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Original scientific paper

EXPERIMENTAL RESEARCH OF THE MECHANICAL PROPERTIES OF THE INJECTION MOLDED PARTS IN MOLDS PRODUCED BY ADDITIVE MANUFACTURING

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A b s t r a c t: In this study, additive manufacturing emerges as an innovative technology for concurrent engineering in the design and production of molds for injection molding processes. The primary objective is to conduct experimental research on the mechanical properties of injection-molded parts using a non-conventional mold produced through additive manufacturing technologies. The state-of-the-art additive manufacturing technologies provide various methodologies and techniques for designing and printing parts. Utilizing these diverse technologies significantly expands the possibilities for rapidly creating molds, thereby enhancing the scope of rapid tooling in the molding process. The study begins by designing and fabricating SLA mold inserts according to the relevant tensile testing standards. To evaluate the mechanical properties, a series of tensile tests are conducted and a comparison is made between the properties of the molded parts produced with SLA mold inserts. The results demonstrate that SLA mold inserts made with additive manufacturing can effectively produce injection molded parts with comparable tensile strength to those manufactured using traditional steel molds.

Key words: additive manufacturing; injection molding; rapid tooling; stereolithography; tensile testing

ЕКСПЕРИМЕНТАЛНО ИСТРАЖУВАЊЕ НА МЕХАНИЧКИТЕ СВОЈСТВА НА ДЕЛОВИ ДОБИЕНИ СО ИНЈЕКТИРАЊЕ ВО КАЛАПИ ИЗРАБОТЕНИ СО АДИТИВНО ПРОИЗВОДСТВО

А п с т р а к т: Во ова истражуваење адитивното производство се разгледува како иновативна технологија за конкурентно инженерство во дизајнот и производството на калапи за процесот на инјектирање. Примарната цел е да се спроведе експериментално истражување на механичките својства на деловите изработени со помош на неконвенционален алат направен со технологии за адитивното производство. Најсовремените технологии за адитивното производство овозможуваат различни методологии и техники за дизајнирање и печатење на делови. Користењето на овие разновидни технологии значително ги проширува можностите за брза изработка на алати во процесот на инјектирање. Студијата започнува со дизајн и изработка на гравури со технологијата SLA според релевантните стандарди за испитување на истегнување. За да се проценат механичките својства, се спроведуваат повеќе тестови и се прави споредба на својствата на деловите изработени во SLA-гравурите. Резултатите покажуваат дека во гравурите изработени со технологијата SLA на адитивно производство може ефикасно да се произведат делови со инјектирање кои имаат споредлива јакост на истегнување со деловите изработени со употреба на традиционални метални алати.

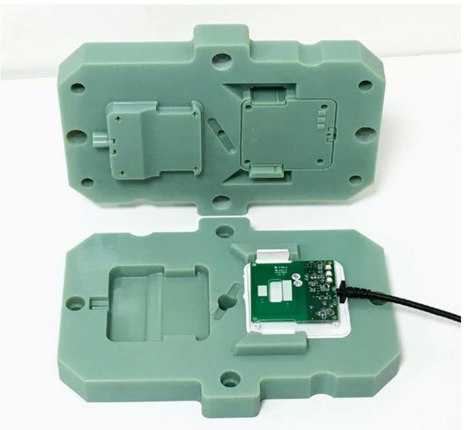
Клучни зборови: адитивно производство; инјектирање; брза изработка на алати; стереолитографија; испитување со истегнување

1. INTRODUCTION

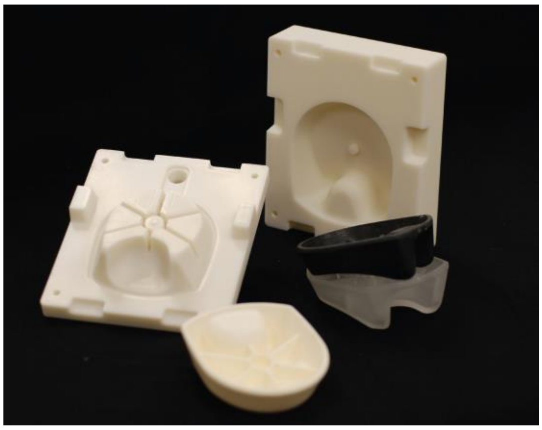
The implementation of additive manufacturing in injection molding represents a groundbreaking approach in the design and production of molds. By leveraging state-of-the-art technologies, this method enables the creation of non-conventional molds, offering increased flexibility and efficiency in the injection molding process. This innovative application facilitates rapid prototyping, customization, and the exploration of diverse design possibilities, ultimately revolutionizing traditional manufacturing practices.

