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WASTE PAPER MOLDING USING 3D PRINTED TOOLS

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Abstract: *The subject of this paper includes research into the possibility of using different waste paper materials for the production of new graphic packaging, in order to reduce the percentage of paper waste, give new life to waste paper materials, and reduce the production and use of virgin paper packaging materials. The subject of this paper also includes research into the possibility of using the FDM technique of additive manufacturing in the production of molds for casting, that is, the design of future paper packaging. The molding process is used to form the shape of paper pulp, while the forming process is used to form the shape of solid paper materials.*

Keywords: packaging, paper pulp, recycled paper, 3D printing

1. INTRODUCTION

The packaging industry is one of the world economy sectors with the fastest growing trend. For many years, packaging has been the focus of political and consumer campaigns to address environmental issues. Packaging creates significant impacts on the environment at all stages of its life cycle, however, these cannot be isolated from the impact of the product it protects. The life cycle of packaging represents a series of interrelated stages through which packaging as a product goes, from obtaining raw materials to its final disposal as waste. It begins with the production of packaging materials and packaging, continues its life cycle with packaging and storage of products, and ends as discarded packaging (Lazić & Novaković, 2010). Although packaging is crucial for the preservation of packaged products, used and discarded packaging can represent a significant environmental problem. In 2019, the total volume of packaging waste generated was estimated at 79.6 million tons, which is an increase of 2.8% compared to 2018. Over the ten-year period, paper and cardboard were the main packaging waste generated, contributing 32.3 million tons to the total packaging waste generated in 2019. Plastic packaging reached a total of 15.4 million tons as the second most significant material (+26.4% compared to 2009). Glass packaging takes third place with 15.2 million tons (+13.9%), wooden packaging 12.4 million tons (+19.8%) and metal packaging 4 million tons in 2019 (+6.7%) (Eurostat Statistics Explained, 2020). Daily per capita waste generation in high-income countries is projected to increase by 19% by 2050, compared to low- and middle-income countries where it is expected to increase by approximately 40% or more (The World Bank, 2022). Plastics and polymer packaging materials are increasingly used worldwide in a wide range of applications, with global production exceeding 300 million tons per year as of 2014 (Plastic Europe, 2016). Due to their durability, low recycling rate, poor waste management, and widespread use, waste polymer packaging can represent a significant problem. Inadequate disposal of polymer packaging and other polymer products causes many harmful defects, leading to more and more plastic being found in natural aquatic and terrestrial ecosystems (Gvoka et al., 2022). The study found that more than 4.8 million metric tons of plastic waste enter the oceans from land each year, and that figure may be as high as 12.7 million metric tons (Cohen, 2015). If current trends continue, oceans could contain more plastic than fish by 2050 (Horejs, 2020). Moreover, food polymer packaging contains a great number of small particles known as microplastics. Scientists have detected microplastics everywhere they have looked: in deep oceans; in Arctic snow and Antarctic ice; in shellfish, table salt, drinking water, beer, and drifting in the air or falling with rain over mountains and cities. These tiny pieces could take decades or more to degrade fully (Lim, 2021). The solution to this problem certainly lies in replacing polymer packaging, primarily polymer wrapping materials, with paper-based packaging whenever possible. Paper is a composite structure in layers with different porosity, obtained by random arrangement of cellulose fibers (Aydemir et al., 2021). It is a widely available material that can be recycled up to four times without significantly losing its characteristics. Each paper changes its physical, mechanical and chemical properties over time - paper ageing – and the process is irreversible (Boeva et al., 2020). If coated or laminated papers, which are coated with other materials to improve their properties, are not used, paper is a biodegradable alternative that is healthy for humans and the environment, as it takes four to six weeks for its complete decomposition, depending on the depositing conditions.

