperature [°C]	Printing speed [mm/s]	Infill [%]	Nozzle diameter [mm]
ABS	240	90			
ABS+kev	260	100	50	99	0.4
PC	260	90			

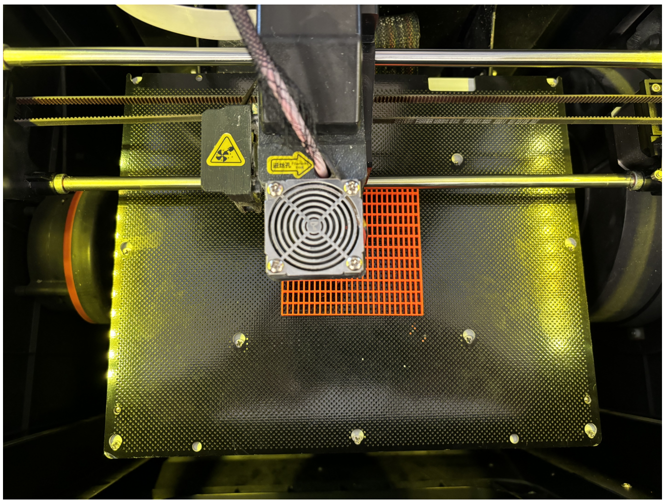

Figure 3. The process of printing thermoplastic "honeycomb" structures using the UP BOX+ 3D printer.

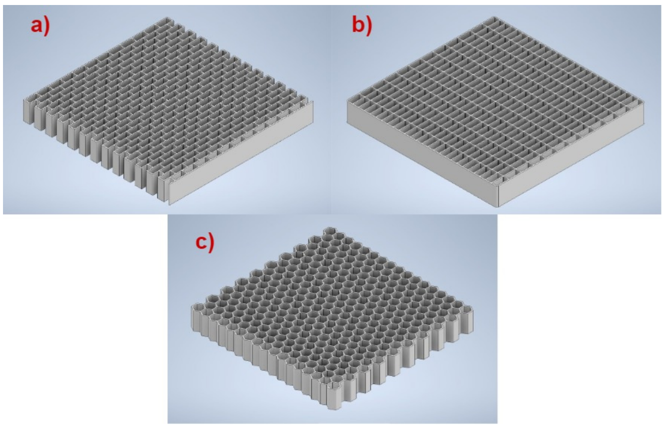

Figure 4. Models of "honeycomb" structures consisting of cells: a) rectangular, with an area of 15 mm^2, arranged alternately, b) rectangular, with an area of 15 mm^2, arranged in parallel, c) hexagonal, with an area of 15 mm^2 or 31 mm^2.

In this way, 80 × 80 × 10 mm cores consisting of the following cells were designed and obtained: rectangular, with an area of 15 mm^2, arranged in parallel (ABS_P(r)15), hexagonal, with an area of 15 mm^2 (ABS_SZ15) and 31 mm^2 (ABS_SZ31), whose models are shown in Figs. 4b) and c). An equally important aspect was to study the effect of the type of polymeric material from which the core was made on its impact properties. Therefore, additional cores were made: from acrylonitrile-butadiene-styrene copolymer filled with Kevlar fibers (ABS/KEV_P(r)15) and polycarbonate (PC_P(r)15).

2.3. Obtaining sandwich composites

Using the vacuum bag method, 5 composites were made for each type of core obtained and shown in Fig. 4. A detailed description of the obtained different types of composites is shown in Table 2.

2.4. Mass measurement of cores and core composites

As already mentioned, an important feature of the obtained composites is their low weight. Therefore, the obtained core structures (Fig. 5a) and the composites containing them (Fig. 5b) were weighed on a RADWAG WTC 2000 precision scale to obtain information on their weight.

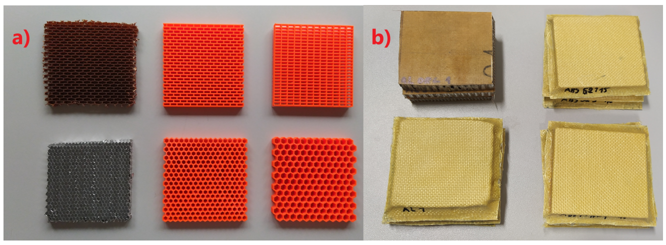

Figure 5. The examples of obtained: a) "honeycomb" structures, b) sandwich composites.