Stereolithography (SLA) additive manufacturing has emerged as a groundbreaking technology with the potential to revolutionize the field of injection molding. Traditional mold production techniques have long posed challenges in terms of time, cost, and design limitations. However, recent advancements in SLA additive manufacturing have paved the way for accelerated prototyping, enhanced design flexibility, cost efficiency, faster time to market, customization, iterative improvements, and material diversity in the injection molding process. Moreover, the cost-effectiveness and reduced lead times associated with molds made with SLA additive manufacturing provide manufacturers with a competitive edge, enabling them to respond rapidly to market demands and optimize production schedules. The customization and iterative improvement capabilities of molds made with SLA additive manufacturing further enhance the product development cycle, allowing for on-the-fly adjustments based on feedback and design iterations. Additionally, the versatility of material selection in SLA additive manufacturing ensures compatibility with various manufacturing requirements, expanding the range of materials that can be utilized in injection molding processes. Both standard SLA and other SLA based technologies like Stratasys's Polyjet have been used to manufacture various tooling inserts (Figure 1).

Using SLA additive manufactured molds is a valuable tool in the prototyping process for injection molding, particularly due to their ability to produce prototypes with the intended plastic as the final product. This feature allows designers and engineers to test the functionality, fit, and aesthetics of their designs accurately before investing in expensive production molds. By using molds made with SLA additive manufacturing, they can create prototypes using the same material that will be used in the injection molding process, ensuring a high degree of accuracy in terms of mechanical properties and surface finish. This method saves time and resources, as it eliminates the need for multiple iterations and costly material changes during the prototyping stage. Moreover, it enables manufacturers to validate the manufacturability of their designs and make necessary adjustments early in the process, leading to faster product development cycles and improved overall product quality.



a)



b)

Fig. 1. Stereolithographic molding inserts: a) Manufactured by the Arad Group using the Stratasys Polyjet technology. b) Manufactured by synthetic engineering using SLA. (Source: [1])

2. THEORETICAL RESEARCH

In addition to the possibility of producing small series of parts using polymer molding inserts, several studies have shown that the physical properties of plastic parts obtained in this way differ from parts obtained from conventional injection molding tools made of steel or aluminum. Segal and Campbell [2] summarize this research very well up to 2001 and their research covers quite a few different types of polymer inserts used in the injection molding process. Stereolithographic molding inserts, inserts obtained by casting polymer resins and other alloys with low melting points were analyzed. Additionally, the polymers that's injected into these molding inserts also range widely and range from conventional polypropylene to glass fiber reinforced polyamide and polycarbonate. Although all the cited papers show differences in the characteristics of parts obtained from molds made with different rapid prototyping technologies, the exact effects that cause these differences have not yet been explained. Furthermore, various research show that there are contradictory results regarding the investigated mechanical properties, specifically the tensile strength of the material. The analysis clearly shows that on the one hand in certain cases, the tensile strength was higher for the parts obtained from conventional steel molds compared to the parts obtained from stereolithographic molds. On the other hand, certain studies obtained the opposite result and concluded that the tensile strength is higher in the parts made in stereolithographic molded inserts.

Michaeli and Lindner [3] conclude that if the injection mold is made of a material with good thermal conductivity, then the produced parts have thick boundary layers and smaller spherulites, while in molds made of materials with a worse thermal conductivity, the boundary layers are thin and the spherulites in the polymer are larger (Figure 2). The presence of larger spherulites is also associated and highly correlated with an increase in the tensile strength of the produced parts.