Today, packaging based on cellulose fibers plays a significant role in the storage and transportation of goods. This packaging is most often made from waste paper material, such as newspapers, used cardboard, and so on. These materials give new life to paper waste and reduce the amount of virgin paper used in packaging to an acceptable minimum. Today, paper pulp is fully recyclable and is considered an environmentally friendly material. It is significantly cheaper to produce, is completely biodegradable, and has no harmful effects on the physical, chemical, and mechanical properties of the product (Gvoka et al., 2022). The quality of the printed image is a function of maintaining the parameters of the printing process within precise limits. Since cast pulp packaging is made from waste paper, it is necessary to use dyes and bleaches in order to improve the optical properties of the material and enable satisfactory print reproduction as substrate whitens is one of the most important parameters in correct colour reproduction (Spiridonov & Shopova, 2013; Spiridonov et al., 2013; Spiridonov et al., 2012; Bozhkova et al., 2017; Spiridonov et al., 2012). Once this is satisfied, it is possible to print elements of the graphic design of the packaging on it, by adding environmentally sustainable inks in the mixture of paper pulp, it is possible to change the colour of the packaging itself, making it more attractive to consumers, and it is also possible to imprint important informative graphic elements directly into the texture of the packaging itself in the process of molding.

2. RESEARCH METHODS

In order to perform the experiment, it was necessary to define the geometry of the tool for forming process. The tool has consisted of two separate mold halves. One half of the mold is designed to form the hollowed-out pattern, while the other half is forming the shape of the sample itself. The overall dimensions of both halves are 50x50 mm, with a draft angle of 2^{o}. It was necessary to design guiding elements that would enable an adequate matching of both halves, without the possibility of shearing, which could later result in an irregular pattern. While modelling the tool, it was necessary to consider a gap of 1.5 mm, which also represents the thickness of the sample material, necessary for the correct forming of the samples. One of the influential factors that needed to be tested was the variable depth, therefore tool pairs were modeled for indentation depths of 1 mm, 3 mm, 5 mm, and 7 mm. These CAD models were created using 3D software Autodesk Inventor Professional 2022, and then converted to an STL document, suitable for further processing in the software Ultimaker Cura 4.11.0. Before 3D printing, imported STL files of the tool model were necessary to be prepared for printing and this preparation included the correct orientation of the model to the printer's platform, adequate scaling of the model to reproduce the realistic values of the given dimensions, and defining parameters of the FDM printing process.

The tool models were printed in the laboratory at the Department of Graphic Engineering and Design, at the Faculty of Technical Sciences in Novi Sad, with an FDM 3D printer Creality 3D CR-10s Pro V2. Each model is printed individually with the addition of the initial layers of the substrate, centered on the platform, to avoid possible printing errors, which has proven to be good practice on this device. Material PET-G 3031 was used for printing, due to its hardness, flexibility, and moisture and gas resistance. In Figure 1 printed models of tools are shown.

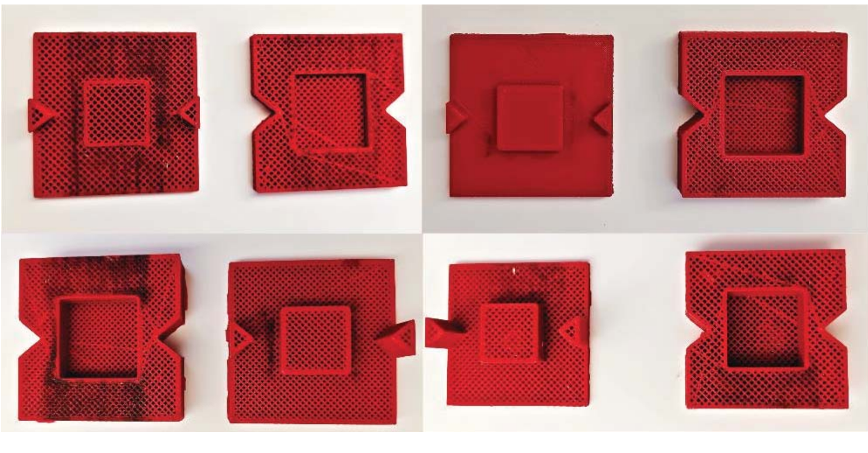


Figure 1: Models of tools printed with FDM 3D printing technology

For the realization of the experiment, it was necessary to prepare two types of samples: (1) paper pulp based samples and (2) samples from waste paper materials in trays. White offset paper with a weight of 80 g/m^2, collected as waste paper material in the laboratory of the Department of Graphic Engineering and Design, was used as the basic material for the production of paper pulp, which was previously cut into pieces whose dimensions are 20x10 mm. The paper was first immersed in a tank filled with a solution of water and dispersion adhesive, and then blended until a thick pasty mixture – the pulp - was obtained. After the pulp was created, it was necessary to press out the excess water through a screen with a weave density of 150 threads, and then create a sample that was 1.5 mm thick, and whose dimensions are 35x60 mm.