2.5. Impact energy determination using the "falling arrowhead" impact puncture test

The obtained sandwich composites were subjected to an impact puncture test using the "falling arrowhead" method. The test was conducted using a drop tower (Fig. 6) designed by Proximo Aero sp. z o.o. (Rzeszów, Poland), based on the PN-EN ISO 6603-2 standard. A weight of 15 kg was dropped onto 80 × 80 mm specimens from a height of 1 m, at a speed of 4.4 m/s. For the test, a hemispherical arrowhead with a diameter of 20 mm was used (Fig. 7). Maximum (E_m), puncture (E_p) and absorption energy (E_a) were determined.

Table 2. The description of the tested composites containing core structures.

No.	Composite name	Description: Core structure	Description: Facings	Thickness [mm]
1	AL_REF	Reference composite containing aluminum structure, with hexagonal-shaped cells, with an area of 23 mm^2, manufactured by HSW S.A.	Two layers of aramid fabric on each side of the core	14.02
2	AL	Aluminum, with hexagonal-shaped cells, with an area of 23 mm^2, supplied by HSW S.A.	Four layers of aramid fabric on each side of the core	12.10
3	A	Aramid, with cells in the shape of a rectangle, with an area of 15 mm^2, arranged in alternately to each other		12.02
4	ABS_P15	Made of ABS, with rectangular-shaped cells, with an area of 15 mm^2, arranged in alternately to each other		11.88
5	ABS_P(r)15	Made of ABS, with rectangular-shaped cells, with an area of 15 mm^2, arranged in parallel to each other		11.86
6	ABS_SZ15	Made of ABS, with hexagonal-shaped cells, with an area of 15 mm^2		11.88
7	ABS_SZ31	Made of ABS, with hexagonal-shaped cells, with an area of 31 mm^2		12.14
8	ABS/KEV_P(r)15	Made of ABS with Kevlar fibers, with rectangular-shaped cells with an area of 15 mm^2, arranged in parallel to each other		12.13
9	PC_P(r)15	Made of PC, with rectangular-shaped cells, with an area of 15 mm^2, arranged in parallel to each other		12.14

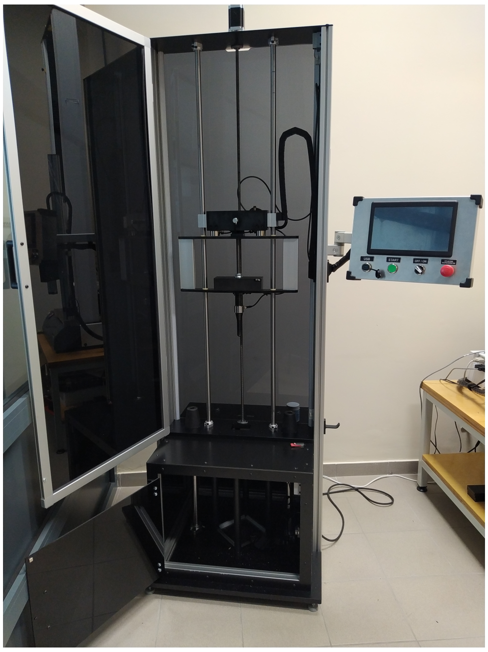

Figure 6. The drop tower for "falling arrowhead" impact puncture tests.

Figure 7. Standard hemispherical arrowhead with a diameter of 20 mm.

3. RESULTS

The results of the various tests and the appearance of the specimens after the impact puncture test are presented in the form of graphs and photos in Figs. 8–12.

3.1. Mass analysis of core structures and the composites

For each variant, five samples of both the core structures and the corresponding composites were weighed. Among all the weighted cores tested, aramid structures were the lightest, followed by aluminum. Thermoplastic structures, especially those made from PC, had the highest mass. Analyzing only the cores obtained from ABS, it was noted that the mass of the core is significantly influenced by the shape, size and cell size of the core. The lightest of the composites tested was the reference composite AL_REF. This may have been due to the use of aramid fabrics of lower mass and in fewer layers (only 2 layers), as well as the use of a different type and a smaller amount of resin to supersaturate the reinforcement. (Fig. 8).