Harris et al. [4] showed that the semi-crystalline polymer polyamide 66 (PA66) experienced twice as much thermal shrinkage when processed in a stereolithography tool compared to molding in a standard aluminum tool. The difference in temperature shrinkage was due primarily to the different processing conditions associated with the different behavior of the materials during cooling due to the different thermal conductivity of the material from which the molding inserts were made. Furthermore, a similar test was done with amorphous polymer Acrylnitrile-Butadien-Styrol-Copolymere (ABS) and in this case no visible differences in temperature shrinkage were observed between the two types of different molds, which means that when applying stereolithographic inserts, special attention in the design compensation for temperature shrinkage should be addressed when it comes to crystalline and semi-crystalline polymers.

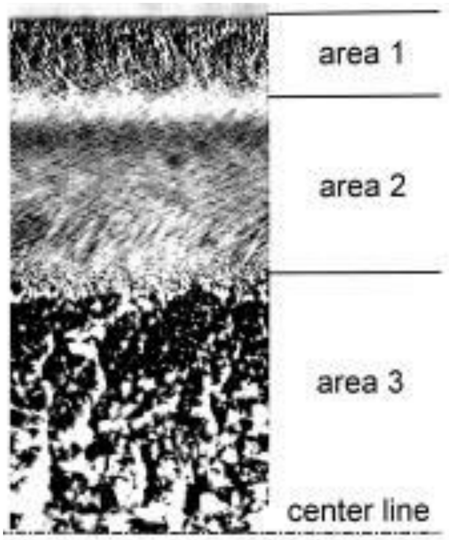


Fig. 2. Boundary layers in a polypropylene sample reflecting the difference in spherulite size of the polymer along its thickness (Source: [3])

Fernandes et al. [5] showed that the mechanical properties of a polypropylene (PP) homopolymer were worse when the part was fabricated in a hybrid tool with an epoxy resin matrix and an aluminum matrix compared to conventional steel tools. The maximum tensile strength, the Young's modulus of elasticity and the maximum elongation until breaking were examined. The degree of crystallization was also investigated and it was concluded that it was higher in the samples obtained by injection molding in the hybrid tool compared to the conventional tool steel. There was also noticeable differences in the transparency of the parts made in the epoxy resin and aluminum composite tooling, as shown in Figure 3.

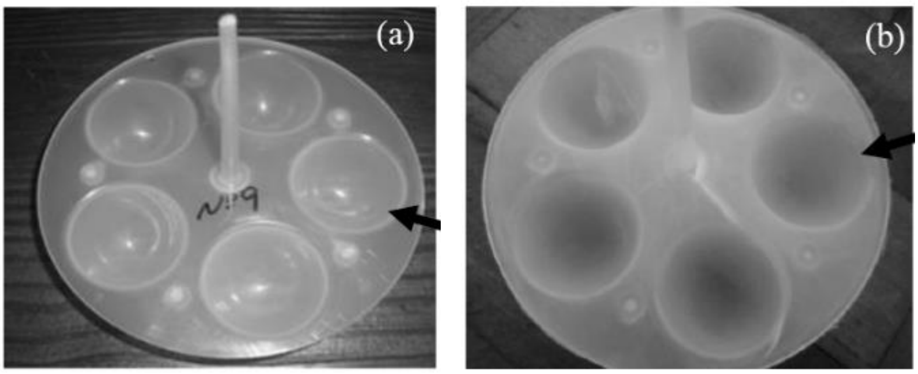


Fig. 3. Difference in transparency of polypropylene parts made in epoxy resin and aluminum molds (a) and AISI P20 steel tooling (b) (Source: [5])

All previous research in this area suggests that the different thermal conditions for processing injection molded parts are the most influential for the varying characteristics of the resulting parts. Harris [6] suggests that control over the degree of crystallization can be performed by regulating the melting temperature and using nucleating agents. Despite all the investigations, there is still no consistent understanding of the influence of tools developed from different materials on the characteristics of manufactured parts, this is mentioned by Segal and Campbell [2] and confirmed by the contradictory results published by Volpato [7].

3. RESEARCH METHODOLOGY

3.1. *Mold design*

Drawing upon both theoretical and experimental investigations, a novel mold design has been formulated. The application of additive manufacturing techniques for rapid tooling and mold production in injection molding processes introduces advanced possibilities for research in the domain of employing cutting-edge designs for injection molding molds. This facilitates a streamlined design process, enabling easier analysis and production. The conventional mold design may be changed by an innovative non-conventional mold design, suported by additive manufacturing principles and rapid tooling methodologies.