The materials that were used in the experiment to create samples represent the most common examples of paper packaging waste and they are: offset paper with a weight of 80 g/m^2, natron paper with a weight of 40 g/m2, newspaper with a weight of 40 g/m^2, tissue paper with a weight of 25 g/m^2, corrugated cardboard (three-layer) weighing 500 g/m^2 and solid grey cardboard weighing 620 g/m^2. These materials are readily available and were collected as waste material in the Department of Graphic Engineering and Design laboratory, except tissue paper. Samples of each material were first cut to dimensions of 35x60 mm in order to fit the molding tool and then stacked according to the sheet-on-sheet principle in layers of 1.5 mm thickness. After preparing the material and forming the stacks, it was necessary to immerse the stacks in a solution of dispersion glue and warm water, so that the paper materials would absorb the water. In contact with water, the fibres swell and the intermolecular forces in the material are released, which makes the paper material flexible for reshaping.

The experiment of pressing the samples and forming the desired shape was performed at the Department of Graphic Engineering and Design, using a Shimadzu Compact Tabletop Testing EZ-LX device, with a measuring cell intended for forces of 2500 N, with a speed of movement of the pressure head of 100 mm/s, at a temperature of 25 ± 2^{o}C and relative humidity of 50 ± 5%. The experiment procedure involved positioning and fixing the tool for forming the shape of the samples on the compressive strength test plates, by taping one half to the lower plate and the other to the upper plate, and then placing the sample on the surface of the mold half. Using Trapezium X software, the device is programmed to apply a pressure force of 2000 N to the sample for each test, in Compression mode, for a duration of 30 seconds. At that moment, the pressure plate, together with the upper molding half, is lowered, squeezing the excess water out of the material through the grid structure of the tool made of polyethylene terephthalate and forming a sample of the material. When the scheduled time expires, the upper pressure plate is lifted manually, by entering the value on the control panel, the formed sample is taken out of the lower half, taken to dry and a new sample is placed in its place for subsequent testing. Testing was performed five times for each material, and it is shown in Figure 2.

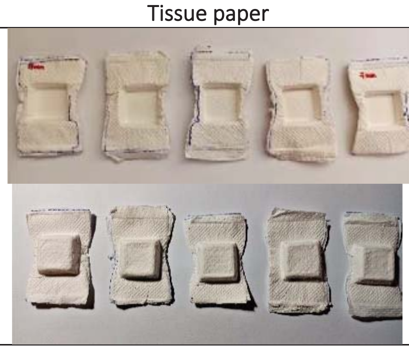
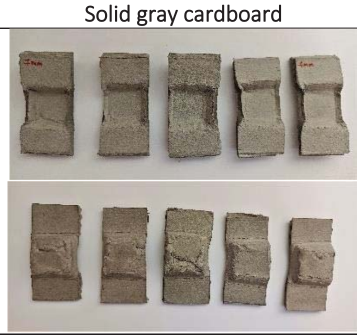
Figure 2: Sample formation on the Shimadzu Compact Tabletop Testing EZ-LX device

3. RESULTS AND DISCUSSION

3.1 Reproducibility of results within the reproduction of the same depth

Table 1 shows the results of samples made from a layer of waste paper materials, whose layer height is 1.5 mm, and which were formed with a 7 mm deep mold and dried at a temperature of 100°C for 20 minutes. The criteria for evaluating samples are the uniform depth of the sample, the clarity of the edges, the reproduced geometry, and material damage.

Table 1: Results of samples made from a layer of waste paper materials produced by molds with a depth of 7 mm

Material	White offset paper	Tissue paper
Picture		
Depth uniformity	The depth is uniform in all five samples	The depth is uniform in all five samples
Clarity of the edge	Satisfactory	Satisfactory
Reproduction of geometry	Satisfactory	Satisfactory
Material damage	Material damage occurs at the bottom of 3 samples	Material damage did not occur
Material	Natron paper	Newspaper
Picture		
Depth uniformity	The depth is uniform in all five samples	The depth is not uniform in all samples
Clarity of the edge	Not so satisfying	Satisfactory
Reproduction of geometry	Not so satisfying	Satisfactory
Material damage	Material damage occurs at the bottom of 4 samples	Material damage occurs in all samples
Material	Corrugated cardboard	Solid gray cardboard
Picture		
Depth uniformity	The depth is uniform in all five samples	The depth is uniform in all five samples
Clarity of the edge	Satisfactory	Satisfactory
Reproduction of geometry	Satisfactory	Not so satisfying
Material damage	Material damage occurs in all samples	Material damage occurs in all samples