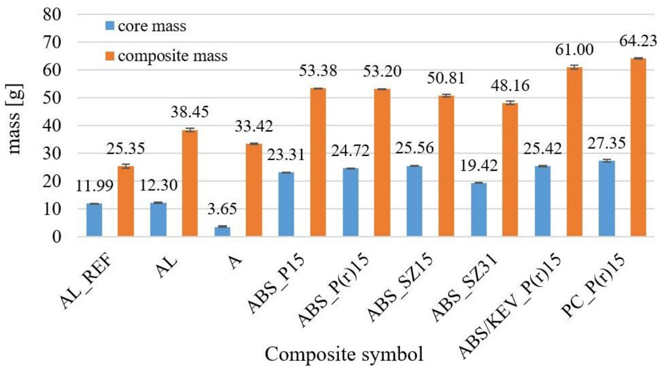

Figure 8. Comparison of the masses of cores and sandwich composites.

Among the composites made, the one with an aramid core (A) was the lightest. Slightly higher in mass (by 5 g) was the composite reinforced only with an aluminum structure. The weights of composites containing an ABS cores ranged from 48.16 to 53.38 g. The ABS/KEV_P(r)15 and PC_P(r)15 composites turned out to be the heaviest. Such significant differences in mass may have been due to increased resin consumption to saturate the reinforcement, insufficient drainage of excess resin (too little breather mat) or impeded resin drainage from under the core, which may have affected the saturation of the composite facing layer.

3.2. Analysis of impact parameters of tested sandwich composites

For the impact penetration tests using the "falling arrowhead" method, five samples were tested for each composite variant. Perforations of both facings and core structures were obtained for all samples tested (Figs. 9A and 9B). Analyzing the values of the various energies for the tested composites, there is a clear difference between the composites reinforced with aluminum-aramid structures and the samples with cores made by 3D printing.

The highest maximum energy value (Fig. 10) was achieved by samples with a polycarbonate core. For composites reinforced with ABS structures, the energy values were in the range of 55.56–60.64 J. The best results were achieved by structures made of unmodified ABS, with small area, hexagonal cells or rectangular shaped cells in a parallel configuration. However, the lowest energy value was recorded for the AL_REF reference sample. The proprietary version of the composite with an aluminum structure achieved higher values compared to both the AL_REF and A composites.

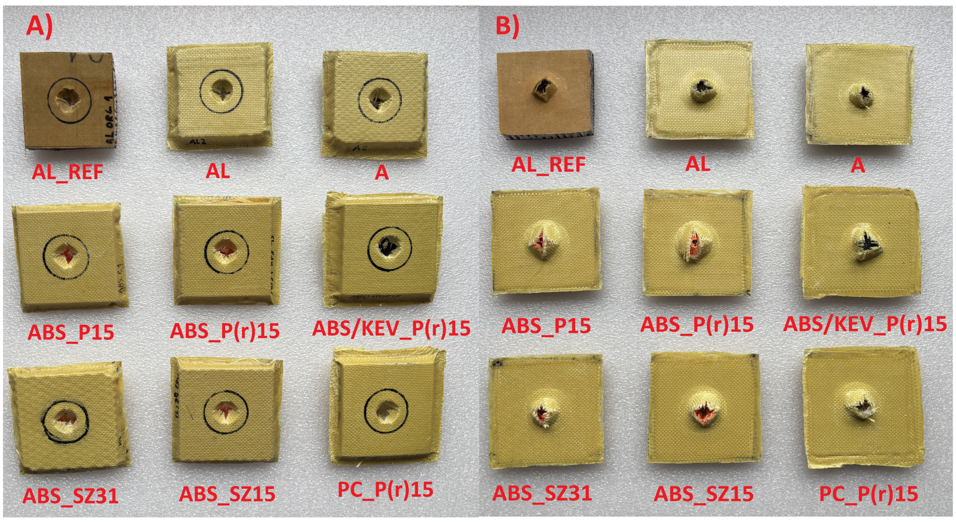

Figure 9. The appearance of the samples after the impact puncture test. A) appearance of the samples from the side of the arrowhead impact "top", B) appearance of the "bottom" side of the samples.