Previous experiences involving the use of stereolithographic inserts in injection molding technology have shown that it is optimal to use a universal metal base that houses the core and cavity inserts. This modular approach affords the utilization of a master base for various inserts, minimizing the size of stereolithographic inserts and thereby conserving time and material during their production. In this study, an existing mold equipped with interchangeable inserts was employed. While the use of such molds imposes certain constraints on the design of stereolithographic inserts, it facilitates the application of the aforementioned approach in configuring the experimental setup. The configuration of the used master base and molding inserts is shown in Figure 4.

The experimental research resulted in the development of novel inserts for injection molds, created through the integration of rapid tooling technologies and the SLA additive manufacturing process (Figure 5).

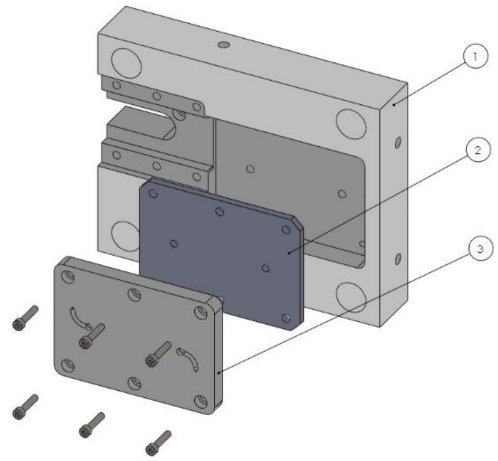


Fig. 4. Exploded view of the mold plate and the molding insert, 1) Mold plate; 2) Support plate; 3) Stereolitography molding insert

Fig. 5. Graphic representation of the basic mechanics of stereolithography (SLA) (Source: https://www.hubs.com)

After printing, the printed models were washed with IPA and post-cured. The post-curing was done by UV radiation from 13 multidirectional LED diodes, each with a power of 39 W and a wavelength of 405 nm [8]. The rotating base of the used device enabled uniform light exposure, with a rotation speed of 1 revolution per minute. The device can provide a post-curing temperature of up to 80 °C [9]. The printed models were cured for 60 min, at a temperature of 70 °C, per the manufacturers' recommendations. The molding insert during 3D printing and the final model are shown in Figure 6.

The Rigid 10k photopolymeric resin that was used for the production of molding inserts has thermal characteristics that make it suitable for use in the injection molding process. To ensure the highest possible Heat Deflection Temperature (HDT) for the material, additional thermal treatment in a laboratory furnace is recommended. This thermal treatment also affects the mechanical characteristics of the material. This procedure was done in a laboratory furnace for 90 min, at a temperature of 125 °C, per the manufacturers' recommendations.

a)

b)

Fig. 6. SLA molding insert made from Rigid 10k: a) during printing; b) after removing the support structure

Processing parameters were held constant during injection molding and are given in Table 1. The melt temperature of the used ABS plastic (Table 2) was chosen at the lower limit of the recommended values, which for this polymer range from 200 to 280 °C. The reason for this was that the used mold was not preheated and its temperature was controlled and measured after each cycle so as not to exceed the recommended mold temperature for processing of ABS that is between 50 and 80 °C. The measuring was done using a thermographic camera as shown in Figure 7.

Table 1

Injection molding parameters used during the experiment

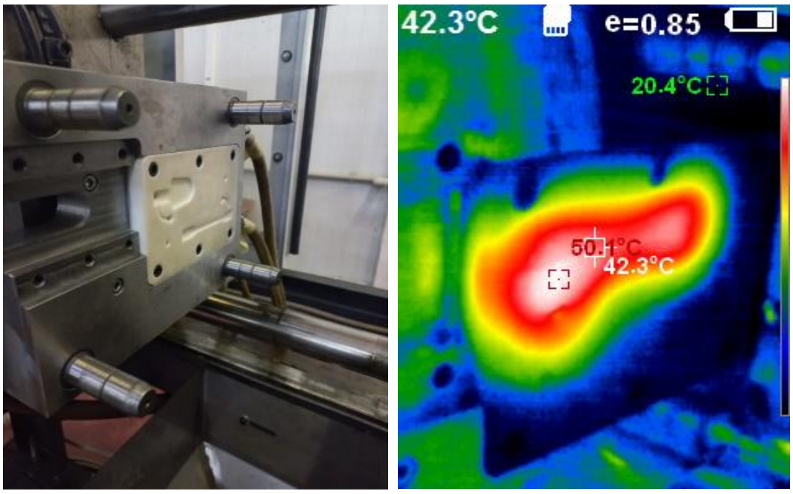
Injection pressure (MPa)	48
Injection temperature (°C)	200
Injection speed (mm/s)	120
Clamping force (t)	15
Fill time (s)	1.63
Pack time (s)	3.5
Pack pressure (MPa)	25
Cooling time (s)	48 – 60