Based on the produced samples, it is possible to conclude that the best reproduction of the geometry was observed on samples made of tissue paper and offset paper, while significant damage was observed on samples made of newspaper and solid cardboard. In the case of samples made of natron paper, one can see the vagueness of the edges. The repeatability of the samples can be seen in Figures 3, 4, 5, 6, 7, and 8. Based on these graphs, it is possible to establish that the repeatability of the samples is at an extremely high level and that most materials are characterized by a similar growth trend, except for tissue paper.

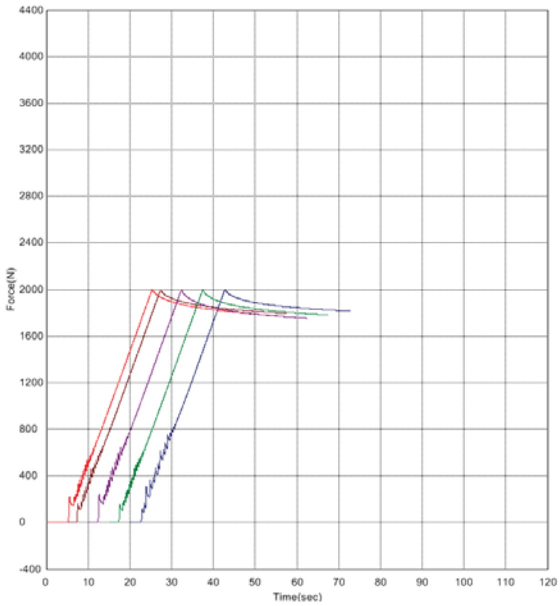


Figure 3: Curve of pressure force in defined pressing time for offset paper samples

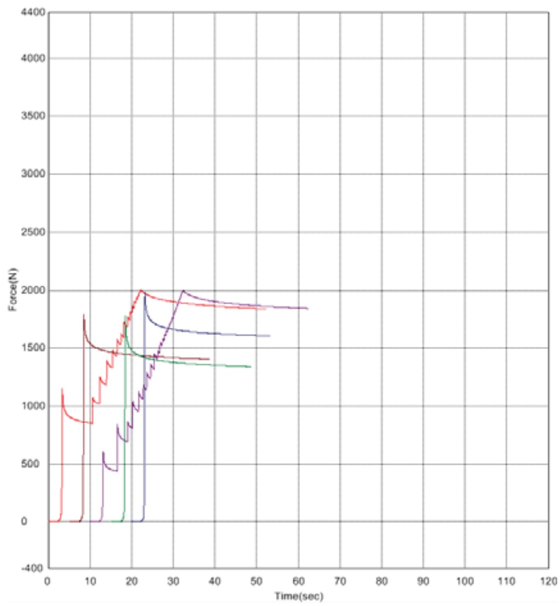


Figure 4: Curve of pressure force in defined pressing time for tissue paper samples

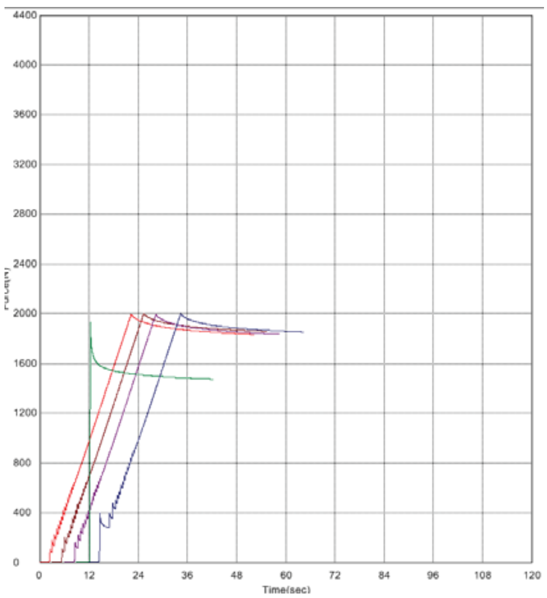


Figure 5: Curve of pressure force in defined pressing time for natron paper samples