The highest puncture energy values (Fig. 11) were achieved by composites reinforced with an unmodified ABS structure, with the best result achieved by the ABS_P(r)15 sample. Slightly lower puncture energy values of 66.92 J and 62.70 J were recorded for the PC_P(r)15 and ABS/KEV_(r)15 composites, respectively. The worst result was achieved by the AL_REF reference sample.

Similarly, composites reinforced with a core of unmodified ABS had the highest impact energy absorption (Fig. 12), especially those with a small cell area and rectangular shape, arranged parallel to each other. In contrast, the AL_REF reference composite showed the weakest energy absorption capacity, achieving a value three times lower than the highest score.

Composites A (32.92 J) and AL (42.69 J) had slightly better impact properties, but the energy absorbed by them was much lower compared to composites reinforced with structures made by the additive manufacturing technique. In this group, the lowest E_a value (67.24 J) was obtained by the ABS/KEV_P(r)15 sample.

4. DISCUSSION

The analysis of the conducted studies revealed that composites with thermoplastic cores manufactured using 3D printing exhibited significantly better impact properties compared to their counterparts with aluminum cores. For composites with aluminum and aramid cores, it was observed that the versions with aluminum cores demonstrated superior energy absorption capacity despite having slightly higher mass than the aramid counterparts. This finding aligns with observations reported by Rathod et al. (2022), who performed experimental and numerical ballistic tests on honeycomb structures with aramid and aluminum cores. They found that although aluminum-core structures showed higher ballistic limit velocity and greater reduction in projectile residual velocity (indicating better ballistic resistance), the aramid structures achieved higher specific energy absorption (SEA), which is critical for applications requiring low weight.

In composites with 3D-printed thermoplastic core structures, the type of material as well as the geometry and arrangement of the cells played a key role in their impact performance. Regarding core material, literature studies demonstrate that mechanical and impact properties vary significantly depending on the polymer used. Gohar et al. (2023) compared mechanical properties of structures with cores made of ABS and TPU combined with various face-sheet materials. Based on bending and edge compression tests, samples with ABS cores and composite face-sheets (PLA reinforced with 15% carbon fibers) exhibited the highest failure stresses. Conversely, structures with TPU cores showed much lower strength, attributed to the lower stiffness of the core material.

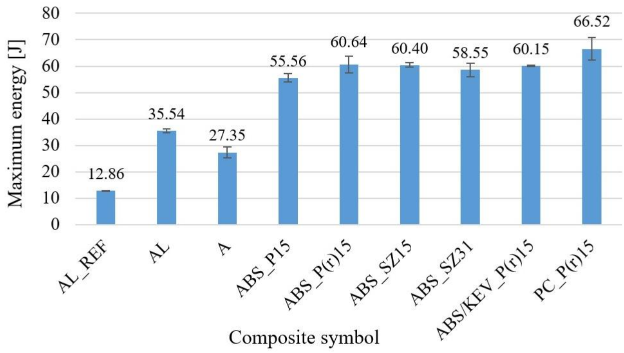

Figure 10. Maximum energy values for the tested sandwich composites.

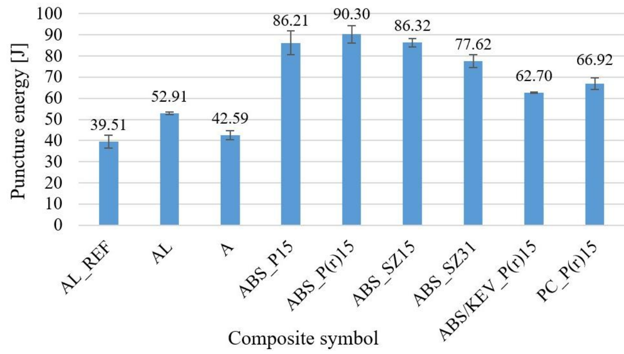

Figure 11. Puncture energy values for the tested sandwich composites.