Table 2

ABS polymer material – referenced mechanical properties (Source: [12])

ABS-50 Ghaed Basir Petrochemical	Value	Unit	Testing conditions	Test method
Tensile elongation	20	%	@ 23 °C, 50 mm/min	ASTM D638
Tensile strength	44.6	MPa	@ 23 °C, 50 mm/min	ASTM D638

The temperature distribution in the mold insert shown in Figure 7 was constant throughout every molding cycle. The highest measured values were at the injection location of the cavity, near the sprue bushing. After the part ejection, temperature measurements were done on the mold until its temperature was in the recommended value interval. After several cycles, roughly 60 second was shown to provide sufficient cooling time to allow the mold to get into the desired temperature range. The average temperature of the molding inserts throughout the cycles was 62 °C, as per the thermographic camera measurements. The lowest insert temperature was the one for the first molding cycle where the mold was at room temperature of 20 °C (Table 3)



a) b)

Fig. 7. Temperature control of the stereolithographic inserts; measurement done after the 3rd cycle; (a) the molding insert placed in the master housing; (b) thermographic camera image of the insert with temperature distribution after injection

T a b l e 3

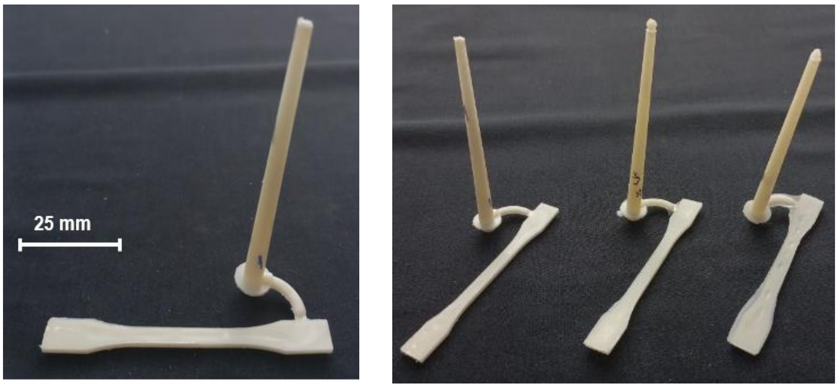
Mold insert temperatures before the start of each cycle

Cycle no.	Insert temp. (°C)	Cycle no.	Insert temp. (°C)
1	20	26	60.8
2	48.1	27	57.7
3	50.1	28	105.1
4	43	29	59.1
5	36	30	98.1
6	49	31	63.7
7	54.5	32	95.7
8	48.1	33	
9	98.7	34	
10	43.5	35	
11		36	
12	Incomplete cavity filling-specimens excluded from the analysis	37	
13		38	
14		39	
15		40	
16		41	
17	80.7	42	
18	71	43	
19	68.1	44	
20	62.9	45	
21	56.2	46	
22	53.3	47	
23	56.2	48	
24	68.6	49	
25	62.9	50	
Average insert temperature (°C)			**62**
Min insert temperature (°C)			**20.0**
Max insert temperature (°C)			**105.1**

The molding inserts were designed to fulfill dual objectives within the testing framework. Primarily, one model was needed to facilitate investigations into the impact of stereolithographic molds on the mechanical properties of components produced by injection molding. Consequently, one of the cavities needed to have the shape of a standardized specimen for tensile testing. Given the spatial constraints in the stereolithographic mold (refer to Figure 6), the selection was made in favor of the Type 1BA specimen per ISO 527 standards ([10], [11]). The second cavity in the shape of a trapezoidal plate was designed to monitor deviations in both angle and radii curvature for further analysis. This study focuses only on the mechanical properties of the components and the models produced from the second cavity are not used in this experimental study.