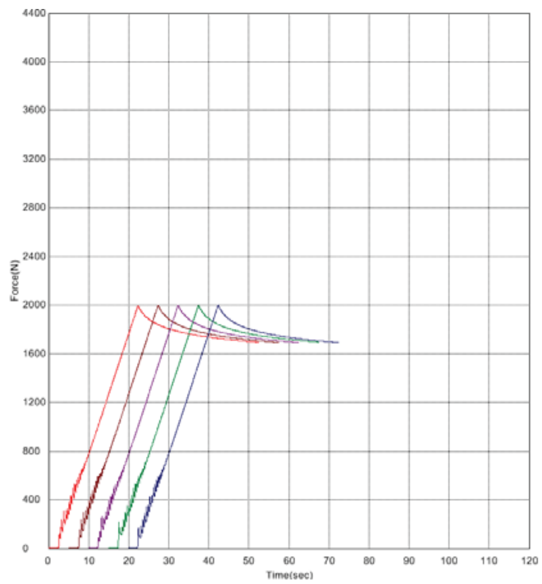


Figure 6: Curve of pressure force in defined pressing time for newspaper samples

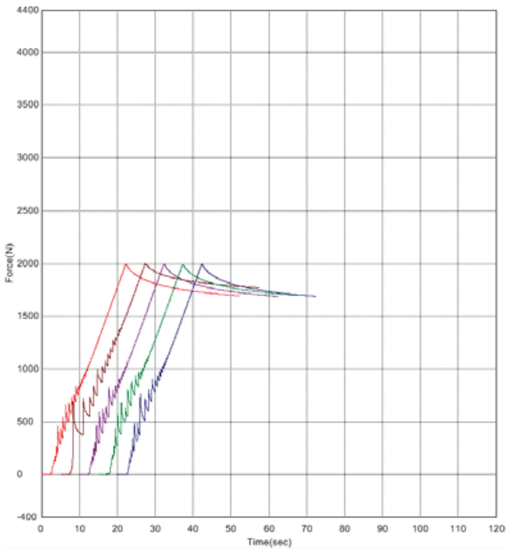


Figure 7: Curve of pressure force in defined pressing time for corrugated cardboard samples

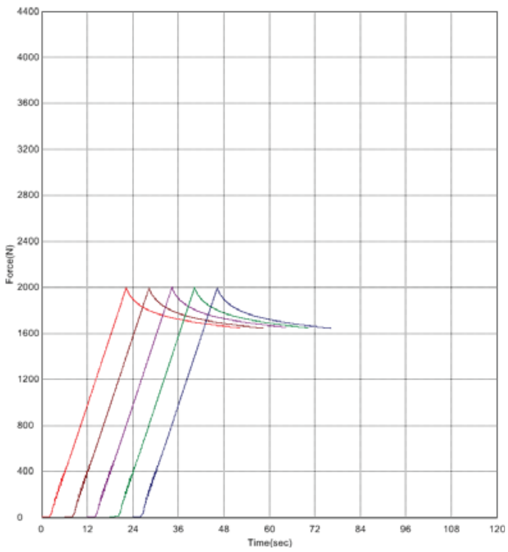


Figure 8: Curve of pressure force in defined pressing time for solid gray cardboard samples

3.2 Evaluation of formed samples of the various depth made of the same materials

Table 2 shows the results of samples made of layers of material, the layer height of which is 1.5 mm, and which were shaped by molds with a depth of 7 mm, 5 mm, 3 mm, and 1 mm. The criteria for evaluating the model are, as in the previous case, the clarity of edges, reproduced geometry, and material damage.

Table 2: Results of samples made from a layer of waste paper materials produced by molds with various depth

Material	White offset paper	Tissue paper
Picture		
Depth uniformity	Uniform in all samples for each depth	Uniform in all samples for each depth
Clarity of the edge	Satisfactory	Satisfactory
Reproduction of geometry	Satisfactory	Satisfactory
Material damage	Material damage occurs in 2 samples	Material damage did not occur
Material	Natron paper	Newspaper
Picture		
Depth uniformity	Not uniform in all samples for each depth	Not uniform in all samples for each depth
Clarity of the edge	Not so satisfying	Satisfactory, except in the 1mm sample
Reproduction of geometry	Satisfactory, except in the 1mm sample	Satisfactory, except in the 1mm sample
Material damage	Material damage occurs in the 7mm sample	Material damage occurs in 3 samples
Material	Corrugated cardboard	Solid gray cardboard
Picture		
Depth uniformity	Uniform in all samples for each depth	Uniform in all samples for each depth
Clarity of the edge	Satisfactory, except in the 1mm sample	Satisfactory, except in the 1mm sample
Reproduction of geometry	Satisfactory, except in the 1mm sample	Satisfactory, except in the 7mm sample
Material damage	Material damage occurs in 3 samples	Material damage occurs in all samples