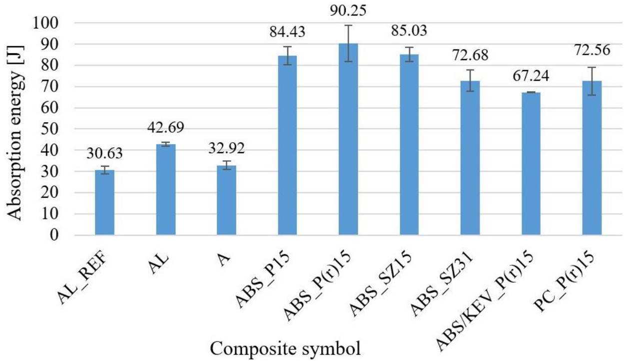

Figure 12. Absorption energy values for the tested sandwich composites.

Similar conclusions were drawn by Khosravani et al. (2020), who investigated two types of core structures (hexagonal and triangular cells) fabricated from ABS and ASA materials. They demonstrated that hexagonal ASA cores subjected to accelerated thermal aging exhibited the highest bending stiffness and strength, retaining high structural stability after aging. This indicated better resistance to long-term environmental effects.

Additionally, Yazdani Sarvestani et al. (2018) analyzed meta-sandwich structures made of PLA with cores of different cell topologies: cubic, octet, and Isomax (an isotropic structure with maximum stiffness). These cores had varying porosities and thicknesses. In three-point bending tests, thinner beams with octet cores at 30% porosity showed the best energy absorption capability. For thicker structures, cores with Isomax and cubic topologies at 50% porosity demonstrated superior mechanical properties. In low-velocity impact tests, all these topologies exhibited similar, yet higher energy absorption than auxetic cores. However, at higher impact energies, octet-core structures outperformed the others.

Both our results and literature data confirm that selecting the printing material and core shape are crucial factors influencing mechanical strength and energy absorption capabilities of 3D-printed sandwich structures. Optimizing these parameters enables the design of lightweight, durable composites with high functional performance.

5. CONCLUSIONS

Summarizing the obtained results, it was found that composites containing thermoplastic cores made by 3D printing showed significantly better impact performance than those containing an aluminum core. However, their disadvantage may be higher mass compared to the reference material. The comparison of the results of ABS_P(r)15 and AL_REF samples shows a threefold increase in absorbed energy with a twofold increase in mass, which can be considered a positive "gain-to-loss" ratio.

Comparing the mechanical properties of the resulting proprietary composites containing both an aluminum (AL) and an aramid (A) core, better impact properties were obtained for the sample of composites with an aluminum core, whose mass was slightly higher compared to composites reinforced with an aramid core.

Analyzing only the tested composites containing printed thermoplastic core structures, it was noted that the type of material, shape, size, and arrangement of the cells forming the core have a significant effect on their impact properties. The best performance was achieved by samples made of ABS, containing structures with a small cell area, especially those with a rectangular shape, arranged parallel to each other.

SYMBOLS

PUR	polyurethane
ABS	acrylonitrile-butadiene-styrene copolymer
E_m	maximum energy, J
E_p	puncture energy, J
E_a	absorption energy, J
AL	composite containing aluminum core
A	composite containing aramid core
PC	polycarbonate
AL_REF	commercial reference composite (containing an aluminum core)
EP624	epoxy resin Epidian 624
Z1	hardener for epoxy resins Z1
ABS+kev	acrylonitrile-butadiene-styrene copolymer filled with chopped aramid fiber
FFF	fused filament fabrication
ABS_P(r)15	composite containing an ABS core, with rectangular-shaped cells, with an area of 15 mm^2, arranged in parallel to each other
ABS_SZ15	composite containing an ABS core, with hexagonal-shaped cells, with an area of 15 mm^2
ABS_SZ31	composite containing an ABS core, with hexagonal-shaped cells and an area of 31 mm^2
ABS/KEV_P(r)15	composite containing an ABS core with Kevlar fibers, with rectangular-shaped cells with an area of 15 mm^2, arranged in parallel to each other
PC_P(r)15	composite containing a PC core, with rectangular-shaped cells, with an area of 15 mm^2, arranged in parallel to each other
SEA	specific energy absorption, J/kg
ASA	acrylonitrile-styrene-acrylate copolymer
TPU	thermoplastic polyurethan
PLA	polylactic acid

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