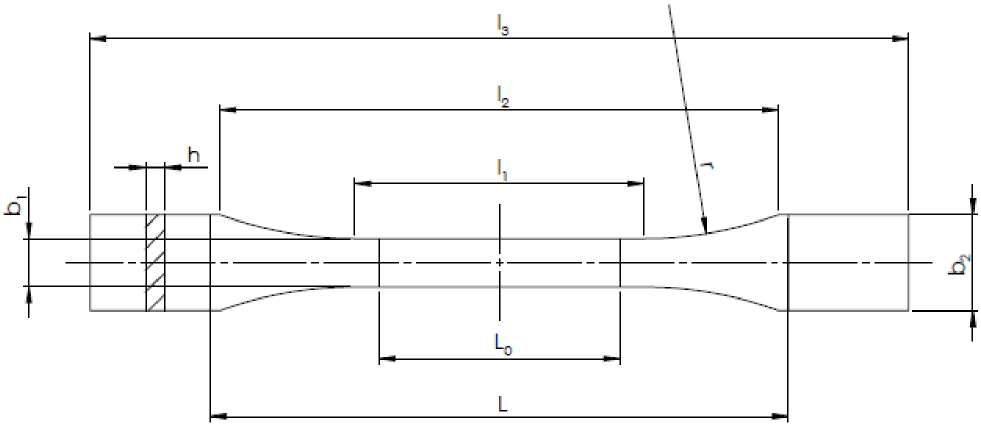
The mold made from Rigid 10k, withstood all of the intended 50 cycles without critical failure. Flash formation was the only conventional defect observed in the specimens. The first small traces of flash appeared after the 25th injection cycle (Figure 8). The intense progressive deterioration occurred after the 40th cycle.

Figure 9 shows the dimensions of the 1BA sample used. According to the standard, this sample is allowed to be used when the standard samples of type 1A or 1B cannot be used due to any restrictions. The dimensions of these standard test tubes are proportionally reduced compared to Type 1B specimens by a factor of 1:2.



a) b)

Fig. 8. (a) Injection molded specimen, (b) the progressive increase of the flash formation (cycles 1, 33, 50)



	Type of specimen 1BA	mm
l_3	Overall length	≥75
l_1	Length of narrow parallel-sided portion	30 ± 0,5
r	Radius	≥30
l_2	Distance between broad parallel-sided portions	58 ± 2
b_2	Head width	10 ± 0,5
b_1	Width of narrow portion	5 ± 0,5
h	Thickness	≥2
L_0	Gauge length	25 ± 0,5
L	Initial distance between grips	l_2^{+2}

Fig. 9. Dimensions of the standard specimen 1BA for tensile testing for polymers according to ISO 527 (Source: [10])

3.2. *Tensile testing*

The tensile test of each specimen was done according to the guidelines in the standard EN ISO 527-2:1996 ([10], [11]), without removing the excess flashing from the specimens. The reasoning behind this is that the thickness of the flash in the gauge length area was negligibly thin. Figure 9 and Figure 10 show that the width of the flash was most prominent in the head area of the specimens. In the gauge length area, the thickness of the flash is 0.12 mm which is only 6% of the nominal thickness of the specimens.

The tensile test was done in the Forming processes laboratory of the Faculty of Mechanical Engineering in Skopje on the Shimatzu Autograph AGS-X machine (Figure 11) with a load cell capacity of 10 kN with a crosshead speed of 1 mm/min. The low test, speed was chosen to ensure quasi-static test conditions.

From each of the test pieces the ultimate tensile stress was calculated as:

$$\sigma_m = \frac{F_M}{A_0}.$$

F_m is the highest measured force and A_0 is the starting cross-section area ($b \times h$) of 10 mm^2.

From each of the test pieces the relative strain was calculated as:

$$\varepsilon = \frac{L-L_0}{L_0}.$$

L_0 is the initial gauge length of 25 mm and L is the length that corresponds with σ_m.