Based on the produced samples, it is possible to conclude that the best reproduction of the geometry was observed on samples made of tissue paper and offset paper, while significant damage was observed on samples made of newspaper and solid cardboard. In the case of samples made of natron paper, a deviation is observed in the geometry reproduction, which is significantly noticeable in the case of a 1 mm sample. It is also possible to conclude that the best reproduction occurs with 5 mm samples, while reproduction problems were observed mainly with all 1 mm samples. However, with 1 mm samples, there is no noticeable damage to the material. The best clarity of the edges is visible in samples made of solid cardboard and tissue paper for all depths.

3.3 Comparison of samples made from a stack of offset paper and paper pulp based on offset paper

Figure 9 shows the results of samples made from offset paper stacks and the results of samples made from cast paper pulp. Both types of samples were obtained using a tool with a depth of 5 mm and a pressure force of 2000 N for 30 seconds.

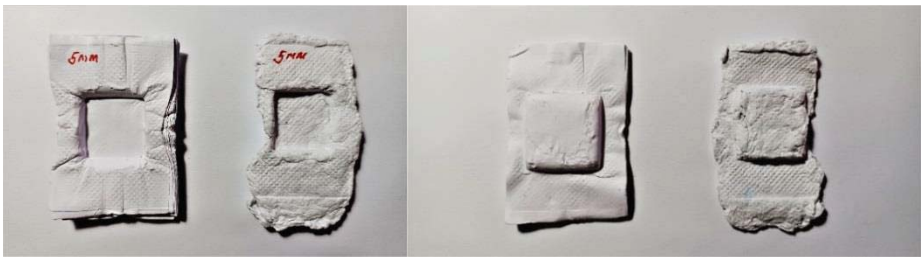


Figure 9: Results of forming samples from offset paper and paper pulp at a depth of 5 mm

After comparing these samples, it was determined by the method of visual quality assessment that the samples made from the offset paper stack proved to be a better choice compared to the paper pulp samples, in terms of the shaping of the material under the influence of pressure force. With paper pulp samples, the reproduction of clear geometry proved problematic due to the intermolecular forces acting within the structure of the material being molded. In terms of resistance to material damage, both materials proved prone to damage to the bottom of the back of the sample. Also, with the sample made of cast paper pulp, the appearance of cracks in the structure of the material was observed, which could pose a problem when using this material for the production of packaging. During the pulp creation process, it was noticed that the production of paper pulp requires the use of a significant amount of water, which, after this process, is contaminated with fibres and other substances such as printing ink, and is released into the effluent. Although the production of paper pulp is considered a good form of recycling waste paper materials, this is a rather dirty process that can have as a negative consequence great amounts of contaminated waste water, which would have to be further purified before being discharged into the effluent. Also, during this experiment, it was determined that the failed pulp can be reused for the production of new pulp, but this results in significantly shortened fibres, which can negatively affect the mechanical and other properties of the samples.

4. CONCLUSIONS

In addition to the obligation that the packaging must fulfil towards the potential customer, it also has an obligation towards health and preservation of the environment. With the increase in the volume of serial production, there is an increasing amount of packaging waste, which, due to improper handling and inadequate disposal, increasingly becomes a polluter of aquatic and terrestrial ecosystems. This is precisely why it is necessary to consider the use of healthy, alternative, environmentally sustainable materials for the production of graphic packaging. Based on the performed experiment, it is possible to conclude that the samples made of waste paper materials, primarily offset paper and corrugated tape, proved to be satisfactory in terms of forming and reproduction of geometry. In the majority of samples made of waste paper material, damage to the material can be seen, especially on the samples made with a 7 mm depth tool, while the samples made with a 5 mm depth tool proved to be the optimal solution. After comparing samples, it was determined by the method of visual quality assessment that the samples made from the offset paper stack proved to be a better choice compared to the paper pulp samples, in terms of the shaping of the material under the influence of pressure force.

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