Fig. 10. Flash formation width near the gauge lenght of the specimen

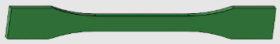
Fig. 11. Shimatzu Autograph AGS-X uniaxial testing machine

4. RESULTS AND DISCUSSION

In this chapter, a summary of the data acquired during the experiment is presented. The standard test pieces produced using the stereolithography inserts underwent a tensile test following the ISO 527 standard. The measured values for the tensile strength and maximum relative deformation were then compared with the reference values provided by the manufacturer of the ABS used during the injection molding process. The summarized findings from all conducted tests are displayed in Table 4.

Table 4

Statistical results of the tensile tests

	Max. tensile strength σ_m (MPa)	Max. relative deformation ε (%)
Number of measurements	44	43
Measured values ≥ then the reference values provided by the manufacturer	17	17
Measured values < then the reference values provided by the manufacturer	27	26
Nominal values	44.6	20
Min	36.961	6.820
Max	51.534	28.932
Range	14.572	22.112
Average	43.702	16.763
Median	43.113	16.768
Standard deviation	3.395	6.334
Average error	–0.898	–3.237
% acceptable	39%	40%

The testing involved a total of 44 fully injected specimens derived from the SLA inserts. The maximum tensile strength (σ_m) was measured across all samples, while the examination of the maximum relative deformation (ε_m) was performed only on 43 samples. One sample, the 10th in the series, encountered a technical issue during the testing wherein the Shimatzu Autograph AGS-X machine lost connection with the testing software, rendering the deformation measurement incomplete. However, since the point of maximum tensile strength had been surpassed, that particular value was known and accounted for in the statistical computations pertaining to the strength evaluation of the injection molded specimens.

Figure 12 and Figure 13 show the charts for the measured maximum tensile strength and maximum relative deformation. The shown nominal value for each chart is taken from the manufacturer's data sheet for the polymer used in the study (Table 2).

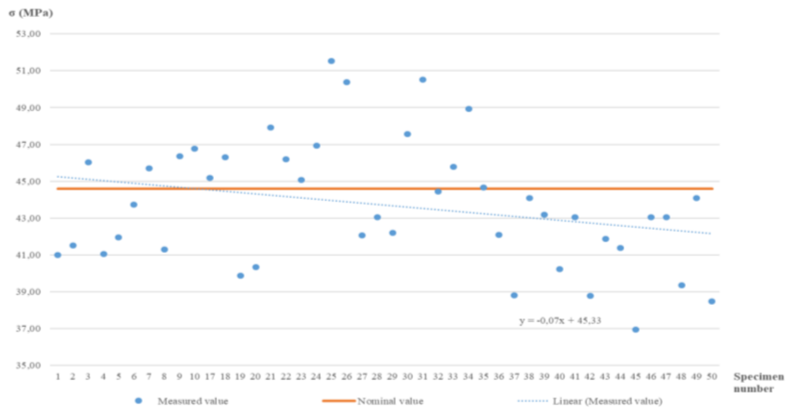


Fig. 12. Chart for the measured values for the ultimate tensile strength of the specimens

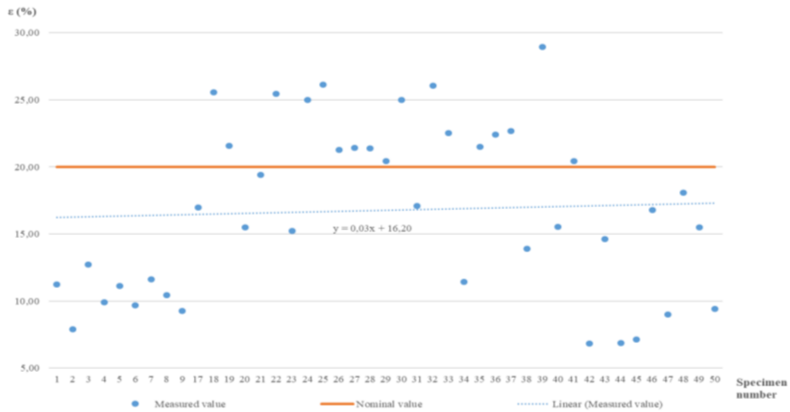


Fig. 13. Chart for the measured values for the relative deformation of the specimens

The results of the tests showed that only 39% of the tested samples have a strength greater than or equal to the nominal one, which according to the official Datasheet of the ABS plastic is 44.6 MPa. However if we take a closer look at the measurements, most of the specimens, 86.36% to be exact, showed a tensile strength that is only 10% lower than the nominal. The distribution of the ultimate strength (Figure 14) in all samples also conforms to a good normal probability distribution.

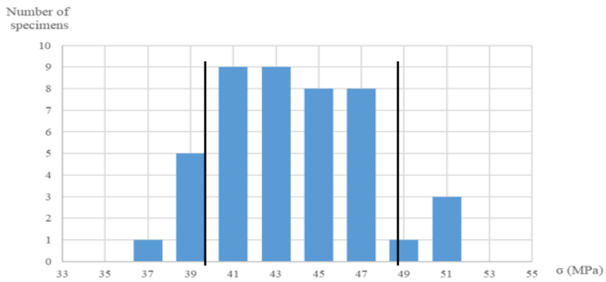


Fig. 14. Chart that shows the distribution of the measured ultimate tensile strength of the specimens

Regarding the maximum elongation, 40% of the samples have a relative deformation greater than or equal to the nominal one, which according to the official Datasheet of the ABS plastic is 20%. In the case of relative deformation, the maximum deviation from the nominal value in some samples is quite large. In 10 of the pieces, a relative deformation of 10% or less was measured, which is more than 2 times less than the nominal value. Moreover, the distribution of the elongation in all samples is quite bad, as can be seen from the chart in Figure 15.

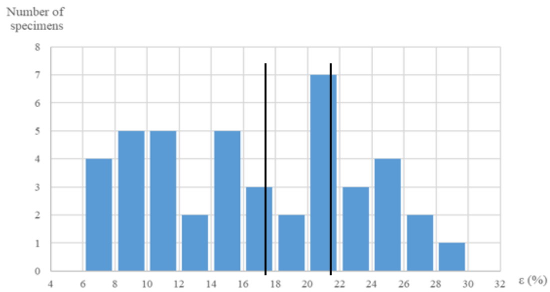


Fig. 15. Chart that shows the distribution of the measured relative deformation of the specimens

5. CONCLUSIONS

The integration of additive manufacturing into injection molding processes brings forth a multitude of benefits that revolutionize traditional manufacturing practices. From accelerated prototyping and enhanced design flexibility to cost efficiency, faster time to market, and easy customization, molds made with SLA additive manufacturing offer a host of advantages that enable manufacturers to drive innovation and efficiency. As the technology continues to evolve, we can expect further advancements in additive manufacturing for injection molding, opening up new possibilities and transforming the landscape of manufacturing.

The findings of this research contribute to the growing field of additive manufacturing by highlighting the potential of SLA mold inserts for producing injection molded parts with satisfactory mechanical properties. The ability to rapidly fabricate mold inserts using SLA technology offers advantages in terms of cost, lead time, and design flexibility. However, further investigations are required to optimize the parameters of the mold inserts made with SLA additive manufacturing and explore their long-term durability and repeatability.

The implication of using molding inserts made with SLA additive manufacturing in the injection molding process causes some unwanted consequences, among which is the appearance of differences in the mechanical characteristics of the manufactured plastic parts. Within this paper, the objective was to investigate the strength of the injection molded parts using the declared strength of the injection molded material from the manufacturer as a reference value for evaluating the obtained material properties.

In conclusion, this study demonstrates that molding inserts made with SLA additive manufacturing can be successfully used for injection molding, producing parts with comparable mechanical properties to those manufactured using traditional steel molds. This research provides valuable insights into the design and optimization of SLA mold inserts, paving the way for cost-effective and time-efficient manufacturing processes in various industries that heavily rely on injection molding.

Based on this research, it can be concluded that the stereolithographic photopolymer from which the mold is made has a generally negative impact on the mechanical characteristics of the manufactured parts, especially on the toughness of the material. Given that the rest of the process parameters were maintained at constant values during injection, this assumption holds validity. However, due to the limited quantity of test specimens, further investigation into this phenomenon is warranted. This is particularly crucial, with a specific emphasis on the method and duration of mold cooling. Previous research in this field has established that the thermal characteristics of photopolymers, notably their low thermal conductivity, emerge as potential factors contributing to the diminished mechanical characteristics observed in parts produced within molds of this nature..

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